United States General Accounting Office

GAO

Report to the Chairman, Committee on Science, Space, and Technology, House of Representatives

October 1991

AEROSPACE PLANE TECHNOLOGY

Research and Development Efforts in Japan and Australia

GAO United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

B-235387

October 4, 1991

The Honorable George E. Brown, Jr.
Chairman, Committee on Science,
Space, and Technology
House of Representatives

Dear Mr. Chairman:

As requested by the former Chairman, we reviewed investment in foreign aerospace vehicle research and technological development efforts. Supporters of the National Aero-Space Plane Program in the Congress are concerned about foreign competition to the program and its impact on U.S. technological leadership. We briefed representatives of the former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), House Committee on Science, Space, and Technology, previously on the results of our review. This report discusses investment in Japanese and Australian aerospace vehicle research and technological development efforts.

This report is the third in a planned series of reports on aerospace investment in foreign countries. We issued our first report, Aerospace Technology: Technical Data and Information on Foreign Test Facilities (GAO/NSIAD-90-71FS), on June 22, 1990. We issued our second report, Aerospace Plane Technology: Research and Development Efforts in Europe (GAO/NSIAD-91-194), on July 25, 1991. A subsequent report will address aerospace investment in the Soviet Union.

We are sending copies of this report to the Secretaries of Defense, State, Commerce, the Air Force, and the Navy; the Administrator, National Aeronautics and Space Administration; and the Directors, Defense Advanced Research Projects Agency, Strategic Defense Initiative Organization, Central Intelligence Agency, Office of Management and Budget, and Office of Science and Technology Policy in the Executive Office of the President. We are also sending copies of this report to other interested parties and will make copies available to others.

Please contact me at (202) 275-4268 if you or your staff have any questions concerning this report. Major contributors to this report are listed in appendix I.

Sincerely yours,

Nancy R. Kingsbury

Nancy R. Kingsbury
Director
Air Force Issues

Executive Summary

Purpose

U.S. leadership and preeminence in the research and development of aerospace plane technologies are being challenged by Japan and other countries. U.S. leadership and preeminence are based on the National Aero-Space Plane Program. As discussed in our prior report on European aerospace plane technology, congressional supporters of the program are concerned about foreign competition and its impact on U.S. technological leadership.

The former Chairman of the House Committee on Science, Space, and Technology asked GAO to identify indicators to measure foreign countries' current state of aerospace plane technological development and progress. The indicators were selected based on the interests of Committee representatives and on discussions with experts. These indicators are (1) space policies and aerospace goals and objectives; (2) aerospace plane program objectives, design goals, schedules, and costs; (3) the current status and rate of progress in the development of critical technologies; (4) the funding for and the number and type of people involved with the programs; (5) test facilities and their capabilities; and (6) the existence of and interest in international cooperation. The former Chairman also asked GAO to collect data and information on the indicators.

Background

The National Aero-Space Plane Program, expected to cost more than $5 billion between fiscal years 1986 and 1997, is a joint Department of Defense/National Aeronautics and Space Administration technology development and demonstration program to build and test the X-30 experimental plane. The program is to develop critical technologies for future hypersonic aerospace planes, which could achieve speeds up to 25 times the speed of sound in air. The program also plans to build and test the X-30 to validate the critical technologies. These technologies include an air-breathing engine that requires air for combustion of its fuel; materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; and advanced computer programs to simulate the effects of the airflow around flight vehicles by solving a set of mathematical equations with a high-speed computer. The program's goal is to demonstrate single-stage-to-orbit space launch capability with horizontal takeoff and landing.

This report focuses on efforts in Japan, since it is developing technologies and conducting feasibility studies for various concepts of operational aerospace planes. Also, efforts in Australia are included because it supports technology development efforts through national research and the use of its test facilities.

Results in Brief

Japan is conducting feasibility studies and developing critical technologies needed for various concepts of operational aerospace planes primarily to achieve autonomy. However, Japan has not officially approved any plan to build an aerospace plane. The United States also has not approved a plan to build an aerospace plane.

The United States is ahead of Japan in hypersonic aerospace plane technologies because of its more technologically challenging National Aero-Space Plane Program. However, Japan is making a determined effort to challenge U.S. superiority in hypersonics, particularly in engines and materials.

Current and planned levels of investment in air-breathing aerospace plane research and technological development efforts by the Japanese government and industry are significantly less than current and planned U.S. government and industry investment in the National Aero-Space Plane Program.

Japanese test facilities are adequate for fundamental research and current efforts in Japan. However, they are not adequate for large-scale testing or developing an aerospace plane. Although Australian test facilities also are not adequate for large-scale testing, they provide a unique capability to test aerospace vehicles up to orbital velocity.

Individually, Japan does not pose a serious challenge to U.S. preeminence in hypersonic aerospace plane technologies. Japan is unlikely to develop and build an aerospace plane by itself because of the extensive technology and funding requirements. However, a major international collaborative effort between Japan and the European Space Agency, or with European countries, and/or the Soviet Union could be competitive with the National Aero-Space Plane Program.

Principal Findings

Japanese Aerospace Plane Programs Are Primarily Concept Studies

Japan is developing the technologies required for various concepts of an aerospace plane to secure independent manned access to space, reduce the cost of launching payloads into orbit, and ensure a competitive role in future high-speed commercial transport aircraft markets. Principal concepts include the National Space Development Agency of Japan's H-II Orbiting Plane, the Institute of Space and Astronautical Science's Highly Maneuverable Experimental Space vehicle, and the National Aerospace Laboratory's single-stage-to-orbit aerospace plane. Each concept is being designed to be launched vertically or take off horizontally from a runway, reach hypersonic speeds, attain orbit, and return to land on a runway.

The United States Is Ahead of Japan in Hypersonic Technology

The United States is ahead of Japan in the development of three critical technologies: air-breathing engines, materials, and advanced computer programs using high-speed computers for design and testing. Moreover, the United States is the only country that has tested major large-scale components of an air-breathing aerospace plane.

U.S. Investment Is Significantly Greater Than Japanese Investment in Aerospace Plane Programs

U.S. government and industry have invested almost $1.8 billion in the National Aero-Space Plane Program between fiscal years 1986 and 1990. Japan has only invested a total of about $150.4 million between 1982 and 1990 in various air-breathing aerospace plane concept studies. The U.S. government plans to spend about $864 million on the National Aero-Space Plane Program from fiscal years 1991 to 1993 and a considerably larger amount in subsequent years if a decision is made to build and flight test the X-30. Future U.S. industry contributions are expected to be marginal. The Japanese government and industry plan to spend up to about $751.2 million between 1990 and 1998 on various air-breathing aerospace plane programs.

Japanese Test Facilities Are Inadequate for Developing and Testing Aerospace Planes

Although the United States is ahead in terms of facility size, productivity, and testing techniques, Japan's rate of progress in refurbishing and modifying old facilities and building new ones is significantly greater than that of the United States. However, only with the development of better test facility instruments and more trained personnel, together with the renovation and modification of older facilities and construction of new facilities, will adequate support be available in Japan for testing aerospace planes.

International Hypersonic Collaborative Effort Could Be Competitive With the United States

The Japanese government, with the support of industry, is developing vehicle concepts and the technology for a broad range of applications on a national basis before seeking international partners. Development of an experimental plane would probably be an international effort, since Japan does not intend and is not presently capable of developing and building an aerospace plane alone because of the extensive technological requirements, tremendous costs, and lack of adequate test facilities. Any future operational aerospace plane built in Japan would also be an international effort. However, the combined convergence of national interests, expertise, approaches, funding, and sharing of test facilities involving Japan and the European Space Agency, European countries, and/or the Soviet Union in a major international collaborative effort in hypersonics could, in the long term, prove to be competitive with the National Aero-Space Plane Program. Although collaborative efforts with the United States on the National Aero-Space Plane Program appear unlikely, the program could benefit from Japanese engine and materials technologies and the use of Australian test facilities.

Recommendations

GAO is not making recommendations in this report.

Agency Comments

GAO did not obtain official agency comments on this report. However, GAO provided a draft of this report to Department of Defense and National Aeronautics and Space Administration officials and incorporated their comments where appropriate.

Contents

Abbreviations

GAO	General Accounting Office
HIMES	Highly Maneuverable Experimental Space [vehicle]
HOPE	H-II Orbiting Plane
HOTOL	Horizontal Takeoff and Landing
NASP	National Aero-Space Plane
scramjet	supersonic combustion ramjet

Introduction

U.S. aeronautical leadership and preeminence are being challenged by Japan's development of a technological basis for future aerospace vehicles. Currently, U.S. aeronautical leadership and preeminence in hypersonics[1] are based on the National Aero-Space Plane (NASP) Program. However, NASP supporters in the Congress are concerned that without a major and sustained initiative in hypersonics, the U.S. lead in aeronautics will be challenged by other countries.

Japan is developing the technologies and conducting feasibility studies for various concepts of operational aerospace vehicles. Australia is developing competence in selected subsystems for future aerospace vehicles, and its facilities are being used to test various U.S. and European aerospace vehicle concepts and components. Australia also conducted feasibility studies for an international spaceport on its Cape York Peninsula that would accommodate future aerospace planes. Australia's investment in aerospace vehicle research is discussed in chapter 8.

U.S. Aeronautical Preeminence in Hypersonics

U.S. aeronautical preeminence in hypersonics is currently based on the NASP Program—a more than $5 billion joint Department of Defense/ National Aeronautics and Space Administration technology development and demonstration program to provide the technological basis for future hypersonic flight vehicles. The program plans to build and test a manned experimental flight vehicle, the X-30, to validate critical or enabling technologies by demonstrating sustained hypersonic cruise[2] and single-stage-to-orbit space launch capabilities. The X-30 is being designed to take off horizontally from a conventional runway, reach hypersonic speeds of up to Mach 25 (25 times the speed of sound, which is orbital velocity), attain low earth orbit, and return to land on a conventional runway. The NASP Program is expected to develop and demonstrate the technology for future NASP-derived vehicles that will have technical, cost, and operational advantages over existing military and commercial aircraft and space launch systems.

[1]Technical terms are defined in the glossary.

[2]The X-30 is being designed as an accelerator vehicle with the primary goal of achieving single-stage-to-orbit capability. Hypersonic cruise capability is now viewed by NASP Program officials as a fallout from the single-stage-to-orbit capability. Specific cruise speed and maneuvering capability while landing are no longer requirements for the X-30. The diminished emphasis on hypersonic cruise is due to both technical and financial considerations. Also, a vehicle designed for hypersonic cruise would look considerably different from a vehicle designed primarily as an accelerator, single-stage-to-orbit space launch vehicle.

The X-30 will be an experimental flight vehicle. It will not be a prototype or operational vehicle. It has no operational mission or requirements. Also, the X-30 will not be a full-scale version of future operational aerospace vehicles. Potential users of a future aerospace plane probably will not develop specific missions or identify firm operational requirements until the X-30's capabilities have been demonstrated.[3]

Many NASP supporters in the Congress are concerned that terminating or delaying the NASP Program will jeopardize the U.S. lead in hypersonics. Having lost U.S. leadership to Japan in other industries, such as automobiles and electronics, some view Japan's space goals as a potential threat to U.S. leadership and preeminence in aeronautics. Others believe that a slower NASP technology maturation phase will not adversely affect U.S. leadership. Still others believe that without a major and sustained initiative in hypersonics, U.S. aeronautical leadership and preeminence will be challenged by other countries' development of technologies for operational aerospace vehicles. A key factor in the National Space Council's July 1989 recommendation to continue the NASP Program, but at a slower pace than the original schedule, is the desire to maintain the U.S. lead in aerospace technologies into the 21st century.

Principal Japanese Aerospace Vehicle Concepts or Systems

The National Space Development Agency of Japan, Institute of Space and Astronautical Science, and National Aerospace Laboratory are independently conducting research and development of technologies for separate, but complementary aerospace vehicle concepts or systems. The principal concepts include the National Space Development Agency of Japan's H-II Orbiting Plane (HOPE), the Institute of Space and Astronautical Science's Highly Maneuverable Experimental Space (HIMES) vehicle, and the National Aerospace Laboratory's single-stage-to-orbit aerospace plane. These concepts are briefly described below and are discussed in more detail in chapter 3.

The National Space Development Agency of Japan's HOPE spaceplane is being studied as an operational, unmanned, reusable, shuttle-like reentry winged vehicle. Expected to be launched vertically by the H-II

[3]For a detailed and technical description of the NASP Program, including U.S. government and industry investment in the program, see our report, National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30 (GAO/NSIAD-88-122, Apr. 27, 1988).

rocket booster, the spaceplane would return to earth and land horizontally on a runway. Although not an air-breathing aerospace plane, HOPE would serve as a technology demonstrator, have an interim operational capability, and be an intermediate step in developing a future Japanese air-breathing aerospace plane.

The Institute of Space and Astronautical Science's HIMES vehicle would be an unmanned, reusable, single-stage ballistic flight test vehicle. HIMES is being designed as a boost-glide vehicle to be launched vertically using rocket propulsion or by a rocket-powered wheeled-trolley or sled and land horizontally. The aerospace plane would serve as a test bed for hypersonic flight and air-breathing engines as well as expand the capabilities of sounding rockets in the upper atmosphere. HIMES also would be an intermediate step in developing a future air-breathing aerospace plane.

The National Aerospace Laboratory's single-stage-to-orbit aerospace plane would take off horizontally from conventional airports, use air-breathing or reusable rocket engines to leave the atmosphere, travel to space stations or other orbital platforms, and return to land horizontally on a runway.

These three Japanese spaceplane[4] concept or system studies are coordinated in a step-by-step approach to develop a future aerospace plane. However, Japan has not officially decided to build a future aerospace plane.

Indicators of Aerospace Vehicle Technological Development and Progress

The indicators we used to measure foreign countries' interest, commitment, and capability to develop and build an air-breathing aerospace vehicle and the current state of aerospace vehicle technological development and progress were selected based on the interests of representatives of the former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), House Committee on Science, Space, and Technology. The indicators were also based on discussions with U.S. government and

[4] Japanese government officials and industry representatives use the terms spaceplane and aerospace plane interchangeably. References to a spaceplane in Japanese documents encompass an aerospace plane as well. In this report, we refer to the HOPE shuttle-like reentry winged vehicle as a spaceplane, since HOPE would be vertically launched by a rocket booster. We refer to the HIMES boost-glide vehicle and single- and two-stage-to-orbit space launch vehicles as aerospace planes, since they would use air-breathing engine cycles in their propulsion systems.

aerospace industry program managers, scientists, and engineers. These indicators are

- foreign governments' space policies and aerospace goals and objectives, if any, for developing, or participating in the development of, air-breathing aerospace vehicles;
- current and future aerospace vehicle program objectives, design goals, schedules, and costs;
- the current status and rate of progress in the development of enabling technologies;
- investment by foreign governments, industries, and universities in aerospace vehicle research and technological development efforts in terms of funding and the number and type of people working on these efforts;
- test facilities and their capabilities; and
- international cooperation.

Enabling Technologies

Enabling technologies are critical to the successful development and demonstration of future hypersonic flight vehicles. These include an air-breathing propulsion system using, for example, a turboramjet or supersonic combustion ramjet (scramjet); advanced materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; and computational fluid dynamics and supercomputers for aerodynamic, structural, and propulsion system design.

Failure to successfully develop and demonstrate any of the enabling technologies could adversely affect Japanese (and other countries') aerospace vehicle programs. Also, the enabling technologies must be fully integrated, since the design of one component can affect the performance of another component. Enabling technologies are discussed in more detail in chapter 4.

Organizational Roles and Responsibilities

The roles and responsibilities of the principal Japanese government organizations and companies involved in aerospace vehicle research and technological development are discussed below.

Space Activities Commission

Space activities in Japan are initiated by the Office of the Prime Minister. The Space Activities Commission, an advisory body to the Japanese Prime Minister, establishes Japanese space policy and guidelines for carrying out Japan's space development. The Commission sets long-term policies on space development activities in Japan and works to unify space activities of various government agencies and to actively promote these activities. In 1987 the Commission's Committee on Long-Term Policy issued a study on the Fundamental Guidelines of Space Policy that recommends how to proceed with Japan's space activities into the 21st century. In 1989 the Commission reviewed and updated the study to reflect changes in Japanese space development state of the art and new international research and development efforts. The Commission determines the schedule of space development in Japan and will decide which spaceplane concept to pursue.

According to officials at the U.S. Embassy in Tokyo, the Commission's space planning objectives are considered so important to Japan's future that they are one of the few technological areas specifically coordinated within the Office of the Prime Minister. The Commission facilitates cooperation and collaboration among Japan's government and quasi-government space agencies (e.g., the National Space Development Agency of Japan, Institute of Space and Astronautical Science, and National Aerospace Laboratory).

Science and Technology Agency

The Science and Technology Agency plans and promotes fundamental Japanese space policy, coordinates space activities between government agencies, and conducts research and development activities through the National Aerospace Laboratory. As the administrative arm for the Space Activities Commission, the Agency also acts as a liaison and conducts negotiations among various government agencies. In 1986 the Agency established a committee to coordinate spaceplane development activities.

National Space Development Agency of Japan

The National Space Development Agency of Japan is Japan's primary space agency. It was established to promote space activities and contribute to fostering space development and utilization. A government corporation, the Agency is supervised by the Science and Technology Agency together with the Japanese Ministry of Transport and Ministry of Posts and Telecommunications. Headquartered in Tokyo, the Agency operates aerospace test facilities throughout Japan.

The Agency is responsible for developing, managing, and implementing major Japanese space programs, including the $2 billion Japanese

Experimental Module,[5] H-II launch vehicle, and remote sensing satellites. The Agency is also responsible for Japan's satellite launch, tracking, and control centers. The Agency is conducting research on satellite and launch vehicle technologies and the launch and tracking of satellites. The Agency implements space programs in cooperation with other related organizations. As Japan's primary space research and development organization, the Agency's purpose is not to implement commercial space programs.

The Agency operates orbital launch facilities at Tanegashima Space Center on Tanegashima Island in the extreme southwest corner of Japan. The Tsukuba Tracking and Control Center in Tsukuba serves as the primary satellite command facility. Associated tracking and data acquisition stations are located at Katsuura, Okinawa, and Masuda at the Tanegashima Space Center. Facilities at the Ogasawara Downrange Station on Chichijima Island in the Bonin Island Chain, the Okinawa Downrange Station, and the Christmas Downrange Station on Kiritimati Island[6] in Kiribati in the Line Islands provide downrange tracking of satellite launches. The Agency's Earth Observation Center is located in Saitama near Tokyo. The Agency's Kakuda Propulsion Center in Kakuda near Sendai is responsible for testing high-performance propulsion systems. The Agency's major technical facility is located at the Tsukuba Space Center in Tsukuba Science City north of Tokyo.

Institute of Space and Astronautical Science

The Institute of Space and Astronautical Science is one of the National Inter-University Research Institutes funded and administered by the Japanese Ministry of Education, Science, and Culture. The Institute is the central organization in Japan for scientific space research and is responsible for research and development of scientific satellites and related launch vehicles. The Institute is headquartered along with the Space Utilization Research Center at its Sagamihara campus near Tokyo and consists of several research centers at major Japanese universities.[7]

In 1966 the Japanese government determined that, in principle, space development would be the exclusive preserve of the National Space

[5]The Japanese Experimental Module is being designed as a pressurized laboratory to conduct microgravity experiments in materials and life sciences. The module would join three similar modules (two American and one European) in becoming a permanent part of the planned U.S. space station

[6]In October 1990 Christmas Island was renamed Kiritimati Island.

[7]The Institute's academic character stems from its establishment in 1981 by a reorganization of the Institute of Space and Aeronautical Science at the University of Tokyo.

Development Agency of Japan, but as a special exception, the Institute of Space and Astronautical Science could continue with its development of space science and technology in an academic environment. The Institute is restricced to (1) scientific research missions, (2) small research rockets,[8] and (3) launches from the Kagoshima Space Center at Uchinoura on the southern tip of Kyushu Island. Even with these restrictions, the Institute has accumulated an innovative technological base. For example, the Institute launched two spacecraft in 1985 to probe Halley's Comet. In January 1990 the Institute launched a lunar probe, making Japan only the third country (after the Soviet Union and the United States) to place a spacecraft in orbit around the moon.

In contrast to the Space Development Agency, the Institute concentrates solely on space science applications. The separate missions of the two organizations fulfill Japan's space development policy of different strategies for science and technology. The goal of the Institute is to develop space science, while the goal of the Space Development Agency is to develop space technology. Nonetheless, cooperation exists between the two agencies. For example, the Space Development Agency's H-II solid fuel boosters are based on technology developed by the Institute for its rockets. The Institute relies on the Space Development Agency's ground tracking stations to collect data during launch of its satellites. However, the Executive Director of the Space Development Agency indicated there is very little collaboration in planning projects. He suggested rivalry between the two agencies could intensify if the Ministry of Finance, which determines whether projects like spaceplane development are funded, questions the efficiency of funding two agencies to conduct similar work.

In addition to its Sagamihara research center, the Institute's principal facilities are the Kagoshima Space Center in Uchinoura, a launch facility about 50 miles north of the Tanegashima Space Center, the Noshiro Testing Center in Noshiro City in northwestern Japan, Sanriku Balloon Center in Sanriku in northeast Japan, Usuda Deep Space Center in Usuda in central Japan, and Space Data Analysis Center and Space Utilization Research Center at Sagamihara near Tokyo.

The Institute's Kagoshima Space Center in Uchinuora is primarily a sounding rocket launch site. It averages one satellite launch every 1 to 2 years. In comparison, the Space Development Agency's

[8]Originally the diameter of the Institute's rockets could not exceed 1.4 meters. This restriction was lifted by the Space Activities Commission in 1989.

Tanegashima Space Center is more active than the Institute's Kagoshima Space Center, since it launches more meteorological, communications, and remote sensing satellites. Launches from both sites, however, are restricted to launch seasons from January to February and August to September because of range safety procedures and concerns by the influential fishing lobby. Japanese fishermen are concerned about the loss of revenue during launches. However, the fishermen are apparently compensated for launches conducted outside of the launch seasons.

National Aerospace Laboratory

The National Aerospace Laboratory was established as a subsidiary organization of the Office of the Prime Minister to expedite the development of aeronautical technology in Japan. After the Science and Technology Agency was created, the Laboratory was placed under its administration.

The Laboratory is the Science and Technology Agency's principal aviation and space technology research organization. It maintains close liaison with the Space Development Agency, with which it jointly conducts various experiments. The Laboratory offers its research data to other organizations and conducts basic as well as advanced studies in aeronautical and space technology.

Headquartered in the Chofu district of Tokyo, the Laboratory has test facilities at its Chofu Airfield Branch and Kakuda Branch in Kakuda near Sendai. Japan's large-scale test facilities (such as wind tunnels, jet engine test cells, rocket engine high-altitude test stands, and supercomputer complexes) are located at the Laboratory's three sites.

The Space Activities Commission's space development policy directs the Laboratory's research on advanced space technology. The Laboratory is one of several laboratories in Japan that promote fundamental aerospace technologies. In aeronautics, its goals are to establish a technology base for future vehicle development. As of March 1991, about 20 percent of the Laboratory's 330 researchers were involved in work on future aerospace plane technology. The Laboratory is pursuing research on innovative component technologies under a program of Research and Development for Innovative Aerospace Transport Systems. This research program focuses on aerodynamics, composite materials, flight control, propulsion, numerical stimulation, and life support technology.

The Laboratory's research activities for hypersonic flight began in 1965 with construction of a hypersonic wind tunnel at Chofu. Research activities for an advanced aerospace plane began in 1987, and overall vehicle definition work began in 1988. Flight control and numerical simulation activities were initiated in 1989 and life support technologies in 1990. Officials at the Laboratory stated that the Laboratory plans to evaluate all research activities in 1991 and 1992 to assess technology maturation. However, as of March 1991, this plan had not yet been approved.

National Aerospace Laboratory officials acknowledge Japan has no hypersonic flight experience. Moreover, flight testing to further hypersonic technology is not well understood. Also, a substantial technology gap exists between Japan's state of the art and the required level of technology to develop an aerospace plane.

To address these conditions, the National Aerospace Laboratory developed objectives to (1) identify feasible aerospace vehicle configurations, (2) assess the status of Japan's technology, (3) identify technology needs, (4) define existing capabilities to satisfy these needs, (5) examine the role that flight testing can fulfill in advancing the technology, and (6) outline the technology advancement and related facilities construction programs.

A Liaison Group for Spaceplane Research and Development has been tentatively established between the National Space Development Agency of Japan, Institute of Space and Astronautical Science, National Aerospace Laboratory, industry, and universities to coordinate development of a future Japanese spaceplane.

Ministry of International Trade and Industry

The Ministry of International Trade and Industry has several small laboratories that conduct space-related work, but its primary role is the promotion of future commercial space applications. The Ministry has identified space development as a potentially strategic technology for the 21st century and one that could benefit from Japan's expertise in electronics and engineering. The Ministry has been involved in the development of various technologies that relate to the industrial utilization of space since the establishment of its Space Industry Division. The Ministry promotes space activities in Japan through financial strategies, such as low interest loans and tax deductions. Formations of cooperative ventures among companies to carry out specific projects are also used as inducements.

Japanese industry is organized into several space-related private organizations to promote the development of space technology. Within the Keidanren, or Federation of Economic Organizations, the Space Activities Promotion Council has a membership of 96 companies. The Council provides a coordinating committee for the membership and is a liaison between its membership and the Japanese government. The Society of Japanese Aerospace Companies, with 147 members, is another group that promotes a coordinated effort among aerospace industries to further space technology development. In 1988 the Society recommended the development of supersonic and hypersonic transports. The Japan Space Utilization Promotion Center, as well as numerous smaller consortia and organizations of companies, promote various commercial space applications. Japanese aerospace officials advocate advancing Japan's hypersonic technology so that Japan can join the United States or other countries in building such a vehicle.

Japan's principal aerospace companies include Mitsubishi Heavy Industries, Kawasaki Heavy Industries, Ishikawajima-Harima Heavy Industries, and Fuji Heavy Industries. Also, large Japanese construction companies, such as Shimizu, Taisei, and Ohbayashi, are working on spaceplane-related transportation concept plans.

Mitsubishi, the lead contractor for the Space Development Agency's H-II launch vehicle, is developing the H-II's LE-7 engine. Mitsubishi is conducting many of the H-II's tests at its Tashiro Test Center in Akita. Nissan Motor Company, one of Japan's leading automobile manufacturers, is developing the H-II's solid fuel boosters.

Japanese industry is working with the Space Development Agency and National Aerospace Laboratory on computational fluid dynamics software, advanced materials, vehicle aerodynamics, and system integration for the HOPE program. Fuji's primary expertise is advanced materials development. Kawasaki is conducting research on integrating structures. Mitsubishi is conducting research on integrating propulsion, structures, aerodynamics, and the total system. However, Science and Technology Agency and Space Development Agency officials stressed that the role of each company for the development of HOPE has not been determined or based on each company's primary expertise.

Aerospace plane research is also being conducted at Japanese universities. The University of Tokyo had been involved in space development for 14 years prior to the establishment of the Space Development Agency in 1969. Other national universities involved in aerospace research include the University of Kyushu, University of Kyoto, University of Nagoya, Tohoku University, University of Hokkaido, and the University of Osaka.

All seven national universities serve as formal and informal advisers to government and industry on aerospace plane development. University research is funded by both public and private organizations. Joint studies on aerospace plane technologies are also conducted between the National Aerospace Laboratory and the University of Tokyo. Cooperative research agreements permit universities to use the Laboratory's facilities.

Objectives, Scope, and Methodology

The former Chairman of the House Committee on Science, Space, and Technology asked us to identify indicators (discussed on p. 12) to measure foreign countries' current state of aerospace vehicle technological development and progress. The former Chairman also asked us to collect data and information on foreign government and industry investment in aerospace vehicle research and technological development efforts, focusing on those critical or enabling technologies that could allow foreign countries to develop and build future aerospace vehicles. The former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), which has authorization and oversight responsibility for the National Aeronautics and Space Administration's aeronautical research and technology programs, including the NASP Program, is particularly concerned about foreign competition to the NASP Program and future NASP-derived operational aerospace planes. NASP supporters in the Congress are concerned that, without a major and sustained initiative in hypersonics, the U.S. lead in aeronautics will be challenged by other countries.

This report is the third in a planned series of reports on aerospace investment in foreign countries. Our first report was in response to the Committee's request that we provide it with technical data and information on foreign aerospace test facilities to assess foreign countries' research, development, and testing capabilities for future aerospace vehicles.[9] The Committee is particularly interested in the potential use of key foreign test facilities by the NASP Program.

[9] For technical data and information on principal European, Japanese, and Australian aerospace test facilities (wind tunnels and air-breathing propulsion test cells) and their capabilities, see our report, Aerospace Technology: Technical Data and Information on Foreign Test Facilities (GAO/NSIAD-90-71FS, June 22, 1990).

Our second report was in response to the Committee's request that we provide it with information on investment in European aerospace vehicle research and technological development efforts.[10] This report focuses on efforts in France, Germany, and the United Kingdom, since they are developing technologies and conducting feasibility studies for various concepts of operational aerospace planes. Also, efforts in The Netherlands, Belgium, and Italy are included because these countries support technology development efforts through national research and the use of their test facilities. In addition, this report discusses the efforts of the European Space Agency because it promotes cooperation in space research and technology among its 13 member countries. A subsequent report will address aerospace investment in the Soviet Union.

The scope of our review was primarily limited to future air-breathing aerospace vehicles, since they could provide competition to NASP or future NASP-derived operational vehicles. Our review included Japan, since Japan is developing the technological basis for various concepts of future aerospace vehicles. In addition, we included facilities (such as wind tunnels) in Australia. Although Australia does not have a national program to develop and build an air-breathing aerospace vehicle, it supports the technology development and its test facilities are being used to conduct research and development of such vehicles by other countries and the European Space Agency.

We collected technical data and information on test facilities, their capabilities, and the number of people working on aerospace vehicle research and development in those countries included in our review. Facilities include (1) wind tunnels and shock tunnels, (2) air-breathing propulsion test cells (engine test facilities for ramjets and scramjets), (3) aerothermal test facilities, (4) aeroballistic and impact ranges, (5) advanced materials research, development, production, and fabrication laboratories, and (6) aerodynamic computation facilities (supercomputers). We also collected cost information on test facilities, including construction, replacement, annual operating, and user cost, where available.

Our methodology involved reviewing studies and pertinent documents and interviewing appropriate officials in Washington, D.C., at the Departments of Defense, the Air Force, State, and Commerce; the

[10]For information on aerospace investment in Europe, see our report, Aerospace Plane Technology: Research and Development Efforts in Europe (GAO/NSIAD-91-194, July 25, 1991).

Defense Advanced Research Projects Agency; NASP Interagency Office;[11] National Aeronautics and Space Administration; Central Intelligence Agency; and the Office of Science and Technology Policy in the Executive Office of the President. We also met in Washington, D.C., with officials of Gellman Research Associates, Inc., of Jenkintown, Pennsylvania, to discuss their methodology for analyzing government support for civil aeronautical research and technology expenditures in France, the United Kingdom, Germany, The Netherlands, and Japan; and with officials of the Washington Office of the National Space Development Agency of Japan.

We also visited the NASP Joint Program Office, the Foreign Technology Division of the Air Force Systems Command, and Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Dayton, Ohio; Arnold Engineering Development Center and the Foreign Technology Division of the Air Force Systems Command, Arnold Air Force Base, Tullahoma, Tennessee; and Lovelace Scientific Resources, Inc., Albuquerque, New Mexico, to discuss its approach and methodology for comparing world civil space programs.

We met with Air Force, National Aeronautics and Space Administration, and contractor officials, scientists, and engineers to help us develop our approach and methodology, determine key enabling technologies, and identify specific data requirements needed to measure the status of a country's technological maturation and capability to develop and build a future air-breathing aerospace vehicle.

Our methodology also involved reviewing studies and pertinent documents; interviewing appropriate U.S. Embassy, international organization, and foreign government, industry, and university officials; and visiting key test facilities in Japan and Australia. The organizations and locations where we conducted our review work in Japan and Australia are discussed below.

[11]Three offices have responsibility for the NASP Program. The NASP Interagency Office in Washington, D.C., coordinates the NASP Program among participating agencies and military services. It also provides oversight, furnishes policy guidance, and maintains support for the program within the U.S. government. The NASP Joint Program Office at Wright-Patterson Air Force Base, Dayton, Ohio, is responsible for overall management and coordination of the NASP Program. It also implements the technical program and manages the contracts. The NASP National Program Office in Seal Beach, California, integrates the prime contractors into one program office under a single program director It directs the contractor team's effort through a single contract with the U.S. government, provides program guidance, ensures adequate contractor team resources, reviews program progress, and resolves contractor team disputes.

Japan

We conducted review work in Tokyo at the U.S. Embassy, Office of Naval Research, Air Force Office of Scientific Research, Army Research Office, Ministry of International Trade and Industry, Science and Technology Agency, Space Activities Commission of Japan, National Space Development Agency of Japan, Ishikawajima-Harima Heavy Industries, Kawasaki Heavy Industries, Mitsubishi Heavy Industries, and The Japan Society for Aeronautical and Space Sciences; in Chofu at the National Aerospace Laboratory; in Sagamihara at the Institute of Space and Astronautical Science; in Tanegashima at the Space Development Agency's Tanegashima Space Center; in Tsukuba at the Agency's Tsukuba Space Center; in Uchinoura at the Institute's Kagoshima Space Center; in Utsunomiya at Fuji Heavy Industries; in Gifu at Kawasaki Heavy Industries; and in Nagoya and Komaki at Mitsubishi Heavy Industries.

We also visited the Japanese Experimental Module mock-up and space vehicle assembly building at the Space Development Agency's Tsukuba Space Center in Tsukuba; Takesaki Range small rocket launch site, Osaki Range Control Center, Mobile Service Tower for the H-I rocket booster, Static Firing Test Facility for the LE-7 engine, Yosinobu Range for the H-II rocket launcher, and the Masuda Tracking and Data Acquisition Center at the Space Development Agency's Tanegashima Space Center in Tanegashima; wind tunnels, materials laboratory, computational fluid dynamics facility, and computer center at the National Aerospace Laboratory in Chofu; sounding rocket launch sites, Mobile Service Tower, balloon launch area for the HIMES vehicle, and data tracking and acquisition center at the Institute of Space and Astronautical Science's Kagoshima Space Center in Uchinoura; wind tunnels under construction and three HIMES gliding flight test vehicles at the Institute in Sagamihara; wind tunnels, materials laboratories, computer centers, and engine test stands at Fuji Heavy Industries in Utsunomiya, Kawasaki Heavy Industries in Gifu, and Mitsubishi Heavy Industries in Nagoya and Komaki.

In addition, we conducted a 1-day Workshop on Japanese Aerospace Vehicle Investment and Technologies at GAO in Washington, D.C., with representatives from the NASP Joint Program Office Fact Finding

Group,[12] who also visited Japan to share technical data and information and exchange views based on the results of our visits to Japan.

Australia

We conducted review work in Canberra at the U.S. Embassy; Department of Physics and Theoretical Physics of The Australian National University; Office of Space Science and Applications of the Commonwealth Science and Industry Research Organization; Australian Space Office of the Department of Industry, Technology, and Commerce; and the National Aeronautics and Space Administration; in the Australian Capital Territory at the Tidbinbilla Space Tracking Station; in Brisbane at the Department of Mechanical Engineering of the University of Queensland; and in Adelaide at British Aerospace Australia.

We also visited the T-1, T-2, and T-3 Shock Tunnels at The Australian National University and T-4 Shock Tunnel at the University of Queensland.

We provided a draft of this report to officials from foreign government and industry organizations in Japan and Australia and asked them to review, verify, and, if necessary, update the information. Their comments have been incorporated in the report where appropriate.

We used annual average exchange rates to convert foreign currencies into U.S. dollars.

We did not obtain official written agency comments on this report. However, we provided a draft of this report to officials from the Department of Defense and National Aeronautics and Space Administration and several U.S. experts in hypersonics for their review. We discussed the information presented in this report with these officials and experts and incorporated their technical and editorial comments where appropriate.

We conducted our review between March 1988 and October 1990 in accordance with generally accepted government auditing standards.

[12] Members of the Fact Finding Group consisted of representatives from the NASP Joint Program Office, Office of Science and Technology Policy, McDonnell Douglas Corporation, and Rockwell International Corporation. The group visited Japan in October 1988 to (1) exchange information about the status of and plans for spaceplane development in Japan and the United States, (2) understand the problems and technical barriers to spaceplane development, and (3) explore specific technical areas for possible use on NASP or for possible collaborative development.

Japanese Space Policies and Aerospace Goals and Objectives

Japan does not have an established national research and development program to build an aerospace plane. However, Japan's aerospace goals and objectives include plans for developing a space transportation system motivated, in part, by its desire for autonomy and a reliable space launch vehicle. Japan's objectives are to secure an independent manned access to space and make launching payloads into orbit more economically viable. According to the High Commissioner of the Space Activities Commission, who advises the Japanese Prime Minister on space activities, and the Director for Space Transportation Research in the Science and Technology Agency, Japan does not intend to use the knowledge gained in hypersonic technology development programs at this time to develop future supersonic and hypersonic commercial transport aircraft.

The Japanese government and industry are conducting concept studies and developing the critical or enabling technologies necessary for future air-breathing aerospace vehicles through various national programs. Development of a flight demonstrator to validate the technologies and actual flight testing of an unmanned or manned[1] aerospace vehicle is also expected to be a Japanese national effort. However, building any future operational Japanese aerospace vehicle would require an international effort.

Space Policies and Aerospace Goals and Objectives for Developing Air-Breathing Aerospace Vehicles

The Challenger accident in January 1986 delayed the launch of several Japanese space programs and provided a strong impetus to the Japanese desire for autonomy in space transportation. The Japanese realized their space plans, particularly those with commercial implications, had been too dependent upon the United States—a nation, at times, perceived as less technologically reliable than Japan. Also, the Japanese desire for autonomy in space has been driven by U.S. technology transfer policies, which have been particularly irritating to the Japanese. For example, the United States would not permit the use of U.S. technology in any Japanese launch vehicle used for foreign commercial launches. As a result, the Japanese are now developing the H-II launch vehicle using only Japanese technology. According to National Aeronautics and Space Administration officials, the Challenger accident and the difficult negotiations over questions of partnership and access to the planned U.S. space station caused Japan to reexamine its space program.

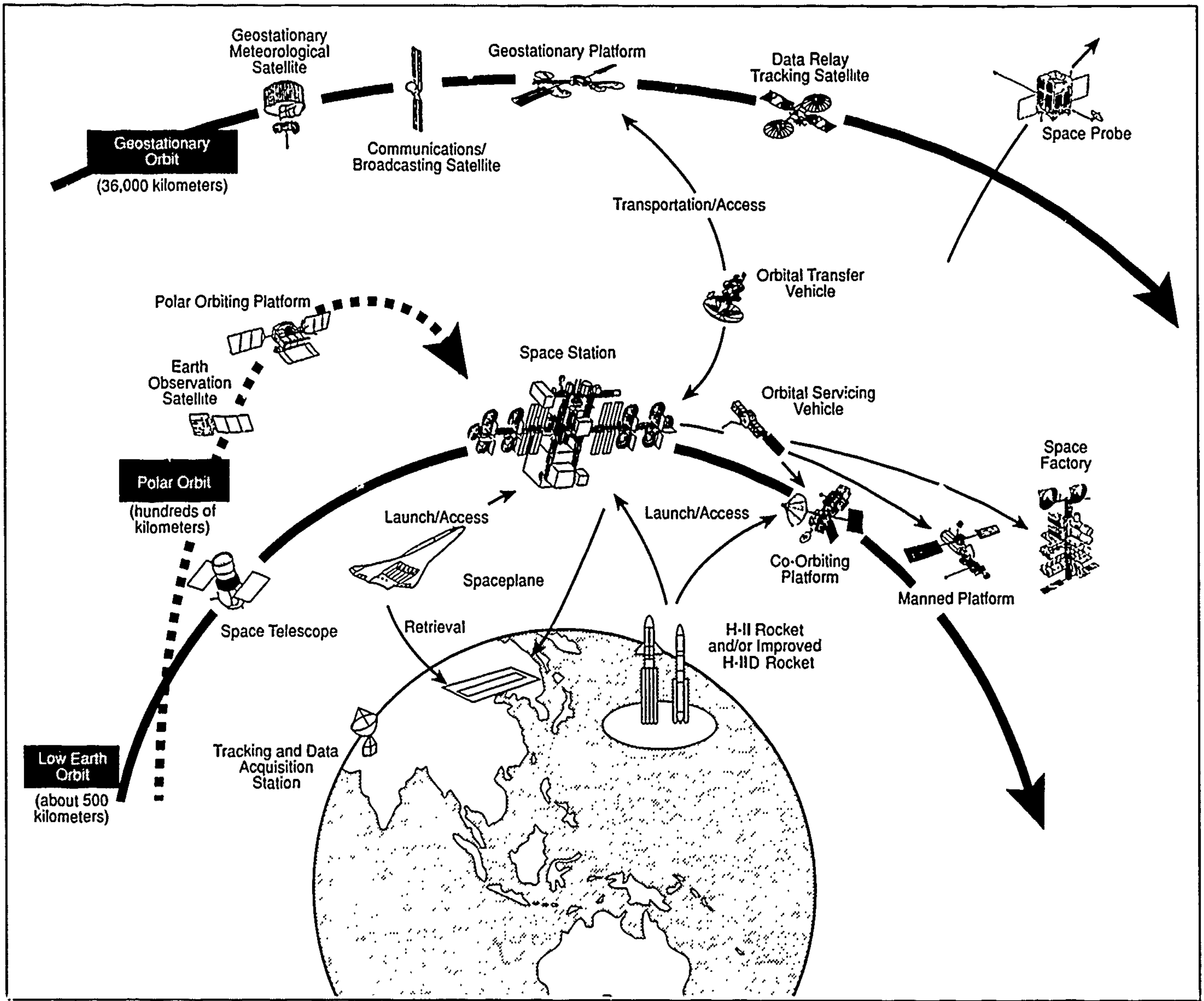
[1] Actual flight testing of a manned Japanese aerospace vehicle has not been scheduled.

Japan's space policy, contained in the Fundamental Guidelines for Space Policy, provides the basis for planning, programming, and promoting specific space development activities. The policy is intended to guide Japan's space activities for the next 15 years. Revised by the Space Activities Commission in June 1989, the Fundamental Guidelines state that it is essential for Japan to maintain and advance independent space transportation technology to meet future space activities. After developing the H-II launch vehicle and HOPE spaceplane, Japan intends to develop anunmanned reusable space transportation system.

The Fundamental Guidelines state that when the planned U.S. space station becomes operational, Japan will initially rely on manned vehicles of other countries for transporting Japanese crew members to and from the Japanese Experimental Module of the space station. At the same time, basic and advanced research will be conducted on a manned spaceplane. As research progresses, the spaceplane's feasibility as a development program will be evaluated.

The establishment of a technological base and, to a much lesser extent, the development and utilization of space, are targeted by the Japanese government as space activities critical to Japan's stimulation of industrial growth. According to the Executive Director of the Space Development Agency, Japan desires to acquire key space technologies and wants to build a technology base that will enable it to play an important role in world space activities. Japanese industry, perhaps more so than any other country's industry, recognizes the commercial potential of space manufacturing and transportation systems and plans to exploit that opportunity. Figure 2.1 illustrates the scope and magnitude of planned Japanese space activities in the 21st century, including a spaceplane.

Figure 2.1: Japanese Space Activities in the 21st Century



Source: Science and Technology Agency.

Japan recognizes it needs to develop efficient space transportation systems to meet the expanding demands of future space efforts. According to the High Commissioner of the Space Activities Commission and the

Director for Space Transportation Research in the Science and Technology Agency, Japan's objective to develop an efficient space transportation system is not to establish manned, permanent facilities in space. Accordingly, the Japanese government has not officially approved a plan to develop and build an aerospace plane. Even the development phase of the HOPE project has not been formally approved by the Japanese government. According to a Ministry of International Trade and Industry official, horizontal takeoff and landing aerospace vehicles are still vague concepts. The Ministry official said he did not know which aerospace plane concept the government will decide to pursue. This was confirmed by the High Commissioner of the Space Activities Commission who told us a date for deciding whether to build a spaceplane has not been determined and no decision has been made regarding which spaceplane concept Japan will pursue.

The United States also has not approved a plan to build an aerospace plane. In fact, no commitment exists to build the X-30 experimental vehicle. A decision on whether to build and test the X-30, based primarily on cost and the maturity of the technologies, is expected to be made in April 1993.

In 1986 the Science and Technology Agency's Advisory Committee on Space Plane was established to review Japan's long-term research and development of a spaceplane. The Committee recommended that:

- space transportation systems, such as spaceplanes, should be fundamental elements of Japan's vision of a space infrastructure to promote future space activities;
- development of spaceplanes is indispensable to Japan's autonomous space activities;
- spaceplanes will improve international space launch options by eliminating the current reliance on limited launch means; and
- spaceplane research and development efforts would provide a technology base for the development of next-generation hypersonic transports.

In 1988 the Science and Technology Agency's Space Plane Evaluation Committee reported that the goal of Japan's future manned space transportation should be based upon Japan's current technology and a need to develop safe, reliable, and economical systems. According to National Aerospace Laboratory officials, development of a reusable, winged, horizontal takeoff and landing manned vehicle or aerospace plane would fulfill this requirement. The Committee recommended that development of a spaceplane should be advanced as a national goal for Japan.

As shown previously in figure 2.1, a future Japanese spaceplane is just one part of a much larger commercial space infrastructure that is dependent on advanced technology. The future Japanese spaceport design concept shown in figure 2.2 indicates the Japanese are concentrating not just on development of a spaceplane, but on the supporting infrastructure as well. According to Japanese government officials, Japan views space as a way to let the rest of the world know that it has a technologically advanced society. The Japanese government views space activity as a field that requires international cooperation, rather than as a field that demonstrates the advancement of space-related technology.

Proposals for spaceports in Japan are part of a planning process not seen in the United States or Europe to build a consensus within Japanese society for developing a future spaceplane and its accompanying infrastructure. Such proposals not only provide for future regional economic development, but also serve as a link between development of a spaceplane and the Japanese people. The Japanese are selling the idea of spaceports to the general public, since competition will be for the entire space infrastructure, not just a spaceplane. Additional Japanese spaceport concepts are discussed in chapter 3.

Figure 2.2: Future Japanese Spaceport Design Concept

Source: Hokkaido Prefecture.

Japanese Aerospace Vehicle Programs

Japan is conducting research and development on three different but coordinated spaceplane concept or system studies that consist of fundamental research on enabling technologies. These three programs are designed to develop the enabling technologies in a step-by-step approach to achieve Japan's goal of building an air-breathing single-stage-to-orbit aerospace plane.

The National Space Development Agency of Japan is studying HOPE as an operational, unmanned, reusable, shuttle-like reentry winged vehicle. Launched vertically by the H-II rocket booster, currently under development, HOPE would service the Japanese Experimental Module of the planned U.S. space station. Although not an air-breathing aerospace plane, HOPE would serve as a technology demonstrator for a future Japanese air-breathing aerospace plane and provide Japan with an unmanned space launch capability. The Institute of Space and Astronautical Science is conducting research and development of HIMES as a reusable, single-stage ballistic flight test vehicle with rocket propulsion to serve as a test bed for hypersonic flight and air-breathing engine technology. HIMES also would be an intermediate step in developing a future air-breathing aerospace plane. The National Aerospace Laboratory is conducting research and development on aerospace plane enabling technologies, developing an experimental hypersonic flight vehicle, and studying concepts for single- and two-stage-to-orbit[1] air-breathing aerospace planes.

National Space Development Agency of Japan's HOPE Spaceplane and H-II Launch Vehicle

The National Space Development Agency of Japan's HOPE spaceplane is planned to be launched by the H-II rocket booster in 1999. HOPE would be unmanned, perform autonomous scientific and engineering experiments in orbit, obtain hypersonic aerodynamic flight experience, and establish a technology base for future aerospace plane development.

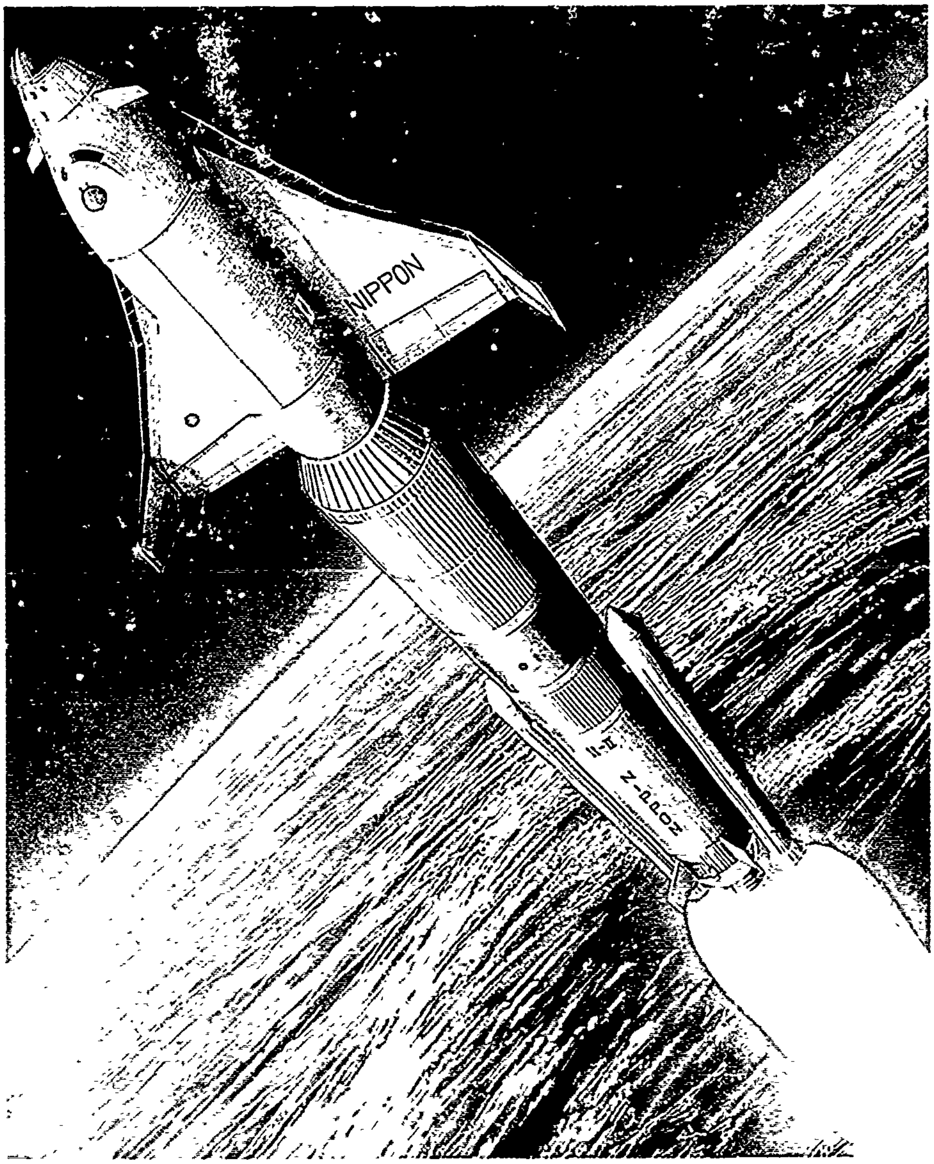
[1] A single-stage-to-orbit vehicle would take off horizontally from a conventional runway, reach hypersonic speeds, attain low earth orbit, and return to land on a conventional runway. A two-stage-to-orbit vehicle would consist of an air-breathing first stage, which would take off and land from a conventional runway, and a rocket-propelled upper stage, which, at a certain altitude, would separate and continue into orbit. The second stage, a reentry winged vehicle, would glide back to earth and land on a conventional runway. A two-stage-to-orbit vehicle could also consist of a heavy-lift transport aircraft first stage and a rocket-propelled second stage.

HOPE Spaceplane

The Space Development Agency's Tsukuba Space Center is studying HOPE as an operational vehicle. It would be launched vertically by the H-II rocket booster, currently under development, from the Tanegashima Space Center, and would return to earth and land horizontally on a runway.[2] Small reaction rockets would be used for maneuvering while in orbit. Figure 3.1 shows the HOPE spaceplane being launched from Tanegashima Space Center by the H-II rocket booster.

[2]The Space Development Agency is exploring several potential HOPE spaceplane landing sites, since the facilities at Tanegashima Space Center are only designed for launching rocket boosters.

Figure 3.1: National Space Development Agency of Japan's HOPE Spaceplane and H-II Launch Vehicle



Source: National Space Development Agency of Japan.

One of HOPE's primary missions is to provide space transportation for supplying the Japanese Experimental Module of the planned U.S. space station. The space shuttle would still transport astronauts, since the shuttle is a man-rated vehicle. Other potential missions include providing transportation to and from components of future Japanese space infrastructure, such as space platforms and space factories in low earth orbit, and demonstrate the basic technology required for future space transportation systems.

HOPE would be 11 meters long, have a wingspan of 6 meters, and weigh about 10 metric tons at launch. HOPE is being designed to transport a cargo payload of about 1 metric ton into low earth orbit. However, Space Development Agency engineers acknowledge that with a payload capacity of only 1 metric ton, HOPE would not be the most efficient way to transport cargo into orbit. Typical missions are expected to last about 4 days.

The Space Development Agency is studying HOPE in a phased approach. HOPE is still in the research stage and is not yet a Japanese government-authorized development program. Phase A (Japan fiscal years[3] 1990 to 1991) is to conduct conceptual studies, define mission requirements, and begin feasibility studies. The Space Development Agency plans to request Phase B funding from the Japanese government beginning in Japan fiscal year 1992. Phase B (Japan fiscal years 1992 to 1997) will concentrate on preliminary design studies and full-scale testing.

Program costs, based on a 1988 estimate, are expected to total about $2.73 billion. This figure includes research, development, and testing through HOPE's first scheduled unmanned flight in 1999. The Director for Space Transportation Research in the Science and Technology Agency added that cost estimates for the HOPE program have not been officially approved.

Space Development Agency officials are also studying a plan to double the size of HOPE to a 20-metric ton vehicle. According to an Agency engineer, a 10-metric ton class orbiter may not be feasible, since its payload capacity may be too small. If the Agency determines that a larger spaceplane is required, then a rocket booster larger than the H-II would also be necessary. Such a rocket booster (the H-IID) would be one of the largest launchers in the world after the Soviet Energia booster and U.S. Titan IV launch vehicle. The Space Development Agency cautioned this project is still under study and configuration details have not yet been determined.

Large portions of HOPE's primary structure would be made of composite materials to reduce weight. HOPE's tip fin and wing leading edges would be constructed of a carbon-carbon composite materials or the superalloy

[3]Japan's fiscal year is from April 1 to March 31.

Rene 41. Ceramic tiles containing silica and alumina fibers would cover the fuselage. Advanced materials for HOPE's thermal protection system being studied include titanium alloy, nickel alloy, and advanced carbon-carbon, according to Space Development Agency thermal and structural engineers. Research is being conducted on new structural materials, such as graphite-polyimide composites, to support the load with the goal of finding a lightweight composite material that can replace conventional aluminum alloy.

The aerodynamic shape of HOPE's wing would be that of a double delta platform to achieve good lift characteristics during hypersonic and low-speed flight conditions. Early in the HOPE program, canards were considered for increasing lift and stabilization characteristics, but thermal and aerodynamic concerns ruled out their use. According to Space Development Agency officials, the HOPE concept is still evolving and all the dimensions, weights, and vehicle configurations could change as the design matures. During 1988 and 1989, for example, the Agency conducted about 1,600 wind tunnel tests on various HOPE configurations.

HOPE's guidance, navigation, and control system will be critical during the vehicle's orbit, rendezvous, docking, deorbit, reentry, and landing phases. The Space Development Agency and National Aerospace Laboratory are conducting research of design concepts for HOPE in aerodynamics, guidance, and structures. In 1990 the Laboratory began functional tests of a navigation and guidance subsystem at Sendai Airport. HOPE is expected to be equipped with a U.S. Navstar Global Positioning System receiver. In 1994 the two agencies plan to launch an experimental model on a suborbital trajectory to demonstrate reentry aerodynamics and guidance beginning at Mach 10.

According to the Director of Aerodynamics at the National Aerospace Laboratory's Chofu facility, the only place where HOPE hypersonic testing is being conducted is in the Laboratory's hypersonic wind tunnel, which can test models up to Mach 11. Currently, the Laboratory is using its computational fluid dynamics capability to simulate HOPE's aerodynamics.

Plans to build a spaceport for the takeoff and landing of future spaceplanes, including HOPE, are beginning to be explored in Japan, since the facilities at Tanegashima Space Center can only accommodate vertically launched rocket boosters. Potential future Japanese spaceports may include Kagoshima on Kyushu Island in southern Japan near Tanegashima, the Iwate Prefecture Spaceport on Honshu Island, and the

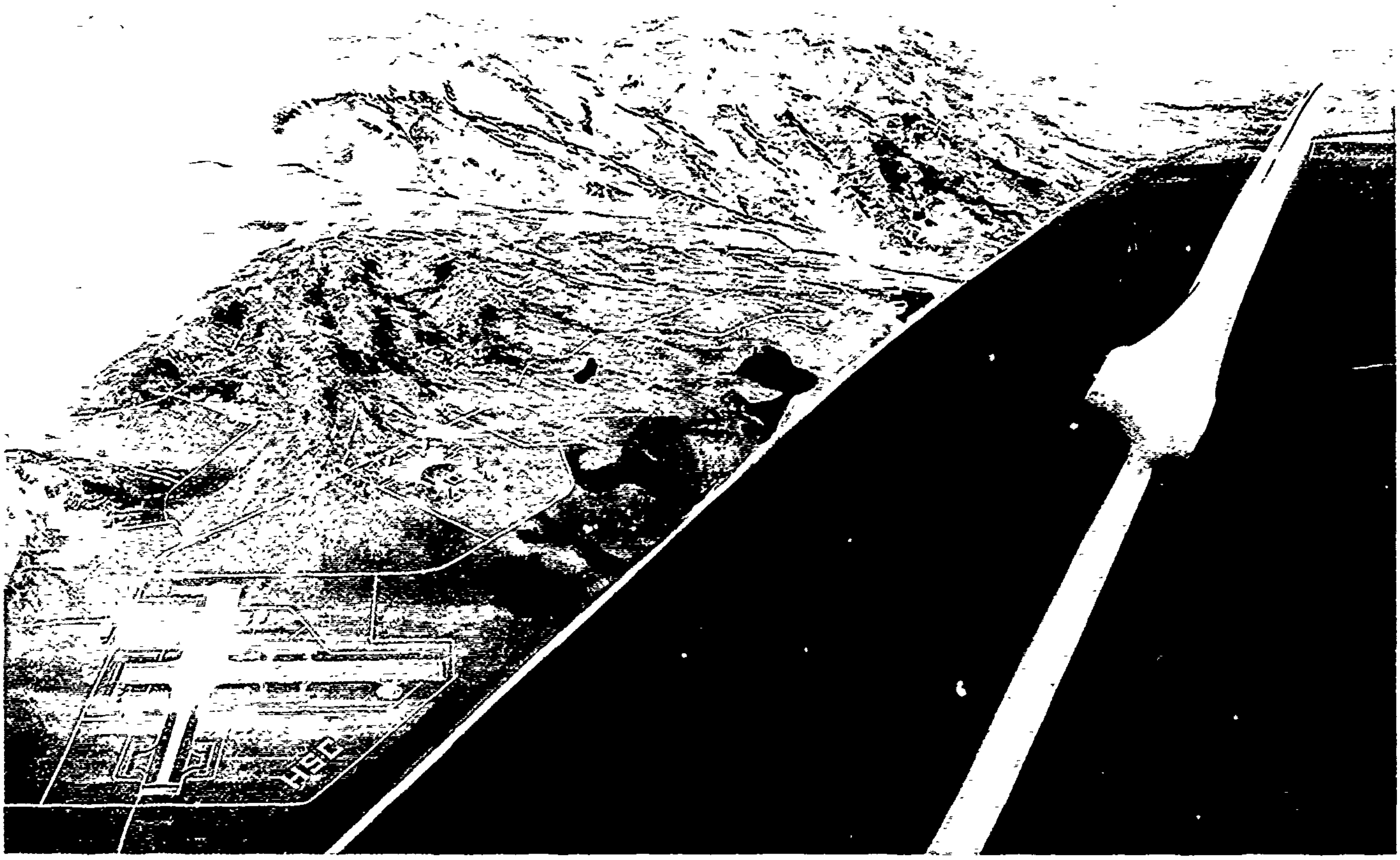
Hokkaido Space Center on Hokkaido Island in northern Japan. Figure 3.2 shows the future Iwate Prefecture Spaceport design concept as presented by the local government.

Figure 3.2: Iwate Prefecture Spaceport Design Concept

Source: Iwate Prefecture.

Figure 3.3 shows the future Hokkaido Space Center design concept as presented by the local government.

Figure 3.3: Hokkaido Space Center Design Concept



Source: Hokkaido Prefecture.

Other potential future Pacific spaceports may include the proposed Cape York International Spaceport in Australia; Kiribati in the central Pacific ocean; Kiritimati Island in the northern Pacific ocean; Hawaii; Vandenberg Air Force Base, California; and the proposed National Space Port 2000 at Edwards Air Force Base, California. Florida is also being considered as a site for a future commercial spaceport by a consortium that includes the state of Florida. The National Space Development Agency of Japan is also considering a water landing with ocean recovery for its HOPE spaceplane.

The High Commissioner of the Space Activities Commission and the Director for Space Transportation Research in the Science and Technology Agency cautioned that Japan has not yet begun a concept study of a future spaceport. The High Commissioner and Director noted that Japan has only programs to study the concept of future aerospace vehicles. They said a concept study of a future spaceport, including potential sites, is premature and should not be started until the concept study of an aerospace vehicle is completed.

Orbiting Reentry Experimental Vehicle

In 1990 the Space Development Agency began a program to establish a data base for hypersonic aerodynamic heating. The Agency plans to develop the Orbiting Reentry Experimental Vehicle to test thermodynamic heating estimations and thermal protection system designs used in the development of HOPE. The experimental vehicle would be launched from the Tanegashima Space Center on H-II's first mission in 1993. The surface of the test vehicle's thermal protection structure would be covered with advanced materials that would be evaluated for use in HOPE's thermal protection system.

Once placed into orbit by the H-II booster, the advanced materials would be evaluated as the vehicle reenters the atmosphere. The test vehicle would fire its braking rocket to reenter the atmosphere at the same angle of attack and velocity as the HOPE spaceplane. Telemetry data collected during reentry would be received before splashdown in the northern Pacific Ocean near Kiritimati Island. The vehicle would not be recovered. A Science and Technology Agency official said funding for the Orbiting Reentry Experimental Vehicle is contained in the HOPE program. According to the Space Development Agency, the total cost of this project has not been officially authorized.

H-II Launch Vehicle

The H-II launcher is being developed as a conventional two-stage expendable rocket booster to replace Japan's H-I launchers. The H-II's primary mission would be to launch satellite payloads into geostationary orbit and launch the HOPE spaceplane. The H-II is being designed as Japan's primary heavy lift launch vehicle for the late 1990s and is similar to the European Space Agency's Ariane 4 and Martin Marietta's Titan 34D launchers. According to the Space Development Agency, the H-II rocket would be capable of placing 2 metric tons of payload into geostationary orbit and 10 metric tons of payload into low earth orbit. Whereas earlier launchers rely on U.S. technology, the H-II would rely entirely on Japanese technology.

Mitsubishi is the integrator for H-II and is responsible for the second stage LE-5 engine. Ishikawajima-Harima is responsible for the main components (turbopumps) of the first stage LE-7 cryogenic engine. Kawasaki is developing the rocket's fairing, and Nissan Motor Company is developing the launcher's two solid rocket boosters. Three Japanese companies are studying the design for the H-IID, an enlarged version of H-II, that could launch a 20-metric ton HOPE spaceplane into a low earth orbit. Mitsubishi is conducting overall integration studies for HOPE and the H-IID launcher. Ishikawajima-Harima and Kawasaki are also involved in H-IID research. Although Fuji is not yet involved in H-IID research, Fuji is studying launching the larger version of HOPE using the H-IID launch vehicle.

According to Space Development Agency officials, cracks in the turbine blades of the LE-7 main rocket engine and problems with its starting sequence have plagued the engine's development. Two LE-7 engine tests at Tanegashima Space Center in 1989 ended in failure. Also, the LE-7 engine caught fire four times during engine tests.[4] These setbacks forced the Agency to delay the first H-II mission from 1992 to 1993.

According to the Space Development Agency, the LE-7 continues to experience test failures. Hydrogen gas exploded during an LE-7 fueling test in May 1991 at the Agency's Kakuda Propulsion Center in Kakuda. A manifold in the LE-7 engine's main fuel injector burst during a Mitsubishi test at its Guided Propulsion Plant in Komaki City in August 1991, causing a pressure explosion. A launch pad for the H-II was built in 1990 at the Tanegashima Space Center.

Rocket Plane

The Space Development Agency is also considering a rocket plane that would use rocket engines instead of air-breathing propulsion. The rocket plane is only being considered by the Space Development Agency and is not a program being conducted by the Japanese government. The reusable rocket plane would be vertically launched and land horizontally on a conventional runway. The rocket plane would consist of an orbiter joined to a strap-on fly-back booster. The rocket plane would weigh approximately 630 tons at takeoff and carry a 15- to 20-ton payload.

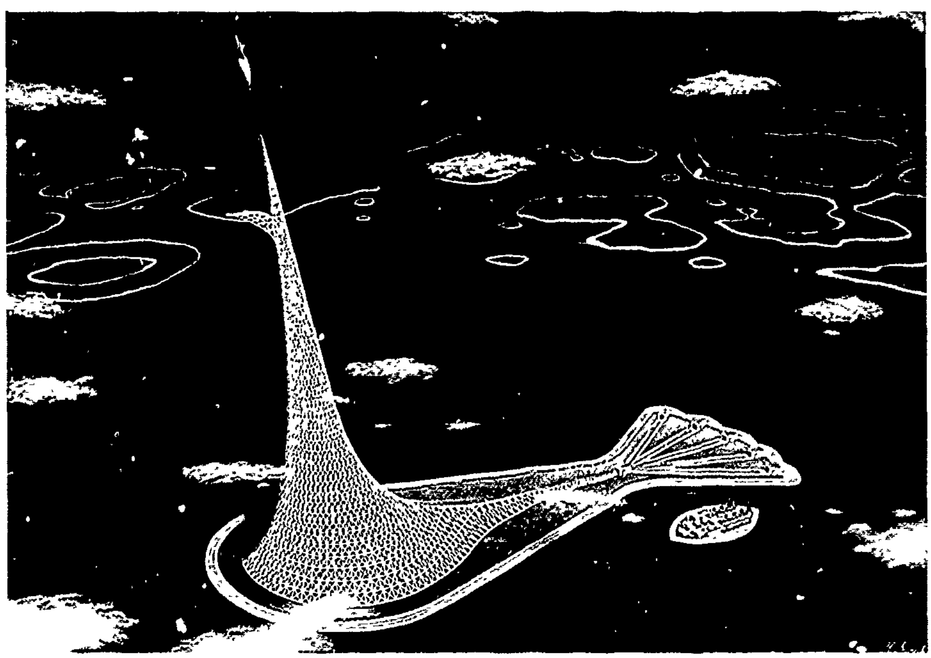
[4] According to Mitsubishi, the full-duration firing test of the LE-7 engine was successfully conducted in February 1991. According to a National Aeronautics and Space Administration official, a second full-duration firing test of the LE-7 engine was successfully conducted in May 1991.

The orbiter would weigh about 130 tons at takeoff, be about 50 meters long, and have a wingspan of about 20 meters. The orbiter would contain liquid oxygen and liquid hydrogen fuel tanks and be powered by the LE-7 cryogenic engine. The fly-back booster would weigh approximately 500 tons at takeoff, be about 55 meters long, and have a wingspan of about 24 meters. The fly-back booster would contain methane and liquid oxygen fuel tanks and be powered by an improved LE-7 cryogenic engine and a turbojet for its fly-back phase. A Space Development Agency official commented the rocket plane would be an interim step between HOPE and an air-breathing aerospace plane.

Alternative Japanese Spaceplane Launch Concepts

Taisei Corporation, a major Japanese construction company, is studying the feasibility of a Linear Motor Catapult (launch) System for a Space Vehicle. The concept would consist of a track on a conical framework constructed of high-tensile steel alloy. The curved launch ramp would measure 2,000 meters high and 3,650 meters long. Tracks from five spaceplane orbiter hangars would feed into the launch track. The spaceplane orbiter would be launched vertically by a linear motor cart system powered by superconducting magnets. Figure 3.4 shows an artist's concept of a linear motor catapult launch system.

Figure 3.4: Taisei Corporation's Linear Motor Catapult Spaceplane Launch System



Source: Taisei Corporation.

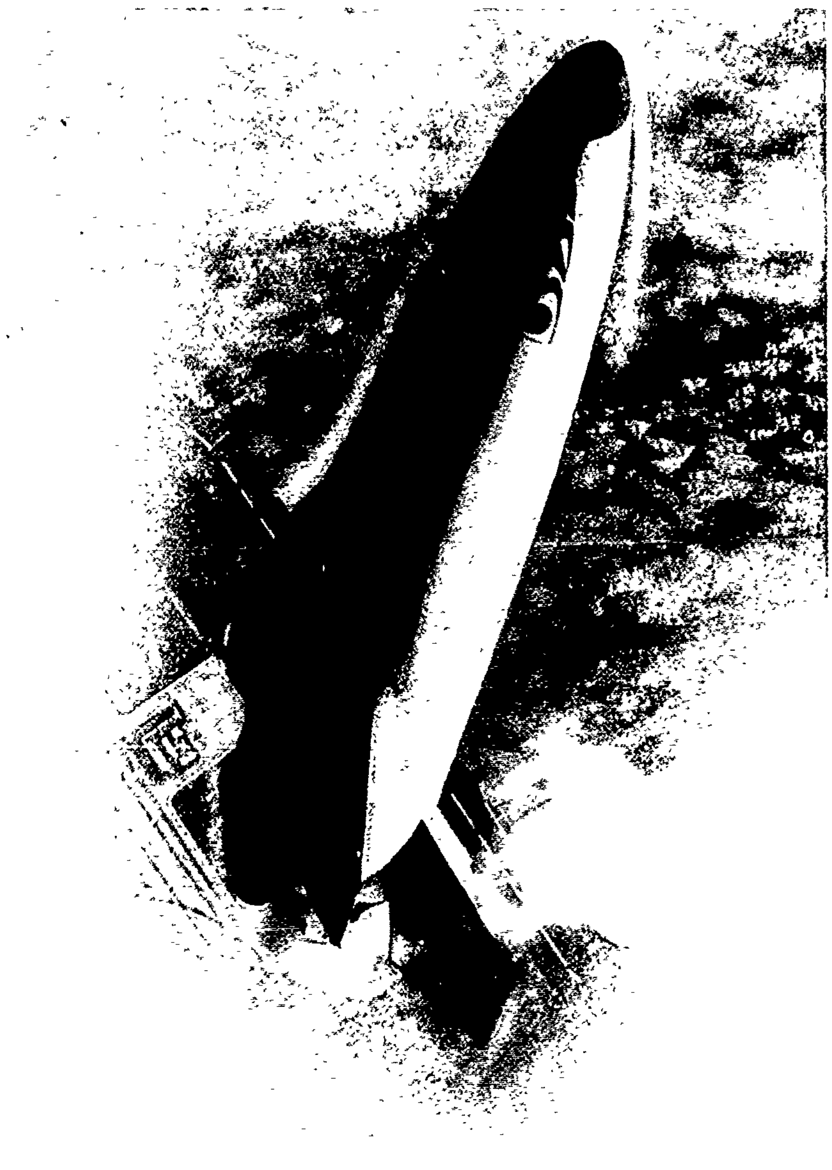
A magnetically levitated cart would carry the spaceplane orbiter along a horizontal stretch of track and then accelerate at high velocity along track inclined at 72 degrees. When the cart reached the top of the ramp, the spaceplane orbiter would ignite its engines and separate from the cart, which would be diverted onto a side track. At an altitude of about 146,000 feet and a speed of Mach 4.2, the spaceplane orbiter would jettison its external engine and continue into space. According to Taisei Corporation, the advantage of a linear motor launch system is the tremendous fuel savings compared with conventional shuttle launches using rockets.

Hazama-Gumi, a large Japanese engineering company, has studied the feasibility of an underground rocket launcher concept known as the Compressed Air Launching System. Compressed air would be used to blow a Japanese manned spaceplane and its booster out of a mile deep silo at a speed of Mach 1. Hazama-Gumi officials believe this concept would save rocket propellant. The launch silo would be 2,000 meters deep and 20 meters wide. An expendable rocket booster and spaceplane, configured like HOPE and the H-II booster, would be stacked above ground then lowered into the silo. Magnetic energy from superconducting magnets would suspend the launch platform between the silo's circular wall. Massive compressed air tanks would then be opened, forcing high-pressure air into the silo under the launch platform. The air would accelerate the vehicle to Mac!. 1 by the time it reaches the surface. The booster's engines would then be ignited as it cleared the silo. According to Hazama-Gumi, this would enable a launch vehicle to place several hundred more pounds into space than the same launch vehicle launched from a stationary pad. These efforts are indicative of Japan's nonaerospace companies' interest in building a space infrastructure for activities in the 21st century.

Institute of Space and Astronautical Science's Highly Maneuverable Experimental Space Vehicle

The Institute of Space and Astronautical Science's HIMES vehicle would be a fully reusable, unmanned, single-stage ballistic flight test vehicle. HIMES is being designed as a boost-glide vehicle to be launched vertically using rocket propulsion or a rocket-powered wheeled-trolley or sled. It would land horizontally. The spaceplane would serve as a test bed for hypersonic flight and air-breathing engines. It would also demonstrate atmospheric reentry flight and expand the capabilities of sounding rockets in the upper atmosphere. Based on current Japanese technology, HIMES is designed to be an interim vehicle in the development of a future Japanese air-breathing aerospace plane. Figure 3.5 shows an artist's concept of a vertically launched HIMES vehicle.

Figure 3.5: Institute of Space and Astronautical Science's HIMES Vehicle



Source: Institute of Space and Astronautical Science.

The Institute has been conducting research and development on winged space vehicles since 1982 and announced its plans for the HIMES project in 1985. In 1982 the Institute established a Working Group for a Winged Space Vehicle to conduct basic studies and flight testing of various spaceplane concepts. This group recommended that the Institute develop HIMES as a technology demonstrator for (1) a fully reusable rocket, (2) an atmospheric reentry test vehicle, (3) a flying test bed for advanced technology for thermal protection, (4) air-breathing propulsion, and (5) unmanned landing technology.

The Japanese Ministry of Education, Science, and Culture provided about $2 million for basic studies of winged vehicles. Institute and industry officials estimate that development costs for HIMES, including new engine technology, will total about $137.5 million. The Institute estimates that the completion date for a HIMES prototype vehicle would be 1998—if it receives approval from the Japanese government to pursue this project. As of November 1988, 10 to 15 researchers at the Institute's Sagamihara facility were working part-time on HIMES and advanced propulsion. They were supported by about 100 engineers, also working on HIMES and advanced propulsion part-time.

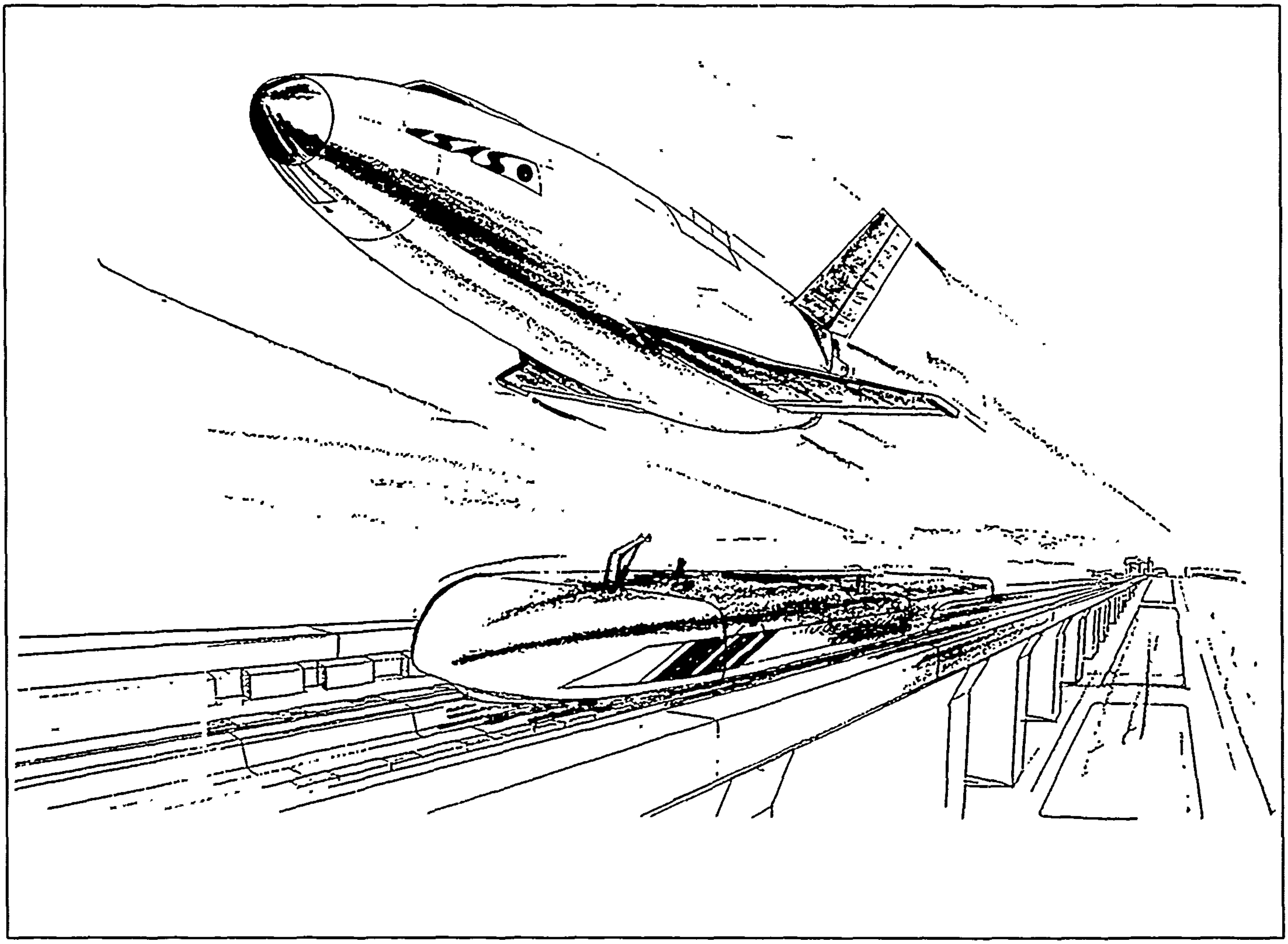
As a flight demonstrator, HIMES would not achieve orbital velocity (Mach 25); however, its flight envelope in the atmosphere would cover regions that offer operational conditions for an air-breathing engine. HIMES would experience relatively high heating flight conditions that future aerospace planes would also encounter during ascent.

Institute engineers stated that although various configurations were under consideration, they expect HIMES to have a delta wing with a span of 9.33 meters, a total length of 13.6 meters, and a takeoff weight of 14 metric tons. HIMES would use conventional materials, such as titanium alloys, for its skin and carbon-carbon composites for its nosecap and leading edges. According to researchers in the Institute, advanced materials currently available are being considered for use in the vehicle to shorten development time.

The multipurpose reusable sounding rocket's propulsion system would use liquid hydrogen and liquid oxygen. The fuselage is expected to be made of conventional aluminum and contain propellant tanks and a small payload bay. Two small rocket engines would provide the vehicle with maneuverability in the upper atmosphere and allow deceleration to avoid a steep reentry.

Institute engineers are also conducting studies on launching HIMES horizontally using a magnetically levitated transportation system. The Institute conducted a feasibility study of an experimental linear-motor-assisted takeoff system consisting of HIMES and a magnetically levitated and propelled sled developed by Japan Railway Tokai in Nagoya, Japan, as shown in figure 3.6.

Figure 3.6: Artist's Concept of Linear-Motor-Assisted Horizontal Takeoff of HIMES



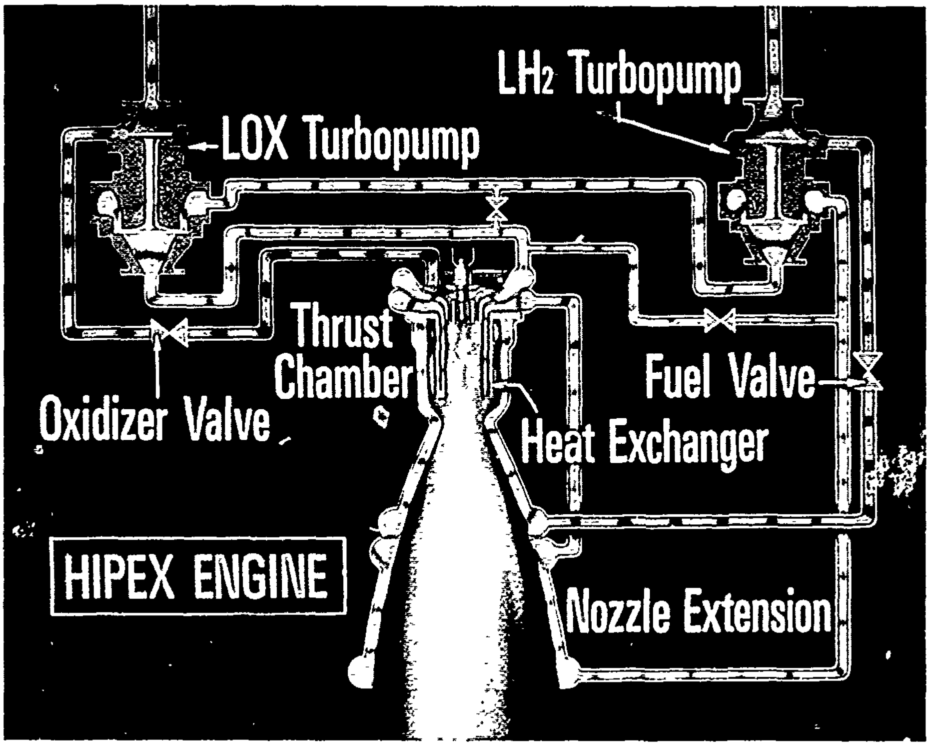
Source: Institute of Space and Astronautical Science.

Using the linear-motor-assisted takeoff system, the sled would accelerate the HIMES vehicle to a speed of 300 kilometers per hour when HIMES' rocket engines would ignite. The rocket engines would accelerate HIMES to a speed of 450 kilometers per hour—enough to aerodynamically lift the vehicle by its wings at a distance of 2 kilometers from the starting point. A fastening mechanism would then be unlocked, separating HIMES from the sled. After takeoff of the HIMES vehicle, the sled would be magnetically decelerated to a stop.

Researchers in the Institute concluded the fundamental technology for a linear-motor-assisted takeoff system is available for a small aerospace plane like HIMES. They also concluded it could be used as an experimental system for launching larger air-breathing aerospace vehicles horizontally.

The Institute is also working on several engine concepts for HIMES. It has formed a liquid propulsion group that is developing a high-pressure expander-cycle cryogenic engine. A heat exchanger is installed in the combustion chamber to extract a larger amount of thermal energy from the fuel's combustion. The engine will use hydrogen from the heat exchanger to drive the turbopumps for HIMES's rocket engines. Figure 3.7 shows a schematic drawing of the high-pressure expander-cycle engine.

Figure 3.7: Institute of Space and Astronautical Science's High-Pressure Expander-Cycle Engine



Source: Institute of Space and Astronautical Science.

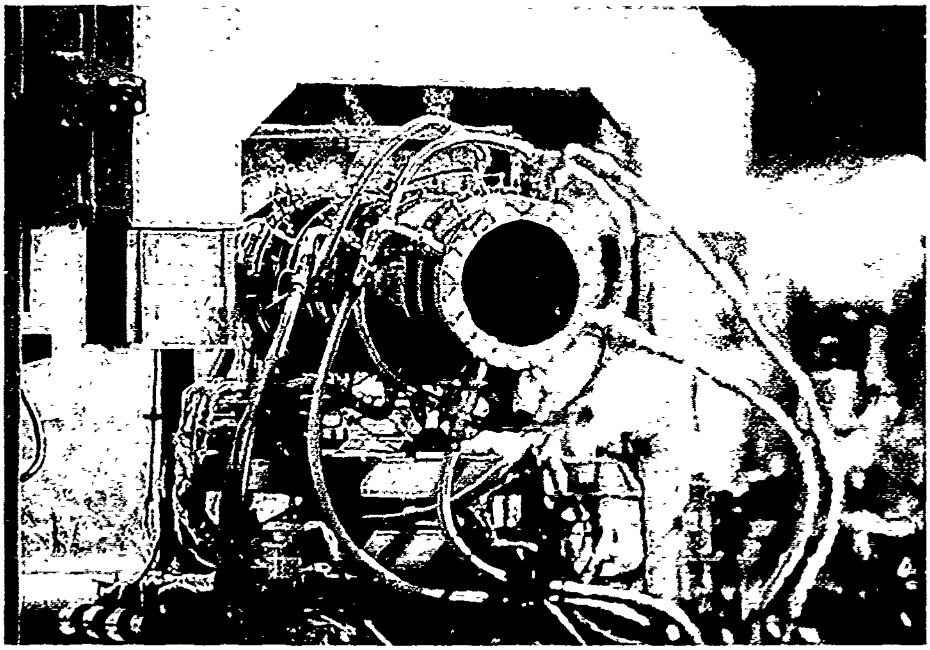
Institute engineers are also studying an air-turborocket for possible use by HIMES to demonstrate air-breathing engine technology. The Institute is evaluating combined turbine/rocket engine systems for use by future aerospace planes. Engineers from the Institute and Ishikawajima-Harima plan to expand and test a high-pressure expander-cycle engine by adding an air-turboramjet[5] with a precooler. Nissan Motor Company is developing carbon-carbon material for the engine's heat exchanger. Three types of turbo engines using liquid hydrogen as a fuel are also being evaluated: air-turboramjets, expander air-turboramjets, and gas generator air-turboramjets. Research on a precooler to protect the turbomachinery for hypersonic flight conditions is also being conducted.

The Institute has been conducting research and development on the air-turboramjet engine since 1988, which is a successor program of the Institute's liquid propulsion rocket system. This effort is a collaborative program between the Institute and Ishikawajima-Harima. The Institute is responsible for the engine concept and testing. Ishikawajima-Harima is responsible for the engine's detailed design and construction. Institute engineers expect that the air-turboramjet engine will be employed by the fly-back booster of the two-stage-to-orbit aerospace vehicle.

In 1990 the first proto-model (a pre-prototype, small-scale research device) of the expander-cycle air-turboramjet was tested at the Institute's Noshiro Testing Center at sea-level static test conditions (see fig. 3.8). Air-turboramjet engine development costs are expected to total about $1.5 million, including investment by Ishikawajima-Harima.

[5]According to a National Aeronautics and Space Administration expert in hypersonic propulsion, the term air-turboramjet is a misnomer resulting from the apparent inadvertent contraction of air-turborocket/ramjet. This combined-cycle engine utilizes an air-turborocket initial mode followed by a conversion to subsonic combustion ramjet mode for high-speed acceleration and cruise.

Figure 3.8: Expander-Cycle Air-Turboramjet Proto-Model Test at the Institute of Space and Astronautical Science's Noshiro Testing Center



Source: Institute of Space and Astronautical Science.

HIMES Subscale Flight Tests

The Institute was, as of September 1990, the only organization in the world outside of the United States and Soviet Union[6] that had conducted actual flight tests of a subscale spaceplane. In 1986 the Institute conducted the first in a series of low-speed gliding flight tests using subscale models of HIMES that were released from a helicopter over the Sea of Japan near Tokyo. The three gliding flight test vehicles that had been recovered were each about 2 meters long, had a delta wingspan of about 1.52 meters, and twin canard tail fins. We observed that the models were made of aluminum and fiber-reinforced plastics and contained an on-board computer for attitude control and radio guidance. Of the four gliding flight test vehicles built, three were constructed by the Institute and one by Kawasaki.

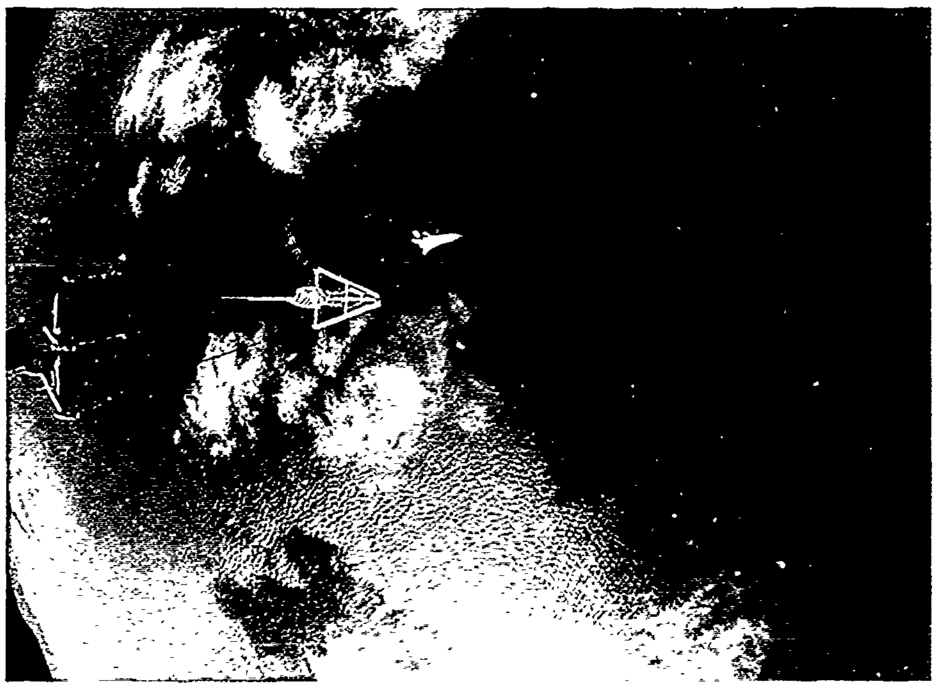
In June 1986 the Institute conducted the first in a series of drop-flight tests to establish a technique for future approach and landing testing. Two test models controlled by on-board computers were suspended from a helicopter flying at an altitude of about 3,000 feet. The first test

[6] Beginning in 1982, the Soviet Union conducted a series of atmospheric reentry flight tests of the BOR-4, a subscale reentry winged vehicle launched into orbit by the IL-16 rocket booster. According to the Chief Design Engineer of the Soviet space shuttle Buran, the BOR-4 was used to test the thermal protection system for the Buran shuttle and as a second stage for a two-stage-to-orbit spaceplane. At least 12 suborbital and orbital flights were made.

vehicle stalled immediately upon release from its cradle and was destroyed after hitting the water surface. The second model glided for about 50 seconds before making a water landing. It was recovered intact.

Figure 3.9 shows the subscale HIMES vehicle being dropped from the helicopter.

Figure 3.9: Flight Test of a Subscale Model of HIMES



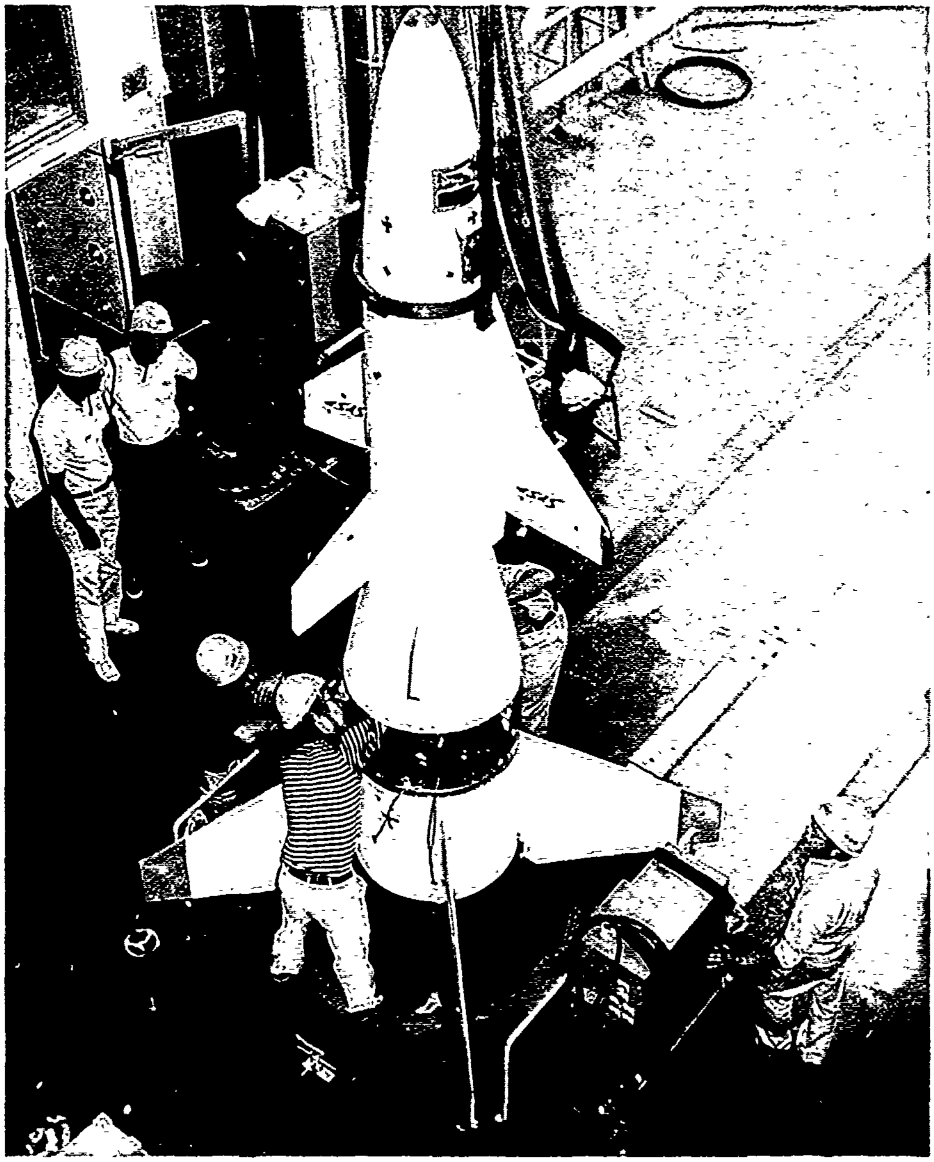
Source: Institute of Space and Astronautical Science.

As a result of these tests, the Institute conducted atmospheric flight tests at its Kagoshima Space Center in 1987 to validate HIMES' flight capability at a high angle of attack during high-speed reentry flight conditions. Subscale winged models of HIMES were carried aloft and launched from a balloon by a solid rocket booster using the Rockoon technique.

In 1987 the first test to verify the helium balloon and vehicle release from a gondola hanging from the balloon was conducted successfully. However, a second test in 1988 ended in failure when the balloon tore at an altitude of 18 kilometers and dropped the $2.2 million test vehicle into the Pacific Ocean. The 500 kilogram model was to ha 'e been boosted to an altitude of 80 kilometers and reenter the atmosphere at speeds up to Mach 4. Institute officials are preparing for another test in early 1992.

Figure 3.10 shows a vertical assembly of the subscale HIMES vehicle with booster that was used in the 1988 atmospheric reentry test.

Figure 3.10: Vertical Assembly of Subscale Model of HIMES and Booster Used in Atmospheric Reentry Test



Source: Institute of Space and Astronautical Science.

National Aerospace Laboratory's Single-Stage-to-Orbit Aerospace Plane Concept

The National Aerospace Laboratory's current activities for an aerospace plane include (1) a system study of an aerospace plane for a manned space transportation system, (2) a conceptual study of hypersonic experimental aircraft and propulsion, (3) development of enabling technologies, and (4) construction of test facilities.

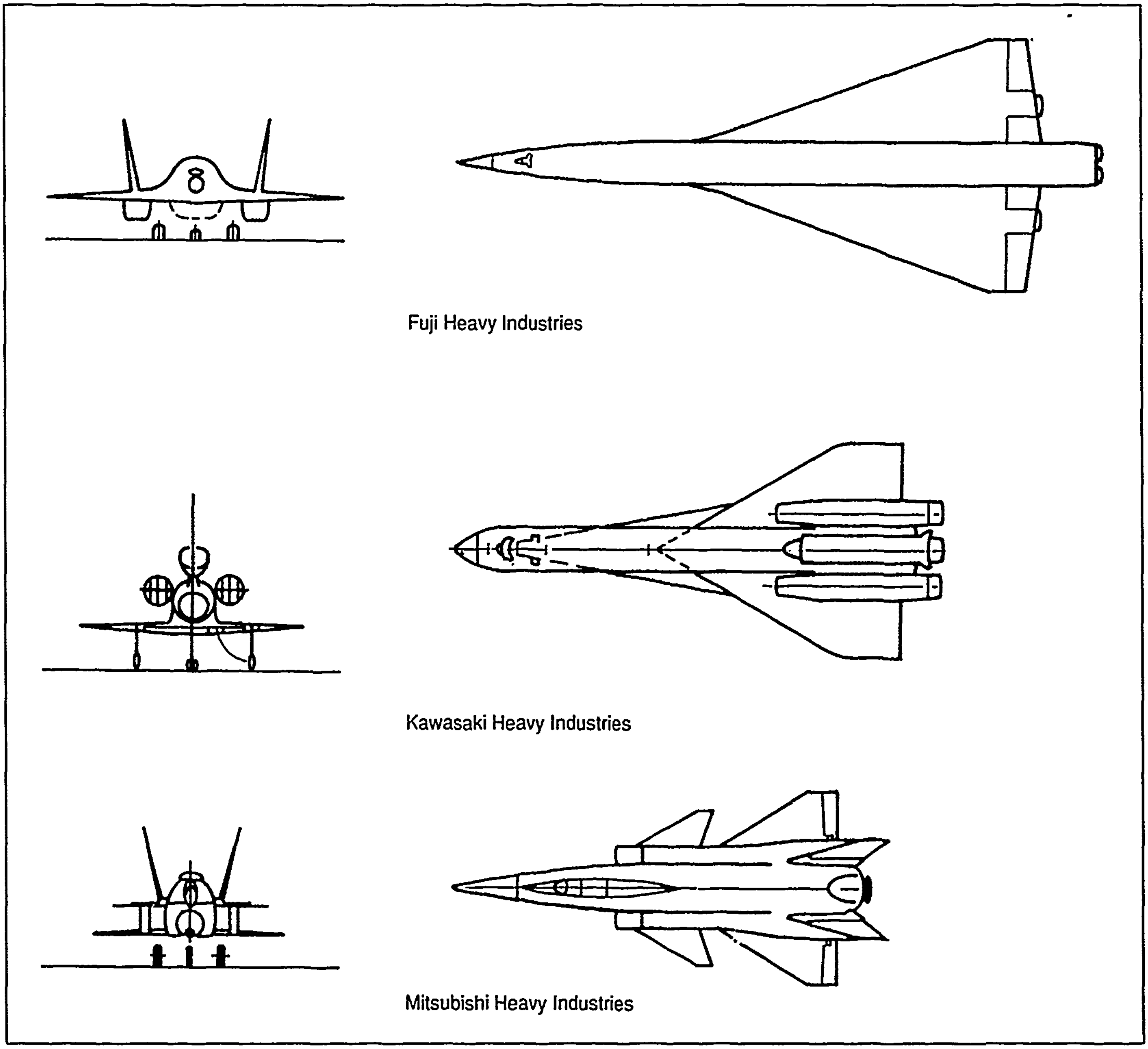
The objectives of the conceptual study for a hypersonic experimental aircraft are to identify the state of the art of Japanese technology bases, establish a flying test bed for air-breathing engines and advanced materials, and use manned hypersonic flight to stimulate the development of an aerospace plane.

The system study envisions an aerospace plane that would transport eight crew members plus two pilots into a 500-kilometer orbit. The space launch vehicle would have a takeoff weight of about 350 metric tons. Its propulsion system would consist of air-breathing and rocket engines. Design configurations to be studied include single- and two-stage-to-orbit aerospace planes.

To achieve the conceptual study's objectives, the Laboratory, at the time of our review, planned to develop a 10-metric ton unmanned hypersonic experimental aircraft that would achieve a maximum speed of Mach 7 and an altitude of 150 kilometers. Its propulsion system would consist of both jet and rocket engines, technology for which is currently available in Japan. The vehicle would also provide a test bed for subscale air-breathing engines. The manned vehicle would have two crew members.

In 1988 the Liaison Group for Spaceplane Research and Development between the National Space Development Agency of Japan, Institute of Space and Astronautical Science, National Aerospace Laboratory, industry, and universities requested that Japanese industry develop a manned hypersonic experimental aircraft concept. Using a National Aerospace Laboratory baseline configuration, Fuji, Kawasaki, and Mitsubishi each designed a subscale experimental aircraft concept for a vehicle with two crew members, two jet engines, and two rocket engines. National Aerospace Laboratory officials told us development of these concepts was voluntary by Japanese industry and did not involve any contracts. Figure 3.11 illustrates proposed Japanese industry manned hypersonic experimental aircraft configurations.

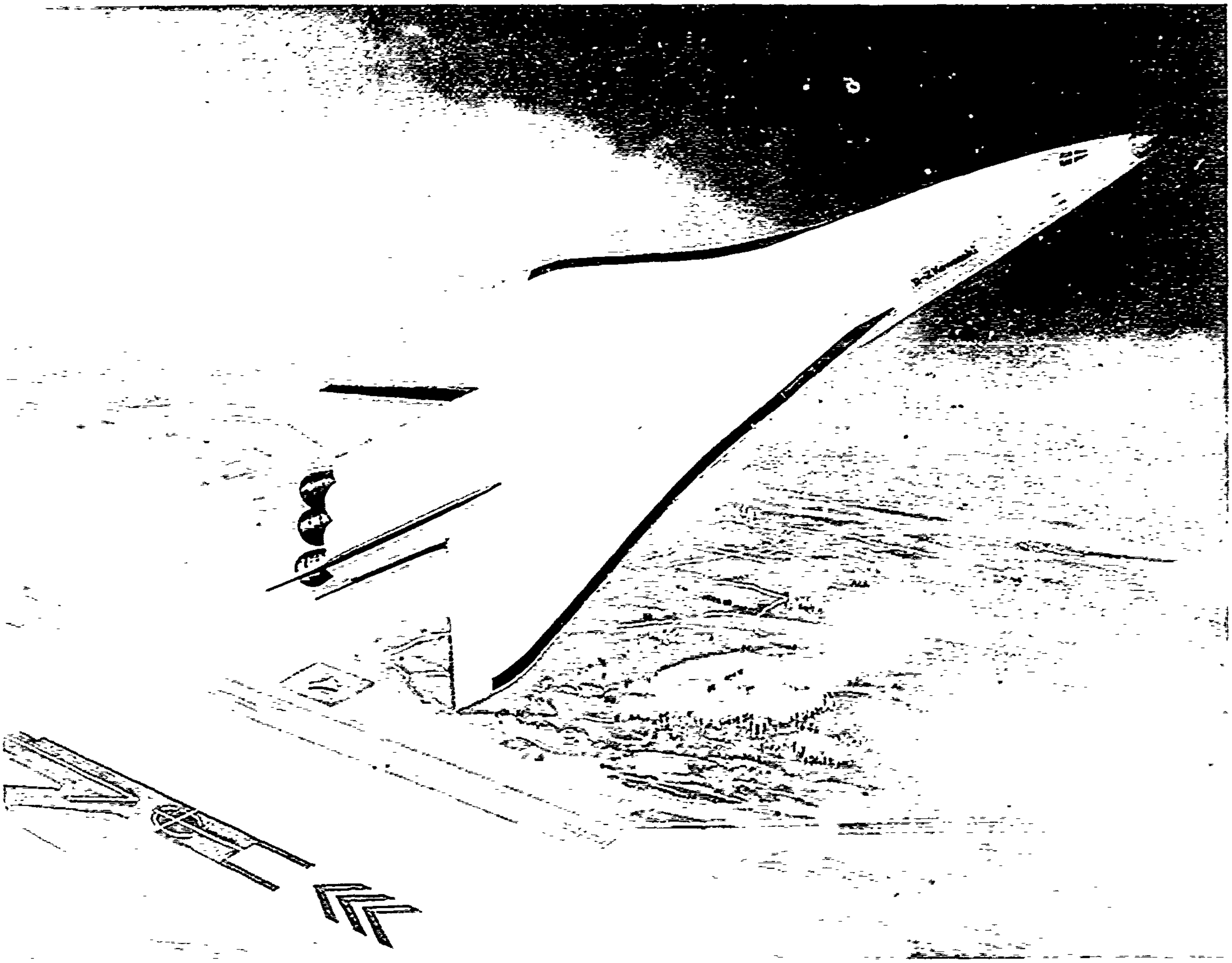
Figure 3.11: Japanese Industry Hypersonic Experimental Aircraft Configurations



Source: National Aerospace Laboratory.

Fuji's proposed configuration is a 50-metric ton, 35.25-meter long, twin-engine, dual-stabilizer concept with a 14-meter wingspan. Kawasaki's proposed configuration is a 40-metric ton, 26.39-meter long, three-engine, single-stabilizer concept with a 11.5-meter wingspan. Mitsubishi's proposed configuration is a 32-metric ton, 22.8-meter long, twin-engine, dual-stabilizer concept with a 10.26-meter wingspan. National Aerospace Laboratory officials noted these preliminary design concepts are being used by the companies in their research on aerospace plane technology but are not expected to be the baseline for an actual vehicle. Laboratory officials stressed that these are not yet competing concepts. Figure 3.12 shows an artist's concept of Kawasaki's single-stage-to-orbit aerospace plane concept.

Figure 3.12: Kawasaki Heavy Industries' Single-Stage-to-Orbit Aerospace Plane Concept



Source: Kawasaki Heavy Industries

According to the Director for Space Transportation Research in the Science and Technology Agency and the National Aerospace Laboratory, the status of aerospace plane activity at the Laboratory as of March 1991 is somewhat different than it was several years ago. Only a single-stage-to-orbit aerospace plane is being studied now and its configuration has not yet been determined. The two-stage-to-orbit aerospace plane concept has apparently been dropped. National Aeronautics and Space Administration officials said that although the Laboratory may have discontinued its study of a two-stage-to-orbit aerospace plane concept, Japan has not ruled out a two-stage-to-orbit vehicle.

In terms of the hypersonic experimental aircraft, Laboratory officials are concerned about the contour of the vehicle; integration of the engine and airframe; advanced materials that are lightweight for the fuselage, wing, and cryogenic fuel tank; a thermal protection system; and test facilities. Laboratory officials are also concerned about appropriate sites for takeoff and landing as well as a flight test range over a densely populated Japan.

The objectives of the conceptual study of hypersonic propulsion are to devise a propulsion system for an aerpspace plane; achieve a conceptual design of hvpersonic air-breathing engines for technology verification; and plan for the engines' development, testing, and operation.

The National Aerospace Laboratory is exploring three hypersonic air-breathing engine systems for future aerospace planes: turbo engines (including a turbojet, supersonic fan, turboramjet, and air-turboramjet), a liquid air cycle engine, and a scramjet. The Laboratory is working with Kawasaki in developing the turboramjet system, Ishikawajima-Harima in developing the air-turboramjet engine concept, and Mitsubishi in developing the liquid air cycle engine concept. Ramjet combustor tests of an air-turboramjet engine have been conducted.

Laboratory engineers are studying component and material applications of scramjet engines. Laboratory officials said scramjet research focuses on the scramjet's torch igniter module and cooling system. Laboratory scientists are conducting research on heat resistance of carbon-carbon composite materials for scramjet engines in a joint program with Ube Industries and Shikishima Canvas Company.

The Laboratory is studying the feasibility of a liquid air cycle engine. Research on the liquid air cycle engine concept was originally conducted in the United States in the 1950s and 1960s at The Marquardt Company. According to the National Aerospace Laboratory's Director of the Engine Aerodynamics Laboratory, liquid air instead of liquid oxygen is used in the combustion chamber of the liquid air cycle engine for higher thrust and lighter weight. According to a Laboratory engineer, the liquid air cycle engine has the potential to (1) operate in the atmosphere up to about Mach 8 as an air-breathing engine and in the vacuum of space as a rocket engine and (2) provide a large amount of thrust while remaining lightweight, since the liquid air cycle engine is essentially a derivative of a rocket engine. The present concept of the liquid air cycle engine does not include the potential to perform the total mission from earth to orbit with one propulsion system, as had been previously suggested by Laboratory engineers. According to the engine program's chief engineer, the engine has a low development risk, since it makes full use of proven liquid oxygen and liquid hydrogen cryogenic technology.

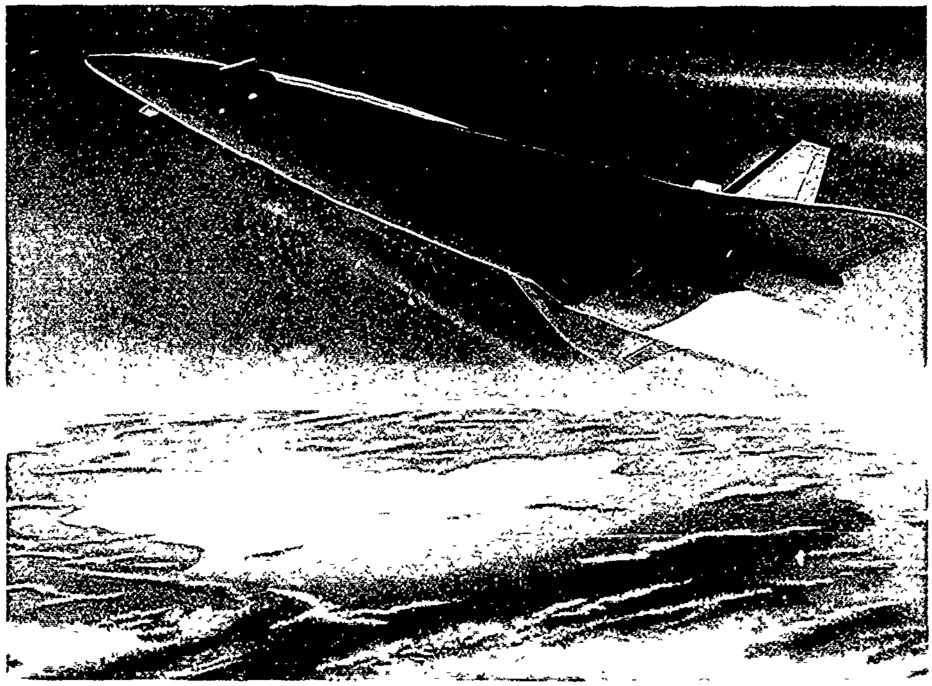
Problems facing Laboratory scientists and engineers in hypersonic propulsion are integrating the engine and airframe, developing engine component technology, and developing advanced materials and structures, numerical aerodynamic simulation, and adequate test facilities.

Related research activities include aerodynamic wind tunnel testing of various hypersonic experimental aircraft configurations, developing composite materials, developing flight control systems, conducting scramjet combustor tests, computational fluid dynamics analyses, and developing life support technology.

Single-stage-to-orbit aerospace plane configurations, including engine components, are being tested at the National Aerospace Laboratory. A 3.2-meter model with automatically controlled surfaces is being tested in a low-speed wind tunnel at Chofu. A scramjet inlet model has been tested in a supersonic wind tunnel at Chofu. Also, an air-turboramjet built with advanced materials has been tested. Construction of test facilities is discussed in chapter 6.

Laboratory officials view research and development of the approximately 10-metric ton unmanned hypersonic experimental aircraft as the first step in a progressively more difficult and ambitious program to develop and build an aerospace plane. The hypersonic experimental aircraft would be conducted as a National Aerospace Laboratory project. Although Japan does not have a plan to actually build an aerospace plane, Laboratory officials suggested the next step would be to develop a 50-metric ton manned hypersonic experimental aircraft using an air-breathing propulsion system as a Japanese national program. Laboratory officials suggested the third step would be to develop a 350-metric ton single-stage-to-orbit aerospace plane prototype using a turboramjet or scramjet and rocket propulsion, also as a Japanese national program. Figure 3.13 shows an artist's concept of the Laboratory's single-stage-to-orbit aerospace plane. Again, the aerospace plane's configuration has not yet been determined.

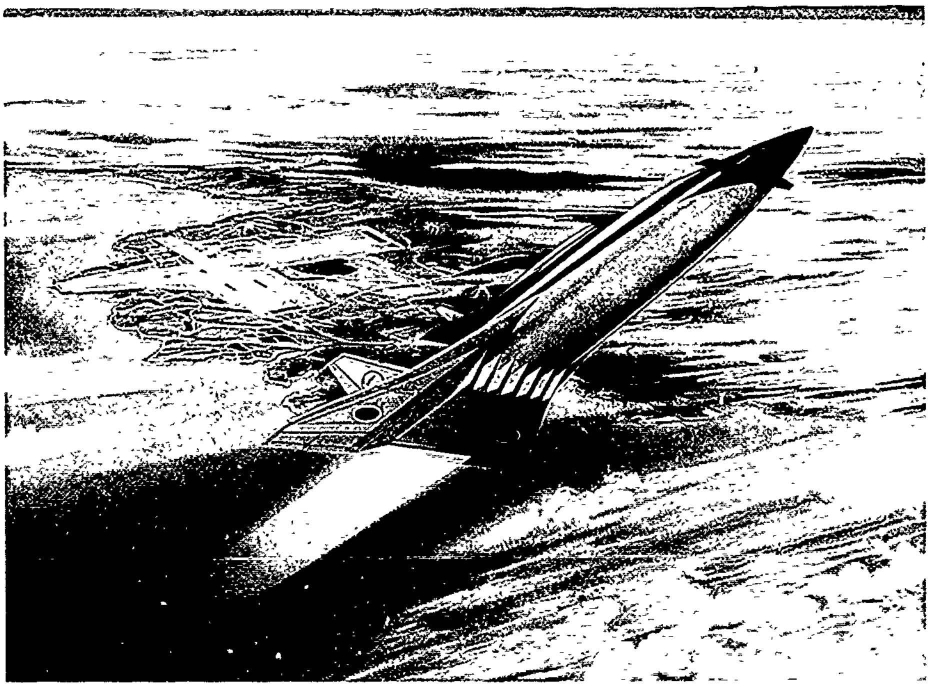
Figure 3.13: National Aerospace Laboratory's Single-Stage-to-Orbit Aerospace Plane Concept



Source: National Aerospace Laboratory

At the time of our visit, Laboratory officials indicated a two-stage-to-orbit prototype would also be developed as a backup. Development of an operational horizontal takeoff and landing single- or two-stage-to-orbit aerospace plane in Japan would require an international effort. Figure 3.14 shows an artist's concept of the Laboratory's two-stage-to-orbit aerospace plane. As of March 1991, the Laboratory was conducting research only on a single-stage-to-orbit aerospace plane concept.

Figure 3.14: National Aerospace Laboratory's Two-Stage-to-Orbit Aerospace Plane Concept



Source: National Aerospace Laboratory

Laboratory officials said the aerospace plane does not even have a name; the vehicle is simply referred to as a single-stage-to-orbit aerospace plane. The Laboratory's aerospace plane is not a formally approved project. The Japanese Ministry of Finance told Laboratory officials the aerospace plane is too expensive as proposed. Any spaceplane program in Japan must be approved by the Science and Technology Agency, Ministry of Finance, and Ministry of International Trade and Industry.

Chapter 4

Development of Enabling Technologies

Although U.S. leadership and superiority in aeronautics face increasing competition from Japanese efforts to develop aerospace vehicle technologies, the United States is ahead of Japan in hypersonic technology. The United States, through the NASP Program, is advancing hypersonic technology further than Japan. The United States is ahead of Japan in the development of three enabling technologies considered critical for an aerospace plane: air-breathing propulsion, advanced materials, and computational fluid dynamics. However, Japan is studying a single-stage-to-orbit aerospace plane using scramjet propulsion, which is the most technologically challenging aerospace plane concept. Nonetheless, the United States is the only country that has gone beyond the initial design phases and tested major large-scale components of an air-breathing aerospace vehicle. Japan is making significant progress in the development of enabling technologies, particularly in advanced air-breathing propulsion and advanced materials.

According to the Chief Scientist of the NASP Program, who visited Japan as part of the NASP Joint Program Office Fact Finding Group, the Japanese perform the necessary engineering work to understand the enabling technologies and are able to show the results effectively through technical presentations. The Chief Scientist said the Japanese are able to show not only the overall detail, but also the finer detail. He was impressed with the breadth of the work and said high quality and state-of-the-art aerospace engineering is evident in Japan.

According to a U.S. expert in hypersonics, the broad-based nature of Japanese spaceplane programs, with extensive ground and flight testing, is a good measure of Japan's commitment to the development of hypersonic technology. A U.S. expert in hypersonic propulsion said that the NASP Program is the most technically challenging program in the world today. However, NASP is almost the exclusive focus of the U.S. effort in hypersonics. The expert cautioned that the United States could fall seriously behind Japan (even if NASP is successful) in high-speed commercial transport aircraft or hypersonic applications due to Japan's broad-based program in hypersonic research.

United States Is Advancing Hypersonic Technology the Furthest

The United States is advancing hypersonic technology further than Japan. The Deputy Administrator, National Aeronautics and Space Administration, testified[1] before a joint hearing on the NASP Program in March 1991 that the United States is "quite a bit ahead" of Europe and Japan in the development of hypersonic technologies due to U.S. levels of investment. In addition, the Director of Defense Research and Engineering, Department of Defense, testified at the same joint hearing that the United States is the "pacesetter" in all hypersonic technologies and is clearly ahead of its competition.

The NASP Program is designing the X-30 as an accelerator vehicle with the primary goal of demonstrating single-stage-to-orbit space launch capability. Hypersonic cruise capability is an expected result of single-stage-to-orbit capability. An experimental flight test vehicle is required, since ground test facilities cannot simulate flow conditions above Mach 8, especially for testing the propulsion system.

The X-30 has progressed into the early stages of the vehicle's preliminary design, i.e., the X-30's basic configuration and technologies have been defined. Its final design is expected to be determined in late 1991 or early 1992. NASP technology development tasks have reached the stage of hardware demonstrations of many subscale and some large-scale vehicle components and systems.

The NASP Program plans to develop an air-breathing propulsion system for the X-30 that has a higher speed and similar altitude capability compared with Japanese aerospace plane concepts. The X-30's scramjet is expected to achieve speeds of up to Mach 25 and sustained hypersonic cruise in the atmosphere in the Mach 5 to 14 range and at altitudes of up to an estimated 150,000 feet. The NASP Program plans to use air-breathing scramjet propulsion up to the highest speed at which it is optimal and then augment the air-breathing propulsion with rocket propulsion. Flight testing of the X-30 will determine the optimal speed for using rocket propulsion to continue the X-30's acceleration and final ascent maneuver to orbit. Future operational space launch vehicles developed with NASP technology will initiate use of rocket propulsion at a speed optimized for their particular design. In comparison, Japan's National Aerospace Laboratory single-stage-to-orbit aerospace plane's

[1]The testimony was part of a joint hearing on the NASP Program on March 12, 1991, before the Subcommittee on Technology and Competitiveness, House Committee on Science, Space, and Technology, and the Subcommittee on Research and Development, House Committee on Armed Services

scramjet is expected to achieve speeds of up to Mach 20 and an altitude of about 160,000 feet.

The X-30 is also expected to be able to withstand the highest temperatures—about 5,000 degrees Fahrenheit[2] —compared to Japan's National Aerospace Laboratory aerospace plane's 4,000 degrees Fahrenheit. According to National Aeronautics and Space Administration officials, temperatures for any aerospace plane will peak at speeds of about Mach 15. The officials said 5,000 degrees Fahrenheit corresponds to the maximum heating of an uncooled vehicle; 4,000 degrees Fahrenheit would still be too high a temperature for the same vehicle even with active structural cooling.

NASP's first flight is scheduled for 1997 and its first orbital flight is scheduled for 1999. HOPE's first unmanned flight is scheduled for 1999. HIMES' first planned flight is expected in 1998. The Japanese aerospace plane's first planned flight is not anticipated until sometime after the year 2000. Like NASP, the National Aerospace Laboratory's single-stage-to-orbit aerospace plane concept includes use of an active cooling system, powered landing capability, and use of a scramjet—considered by U.S. and foreign government officials and industry representatives as the most advanced and technologically challenging air-breathing engine.

U.S. Leads Japan in Testing of Major Aerospace Vehicle Components

The United States is the only country that has gone beyond the initial design phases[3] and tested major subscale air-breathing aerospace plane components. For example, the NASP Program has tested major components of a subscale scramjet up to speeds of Mach 17 and simulated the airflow within a scramjet up to speeds of Mach 24. Large-scale ramjet and scramjet models have been tested up to Mach 5 and tests are planned up to Mach 8. Over 1,000 test runs have been completed with subscale (one-fourth to one-sixth scale) scramjet engines up to Mach 8 in

[2]According to a U.S. expert in hypersonics, 5,000 degrees Fahrenheit is too high a temperature for most airframe or engine materials to withstand without active cooling. According to the Deputy Program Director of the NASP Joint Program Office, those areas of the X-30 exposed to extreme temperatures of 4,000 to 5,000 degrees Fahrenheit (such as the nose cone, the wing, tail, and engine cowl leading edges, and the inside walls of the engine's combustion chamber), would be actively cooled, even though they will be made of advanced heat-resistant materials.

[3]The design process for an aerospace vehicle generally includes (1) a conceptual design that results in a calculated, initial number for the vehicle's weight, size, and performance characteristics, (2) a preliminary design that incorporates specific hardware and utilizes test data while continually improving and changing the design, and (3) a detailed design that integrates specific hardware in a frozen design. Although the NASP Program is moving into the preliminary design phase, the X-30 will require additional testing and concurrent technology development. Major tests are still being conducted for subscale and/or non-flight-weight hardware.

scramjet test facilities. Components, such as inlets, combustors, and nozzles, have been tested up to Mach 17 in shock tunnels or high-speed facilities with brief run times. However, not all major components of the final scramjet engine can be tested, since the final engine configuration has not yet been determined.

However, according to a U.S. expert in hypersonics, the NASP Program has not tested any actual flight-weight scramjet component at any speed. Designing and testing actual flight-weight scramjet components would occur in Phase III of the NASP Program once the final engine design is established. In fact, the program has not yet designed a flight-weight scramjet engine component. Rather, the program has conducted only aerodynamic performance-type tests of parts that are geometrically similar to scramjet engines made of heat-sink type materials.[4] As of July 1991, tests have not included the materials and systems (such as cooling, fuel, control, and thermal protection) that an actual engine component must have.[5] A number of components, including the scramjet module inlet and fuel injectors, have been tested with partial simulation at speeds of Mach 12 to 17. The flow within a scramjet has not been simulated at speeds above Mach 8, because no facility currently exists that can actually simulate the flow within a scramjet at speeds above Mach 8. Tests have been made that simulate some portion of the flow within a scramjet at higher speeds. According to the Deputy Program Director of the NASP Joint Program Office, the NASP Program has conducted tests of a subscale scramjet up to Mach 8.[6] It has also conducted tests of scramjet inlets, combustors, and nozzles individually but not together at speeds above Mach 8 and tests of scramjet combustion and airflow at significant levels (at speeds above Mach 24) in shock tunnels. Sets of combustor components with simulated inlet and nozzle effects

[4]Hundreds of wind tunnel test points have provided NASP scramjet performance data in numerous wind tunnel facilities. The models were designed for wind tunnel testing and not flight operations. The models were appropriately designed, sized, and instrumented for ease and efficiency of testing for on- and off-design conditions.

[5]National Aeronautics and Space Administration officials explained that the flow paths for the complete or partial engines (i.e., inlets, combustors, and nozzle segments) are correct, but the materials used in the tests are typically high-conductivity metal. Thus, the test process remains unencumbered with the need to accomodate operational hardware, such as systems for active cooling. Research and development wind tunnel models are made to be as simple, operationally flexible, and inexpensive as possible. The models meet the needs of current NASP testing requirements. The models are not intended to meet flight conditions with fully developed systems for a final engine design.

[6]Test periods of minutes are available in several facilities at conditions for aerospace vehicle speeds up to approximately Mach 8. At speeds of Mach 12 or higher, test periods in shock tubes or other facilities are very short. Since full-scale scramjet flows spend only milliseconds in the engine's combustor, test times for very high speed facilities actually provide similar "residence" times. The challenge is not only achieving a steady-state flow in milliseconds but also in measuring the results.

have been tested at Mach 12. According to NASP Program officials, many high-speed propulsion tests are better conducted during actual flight of an experimental vehicle.

The United States has also completed aerodynamic wind tunnel testing on several NASP design configurations. Large sets of data are available from a series of wind tunnels representing a range of conditions from takeoff (with ground effects) to high hypersonic speed (with and without powered effects). Testing with power on and off has helped define techniques to guide integration of the engine and airframe. Advancements in computational fluid dynamics now allow the calculation of details of internal and external flow fields up to orbital velocity.

Structural and material technology has been advanced through the fabrication and testing of small and large-scale components. For example, McDonnell Douglas Corporation has built a full-size (8 by 8 by 4 feet) X-30 fuselage section from silicon carbide-reinforced titanium and manufactured a 900-gallon cryogenic hydrogen fuel tank from a graphite-epoxy composite and installed it in a titanium aluminide composite structure representative of a segment of the X-30's fuselage. The tank-fuselage assembly was instrumented and is being tested at Wyle Laboratories in Norco, California. Other X-30 structures being tested include wing sections, fuselage panels, elevons, and actively cooled panels.

Although General Dynamics Corporation has fabricated and tested large, oxidation-coated carbon-carbon composite structures, carbon-carbon composites still lack the strength to be used as structural materials, according to U.S. aerospace industry representatives. Nonetheless, NASP Program officials said that manufacturing and coating techniques for advanced (very high-temperature) carbon-carbon are progressing well. The material is strong, lightweight, and heat resistant. Other NASP technology development and testing includes vehicle flight controls; the production, handling, and storage of slush hydrogen; and special high-temperature instrumentation.

In October 1990 the NASP National Program Office selected a single composite design configuration for the X-30 from multiple competing concepts: a lifting body incorporating short wings, twin vertical stabilizers, a two-person dorsal crew compartment, and three to five scramjet engine modules incorporating a small rocket.

Japan, on the other hand, is still in the initial definition and design phase of its air-breathing aerospace vehicle program. For example, the National Aerospace Laboratory has developed several aerospace plane designs and has tested small models of these design configurations in wind tunnels up to Mach 11. A scramjet engine inlet model and cooled structural panels that could be used in a scramjet engine have been tested up to Mach 4 at the Laboratory's Kakuda Branch.

According to National Aeronautics and Space Administration officials, Japan is taking a vigorous approach to hypersonic propulsion. Japan is hiring foreign companies to help it quickly gain international competence in both hypersonic technology and hypersonic test facilities.

High-Speed Air-Breathing Propulsion

The most critical enabling technology is the propulsion system. For a single-stage-to-orbit aerospace vehicle, a propulsion system must be developed with sufficient thrust and efficiency to power the aerospace vehicle over the full range of speed from takeoff to Mach 25, which is orbital velocity. Similarly, for a two-stage-to-orbit aerospace vehicle, such as the concept once considered by the National Aerospace Laboratory, a propulsion system must be developed to power the vehicle from takeoff to Mach 6 to 7—separation velocity of the rocket-powered second stage from the air-breathing first stage.

Propulsion systems envisioned for future aerospace vehicles must operate over a range of speeds. Currently, the ramjet is the primary propulsion system for aircraft and for some missiles operating at speeds of about Mach 2 to 6.5. However, the ramjet is generally not applicable at speeds below Mach 2 and above Mach 6.5 due to the lack of sufficient net thrust.

Propulsion technology, according to a U.S. expert in hypersonic propulsion, is the best indicator of where a country intends to go in future hypersonic vehicle applications. Unlike materials technology, for example, hypersonic propulsion has virtually no spinoff to other applications. Thus, hypersonic propulsion is a clear indicator of the future markets a country intends to capture. Moreover, hypersonic propulsion can only be developed by building and testing engine components and entire propulsion systems that are expensive and often require specialized facilities. Finally, the type of propulsion concepts being developed indicate the type of application being considered. For these reasons, the expert believes that the intentions of another country in hypersonics can best be determined by looking at what it is doing in hypersonic propulsion.

Hypersonic air-breathing (primarily scramjet) propulsion technology is a Department of Defense high-priority effort in air-breathing propulsion technology. It has the potential, through the NASP Program, to extend military missions to new flight regimes and to provide more cost-effective and on-demand assured access to space. A hypersonic cruise airplane with sustained cruise capability between speeds of Mach 5 and 14 could enhance military capability by carrying out potential military missions, such as interdiction, reconnaissance, surveillance, precision targeting and weapons guidance, strategic bombing, and strategic airlift.

According to the Department of Defense, Japanese research and development in the following areas indicate a moderate technical capability with possible leadership in some niches of air-breathing technology and a potential capability for making important contributions to meeting U.S. challenges and goals in air-breathing propulsion:

- development and design integration of lightweight, high-temperature, high-strength materials and
- reduction of observables in high-temperature, air-breathing propulsion systems.

According to the Department of Defense, trend indicators show that Japan's capability for developing and integrating advanced materials is increasing at a rate faster than that of the United States. Trend indicators also show that Japan's capability to reduce observables in air-breathing propulsion systems is increasing at a rate slower than that of the United States.

Japanese research and development in two other areas indicate a general lagging behind the United States but a potential capability for making contributions in selected areas, according to the Department of Defense:

- modeling and simulation (including computational fluid dynamics) of complex aerothermodynamic flow and empirically calibrated data bases and
- development of scramjet propulsion.

According to the Department of Defense, foreign activity in the development of hydrogen-fueled scramjets is not comparable to the U.S. level of activity in the NASP Program. However, according to the Department of Defense, Japan has a strong interest in scramjet and combined-cycle engines. Japan is accelerating its technical effort. Japanese programs include development of a methane-fueled ramjet capable of stable flight up to Mach 5 and a small combined-cycle ramjet/turbojet engine. Japan also has initiated a major effort to enhance its aerospace materials and propulsion capabilities by establishing the Material Research Center and Institute to study ultra-heat-resistant materials for use up to 2,000 degrees Celsius. If successful, according to the Department of Defense, this research could result in major advances in the field of hypersonic air-breathing propulsion.

Status of Japanese Advanced Propulsion Systems

Japanese advanced propulsion systems are in various stages of maturation ranging from concept development to being operational. The gas generator cycle LE-5 cryogenic propulsion engine for the second stage of the H-I expendable launch vehicle is presently operational. Development of the LE-5A expander bleed-cycle engine and LE-7 pre-burner cycle cryogenic engine for the first stage of the H-II launcher is underway. The experimental high-pressure expander-cycle engine represents an additional new liquid-hydrogen engine development. The liquid air cycle engine, also in advanced development stage, is a generic propulsion system oriented toward advancing air-breathing propulsion systems, such as strap-on boosters for larger versions of the H-II or hypersonic propulsion applications.

In terms of air-breathing engines, the air-turboramjet experimental engine, an expander-cycle air-turboramjet system that uses much of the technology from the high-pressure expander-cycle engine, is also in the advanced development stage. A Mach 0 to 5 turbojet/ramjet engine development program, announced in April 1989, is being supported by the Ministry of International Trade and Industry as a basic research and development project composed mainly of component research. The hybrid engine would integrate a turbojet and ramjet. Finally, scramjet concept development is underway at the National Aerospace Laboratory for future hypersonic aerospace vehicle applications.

Japanese Adaptation of Engine Components From Existing Programs to New Efforts

Japanese space propulsion programs, as of August 1990, are characterized by the adaptation of components from existing rocket programs to new propulsion efforts. For example, the liquid air cycle demonstrator engine uses the liquid hydrogen pump and combustor from the LE-5 engine, along with new components for the air liquefier and the liquid air pump. According to U.S. government and university propulsion experts who were members of the Japanese Technology Evaluation Center[7] panel on Japanese aerospace propulsion, the Japanese do a very effective job of using previously demonstrated components in advanced projects. In addition to the liquid air cycle engine, the high-pressure expander-cycle and air-turboramjet experimental engines are similar to Japanese liquid rocket engines as well. For example, the air-turboramjet experimental engine relies upon Ishikawajima-Harima's existing turbojet-turbofan production and design experience, as well as the expander-cycle technology developed in the high-pressure expander-cycle engine. This interchangeable component technology appears to provide cost-effective progress in Japan's new programs, while enhancing the reliability of its liquid rocket engines.

Although a considerable amount of technology development is directed toward scramjet applications, Japanese scramjet work is only in the concept definition phase, and scramjet demonstration engine development is not imminent. According to Japanese Technology Evaluation Center panel members, the technology is now available for the liquid air cycle and air-turboramjet experimental engines, but technology for a scramjet engine is not yet accessible.

Japanese scramjet technology programs include experimental studies of supersonic combustion, including ignition and diffusion flame studies, and shock tube studies of elementary reaction kinetics of hydrogen. In addition, high-speed inlet tests are currently underway on a scale model. This work is being conducted at the National Aerospace Laboratory and at several universities. Two new Japanese university efforts are underway involving 20 faculty members at several universities oriented toward hypersonic reacting flows and component technology for advanced propulsion systems.

To complement these experimental studies, computational fluid dynamics studies of scramjet configurations are being conducted by the

[7]The Japanese Technology Evaluation Center is operated for the U.S. government by Loyola College in Baltimore, Maryland, to provide assessments of Japanese research and development in selected technologies. The National Science Foundation is the primary support agency. Other sponsors include the Defense Advanced Research Projects Agency, the National Aeronautics and Space Administration, and the U.S. Department of Energy. The Japanese excel at acquisition and perfection of foreign technologies. As Japan becomes a leader in research in targeted technologies, the Center helps the United States get access to the results. The Center's assessments contribute to more balanced technology transfer between Japan and the United States by alerting U.S. researchers to Japanese accomplishments. The assessments are conducted by a panel of technical experts selected from government, industry, and academia. Panel members are leading authorities in their fields, technically active, and knowledgeable of Japanese and U.S. research programs.

National Aerospace Laboratory's Chofu facility, where researchers are using this experimental data to validate computational fluid dynamics codes. Scramjet test facilities in Japan are located at the Laboratory's Chofu Headquarters, Kakuda Branch, and the University of Tokyo, all of which have capabilities to test some aspect of internal flow of a scramjet up to speeds of Mach 2. A new scramjet engine test facility is being built at the Laboratory's Kakuda Branch and is expected to be in operation in 1993.

Fuels Development

Japan is also pursuing advanced fuels development and plant construction for stepping up its hydrogen production capabilities to serve the H-II rocket booster. Japan has the resources to develop advanced fuels for rockets as well as the capability to manufacture, store, and transport hydrogen. According to the Japanese Technology Evaluation Center propulsion panel, Japan will soon be moving into hydrogen production for the new series of hydrogen-fueled rockets and spaceplane research.

Applications of Computational Fluid Dynamics to Advanced Propulsion

According to Japanese Technology Evaluation Center panel members, computational fluid dynamics represents an area of strength in Japan. Japanese supercomputers are among the world's best, and major supercomputing facilities are located at the National Aerospace Laboratory and at the privately owned Institute for Computational Fluid Dynamics.[8] Japanese national universities also have excellent supercomputing capabilities. The availability of and access to supercomputers in Japan has resulted in rapid progress in computational fluid dynamics. The Japanese routinely include real gas effects and complex reaction kinetics in flow field analyses, and their computational fluid dynamics codes are based on the latest algorithms. According to Japanese Technology Evaluation Center scientists, Japanese visualization and postprocessing capabilities are also on the leading edge.[9] The Japanese have demonstrated appropriate computational fluid dynamics capabilities that could allow them to move rapidly in this aspect of propulsion development.

[8] The Institute is operated by an Institute of Space and Astronautical Science professor out of his home.

[9] A Science and Technology Agency official said, in Japan, these advanced techniques would not generally be used.

Engine Contractor Selection in Japan

According to the Japanese Technology Evaluation Center panel, selection of an engine contractor in Japan differs considerably from that in the United States. Although competition exists, particularly at the concept development level, the award of new propulsion contracts is generally based on the technical capabilities that the contractors have demonstrated in previous projects. For example, Mitsubishi is generally the overall engine developer for liquid rocket engines, while Ishikawajima-Harima is expected to emerge as the turbomachinery contractor, according to the Japanese Technology Evaluation Center panel. In Japan, a company's share of a project's contract generally appears to be set by historical factors, rather than by competitive procedures. Moreover, the role of Japanese industry is coordinated and strengthened through the Keidanren and the Society of Japanese Aerospace Companies. However, according to the Executive Director of the National Space Development Agency of Japan, the Space Development Agency does not award contracts for its projects based on the results of coordination by either the Keidanren or the Society of Japanese Aerospace Companies.

The High Commissioner of the Space Activities Commission and the Director for Space Transportation Research in the Science and Technology Agency disagree with the panel's view on engine contractor selection and believe the way to select an engine contractor in Japan would be similar to that in the United States. The High Commissioner and Director suggested selection of an engine contractor in Japan is primarily based on the technological capabilities demonstrated in previous projects through competition, since an aerospace vehicle engine would require strict reliability.

Japanese Engine Development Work

The Japanese are conducting several analytical investigations and experimental programs involving component testing and demonstration engines on several aerospace plane advanced propulsion systems, including a turbojet, ramjet, turboramjet, air-tur... amjet, liquid air cycle engine, and scramjet. The propulsion systems of primary Japanese interest are (1) those in the Mach 3 to 6 range for hypersonic cruise airplanes and single-stage-to-orbit space launch vehicles, (2) strap-on booster augmentation engines for vertical launch systems, and (3) air-breathing engines for a high-speed commercial transport aircraft. Japanese technology development efforts in higher Mach number propulsion systems are aimed more at accumulating a data base.

Two classes of engines are currently in the prototype phase of development in Japan: Ishikawajima-Harima's air-turboramjet experimental engine and Mitsubishi's liquid air cycle engine. Kawasaki is developing a turboramjet. Even though this is probably the least complex and risky engine cycle of the advanced propulsion systems, Japanese Technology Evaluation Center propulsion engineers indicated it does not appear that the engine components are currently available for this engine. Although demonstration engines have been built for the liquid air cycle and air-turboramjet experimental engines, the development programs had been temporarily put on hold beginning in 1989 because liquid hydrogen facilities in Japan were dedicated to LE-7 engine development.

Ishikawajima-Harima's Air-Turboramjet Experimental Engine

Ishikawajima-Harima's detailed design and construction of the air-turboramjet is part of a collaborative program with the Institute of Space and Astronautical Science. The air-turboramjet experimental engine cycle is based on the heat capacity of liquid hydrogen (expander cycle). Ishikawajima-Harima is the lead contractor. Like the liquid air cycle engine concept, an earlier version of this engine was developed in the United States by Aerojet in the late 1950s. However, the Aerojet engine was based on the gas generator principle and not the expander cycle.

Ishikawajima-Harima's analysis indicates that the air-turboramjet system would be competitive with the liquid air cycle engine or turboramjet up to Mach 5 and would be effective up to Mach 7 or 8. According to Japanese Technology Evaluation Center engineers, hardware has been developed so that tests of a complete engine could be conducted when liquid hydrogen test facilities become available in Japan. According to Ishikawajima-Harima, development of the engine may take 8 to 10 years.

Kawasaki's Turboramjet

The Japanese have analyzed turboramjet engine cycles for conditions appropriate for an aerospace plane up to Mach 6. This cycle is the least complex and least risky cycle to be developed for this flight regime. According to Kawasaki, the engine cycle analysis, conceptual design, and hydrogen ram combustion test/analysis have been studied.

Mitsubishi's Liquid Air Cycle Engine

The liquid air cycle engine is essentially a hydrogen/oxygen propellant rocket engine that uses atmospheric oxygen liquified during flight as an oxidizer. Mitsubishi is the lead contractor for the liquid air cycle engine. According to the company, its studies indicate that the liquid air cycle engine would perform well up to Mach 6 and may be effective up to Mach 8.

The liquid air cycle engine would power both a single-stage-to-orbit aerospace plane or vertically launched conventional rocket boosters. Air enters the engine through an internal contraction inlet, which reduces the airflow to subsonic speeds. The air is then condensed in a liquefier, pumped as a liquid to high pressure, and injected into a rocket motor type combustion chamber, where it is burned with gaseous hydrogen fuel. Liquid hydrogen is pumped to high pressure in a turbopump and is then used to liquify the air in the heat exchanger. Gaseous hydrogen is then injected into the combustion chamber.

The turbopump is driven by hot gas produced in a gas generator instead of by the hydrogen fuel itself. The LE-5 rocket engine's hydrogen pump and the combustion chamber nozzle are used in the liquid air cycle engine. According to Japanese Technology Evaluation Center propulsion engineers, this component interchange demonstrates compatibility among programs and appears to be a distinctive feature of Japanese propulsion system development programs.

The objective of the liquid air cycle engine is to increase launch specific impulse by eliminating a large portion of the liquid oxygen tankage that a conventional rocket booster must carry to reach orbit. However, a potential problem with the liquid air cycle engine concept is that savings in tankage weight could be offset by the potential weight of the engines.

Mitsubishi officials said liquid air cycle engine development is a relatively low-risk effort since much of its machinery is based on existing cryogenic technology. Mitsubishi program managers at the company's headquarters in Tokyo commented that although its ultimate goal is to develop the liquid air cycle engine for use in a single-stage-to-orbit aerospace plane, company engineers believe the liquid air cycle engine could also be integrated into a later version of the H-II launch vehicle as a strap-on booster.

In a technological advancement, the Japanese may have solved the fundamental problem of icing in development of a liquid air cycle engine. The concept of the liquid air cycle engine was originally developed in the United States and patented by The Marquardt Company in 1958. The Marquardt Company continued to conduct tests on the engine through 1964. However, the company encountered frost buildup on the heat exchanger surface, which drastically changed heat exchanger performance. The Marquardt Company abandoned the liquid air cycle engine in 1968 with cancellation of an aerospace plane program, because the technology was insufficient and no application was seen for a liquid air cycle engine.

Mitsubishi began development of its own heat exchanger in 1986 and began testing critical liquid air cycle engine components in 1988. According to Mitsubishi officials in Nagoya, hardware for an air liquefier has been tested twice. We viewed video tapes of these tests at Mitsubishi's Nagoya plant and again in Washington, D.C., with U.S. propulsion experts. The tests demonstrated that Mitsubishi had solved the icing problem.

The liquefier is a critical component because of the possibility that the heat transfer surfaces can become clogged with water and carbon dioxide, which solidify at the temperature required to liquify air. Failure to solve this problem was the primary reason the United States stopped working on a liquid air cycle engine in the 1960s. Mitsubishi engineers said that by modifying the tube arrangement, providing spacing between the tubes, and changing the sequence from ambient temperature to cryogenic temperature, they were able to demonstrate that frost buildup can be avoided. The key manufacturing technique, according to Mitsubishi engineers, is to densely arrange the tubes. Tubes may be built of columbium or ceramics, although ceramics are difficult to shape. National Aerospace Laboratory engineers at the Laboratory's Kakuda Branch suggested that vibration of the heat exchanger tubes may have prevented icing in the Mitsubishi tests. U.S. engineers told us that, if this is the solution, then metal fatigue may be a problem.

Mitsubishi is developing a heat exchanger for a 10-ton engine. Testing occurred between 1985 and 1988. In 1989 the heat exchanger was scheduled to be tested with the 10-ton engine and turbopumps. Since 1989, tests have been stopped due to use of liquid hydrogen facilities for LE-7 development work.

An LE-7 engine modified to the liquid air cycle engine configuration would perform as a liquid air cycle engine at speeds up to about Mach 5 and altitudes up to 40 kilometers. Above Mach 5, the engine would function as a rocket.

A liquid air cycle engine developed for a single-stage-to-orbit aerospace plane would differ from those used in a vertically launched rocket booster. Mitsubishi officials commented that aerospace plane liquid air cycle engines would probably use higher density, lower volume slush hydrogen and slush oxygen. To improve specific impulse at takeoff, only slush hydrogen would be burned by the engine during the air-breathing portion of flight, which would end at a speed of Mach 10 at an altitude of 40 kilometers.

Although much of the liquid air cycle engine concept is based on existing technology, development of a lightweight liquefaction system, advanced materials development, and heat exchanger design difficulties must be overcome before a fully functioning liquid air cycle engine can be developed, according to the manager of engine engineering at Mitsubishi.

A working first stage heat exchanger for a 10-ton thrust liquid air cycle engine was fabricated in 1988 and tested at Mitsubishi's Tashrio Field Laboratory in northern Japan. The heat exchanger houses more than 10,000 cooling tubes, each of which is less than 3 millimeters in diameter and has used liquid hydrogen to achieve an air liquefaction ratio of 3 to 1.

Mitsubishi officials said the company expects to adopt the liquid air cycle engine concept but has not determined a firm schedule. They want to demonstrate the liquid air cycle engine to the National Aerospace Laboratory and evaluate the feasibility of the engine for use in an aerospace plane by 1991 or 1992. Mitsubishi expects to receive Japanese government contracts in the future for work on the engine.

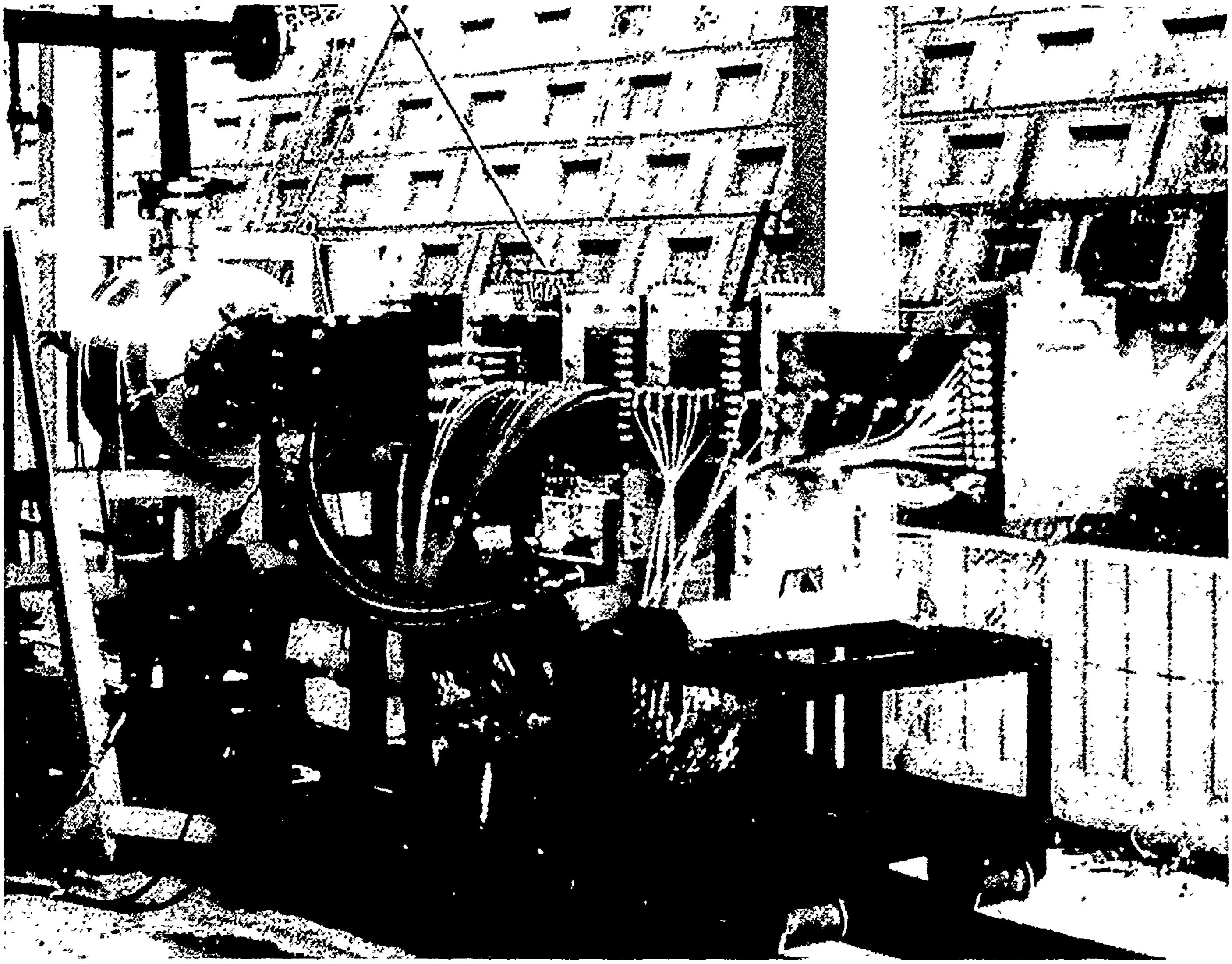
Scramjet Technology

Several Japanese government and industry officials indicated work on scramjets would be delayed, since the technology is not available. Mitsubishi officials said whereas the liquid air cycle or air turborocket cycle engine systems are currently technologically accessible, the scramjet cycle is not. However, the Japanese are carrying out basic scramjet technology experiments at several locations in Japan. This work includes experimental and computational fluid dynamics efforts in inlet configurations and in mixing and combustion technology.

The Science and Technology Agency is planning to spend the next 3 years building a subscale model of a scramjet, which Agency officials believe is the most likely candidate for Japan's single-stage-to-orbit aerospace plane. The scramjet model is expected to be about one-fifth the size of a full-scale engine. The model would be less than one meter in diameter and about two meters long. The Agency is expected to conduct the studies and test components, such as the air-intake duct and combustion chamber, before assembling the complete scramjet model. Mitsubishi is expected to build the subscale engine under contract from the Japanese government.

The National Aerospace Laboratory is conducting scramjet inlet testing at its Kakuda Branch using a small Mach 4 supersonic wind tunnel. Figure 4.1 shows a scramjet test in the Laboratory's Ram/Scramjet Combustor Test Facility at its Kakuda Branch.

Figure 4.1: Scramjet Test in the National Aerospace Laboratory's Ram/Scramjet Combustor Test Facility



Source: National Aerospace Laboratory.

U.S. government and industry propulsion experts told us the test program at the National Aerospace Laboratory's Kakuda Branch appears to be well coordinated with its Numerical Computations Center in Chofu. National Aerospace Laboratory managers stated that, as scramjet inlet testing progresses, different scramjet configurations will evolve with emphasis on both high-speed and low-speed configurations. Scramjet tests at various Mach numbers are planned in the National Aerospace Laboratory's 50 centimeter Hypersonic Wind Tunnel at Chofu.

Ishikawajima-Harima began studying scramjets in 1986 and is involved in computational fluid dynamics and scramjet combustion testing at the Laboratory's Kakuda Branch.

In addition to computational fluid dynamics analysis of scramjets, a number of cycle codes are being developed at the National Aerospace Laboratory to predict the performance of the scramjet as a function of geometry, area ratio, and mixing schedule. U.S. propulsion experts stated that the mixing schedule from the Langley Hypersonic Propulsion Branch at the National Aeronautics and Space Administration's Langley Research Center in Hampton, Virginia, is being used as the technique to model fuel mixing in the combustor. They also noted that a scramjet optimization code being developed in Japan is unique.

Advanced Propulsion Activities at Japanese Universities

Supersonic mixing and combustion studies are being conducted at National Aerospace Laboratory facilities at Chofu and Kakuda and at the University of Tokyo. Four Japanese universities are also conducting research with the national laboratories and industry on propulsion and combustion. They are the University of Kyushu (aeroengine), University of Kyoto (propulsion), University of Nagoya (aeroengine and propulsion), and University of Tokyo (space propulsion, rockets, jet propulsion, and aeroengine).

Supersonic combustion research has been conducted at the University of Tokyo since 1974 when the Mach 2 pebble bed heater facility was built at the Research Center for Advanced Sciences and Technology. The University of Tokyo is conducting Mach 2 direct connect tests to study both perpendicular and parallel mixing and combustion to validate computational fluid dynamics codes.

About 20 professors at the University of Nagoya are coordinating a study of hypersonic reactive flows in scramjet engines. In 1989 a joint institute of the University of Tokyo and National Aerospace Laboratory was formed to conduct joint research on high-speed, air-breathing engine technology. This group will concentrate its research on the (1) performance of air-breathing engines, (2) fundamental component technology for turbo-engines, (3) fundamental component technology for ram/scramjet engines, and (4) measurement technology for internal flow of engines.

Scramjet combustion research is also being conducted by the National Aerospace Laboratory's Kakuda Branch with Ishikawajima-Harima and the University of Tokai. The University of Nagoya has an active high-speed combustion research program.

Assessment of Advanced Propulsion Work in Japan

According to the NASP Program's Chief Scientist, advanced propulsion work in Japan is appropriate for the stage of aerospace plane development in Japan. The Japanese are conducting research on a wide variety of advanced propulsion concepts and their approach is state of the art, according to the Chief Scientist. He said the results look plausible and realistic.

The Chief Scientist said Japan has done the necessary preliminary work (computations and some experimental tests) on advanced propulsion systems for an aerospace plane. For example, in 1988 Japan conducted heat transfer computations inside a scramjet, including computations for fuel flow. These computations included the intake, strut, combustor, and nozzle. The Japanese then conducted a systems study comparing engines. They concluded the system with the least weight in hardware and propellant is the best engine. The two best combined engine concepts the Japanese came up with, according to the Chief Scientist, were the air-turboramjet/scramjet/rocket and the liquid air cycle engine/scramjet. These are the same two combined types of engines the United States determined were the best more than 30 years ago. Importantly, Japan now has an engineering basis for selecting these two engines for further development.

Some National Aeronautics and Space Administration and U.S. aerospace industry propulsion experts expressed concern to us that Japan is developing several important aerospace plane propulsion systems that the United States has either abandoned or is not working on at the present time. These systems include the liquid air cycle engine, air-turboramjet experimental engine, and high-pressure expander-cycle engine. They are concerned the United States is placing all of its emphasis on a scramjet propulsion system for the X-30.

In 1988 Japanese engineers at the National Aerospace Laboratory's Kakuda Branch took a National Aeronautics and Space Administration Langley Research Center engine design from the 1970s and repeated U.S. tests on the engine to gain experience. They were able to duplicate the National Aeronautics and Space Administration's test results. These tests provide Japan with experience in hypersonics, something the Japanese repeatedly told us they lack.

The Japanese have a broadly based advanced propulsion program. According to Japanese Technology Evaluation Center propulsion engineers, the Japanese schedule is ambitious, but achievable. Currently, the Japanese advanced propulsion program is behind that of the United States, but they are making rapid progress in selected systems. The Japanese are one of the world's leaders in such key technologies as advanced materials, and they enjoy a high level of project consistency and continuous funding. Japan's aerospace plane development has been evolutionary in nature, while the U.S. program has placed greater emphasis on revolutionary advances through technological breakthroughs.

Japanese projects tend to be smaller than those in the United States, focusing on incremental advances in technology, with a good record of applying proven technology to new projects as seen in their high-pressure expander-cycle engine, liquid air cycle engine, and air-turboramjet experimental engine programs. This evolutionary approach, coupled with an ability to obtain technology off the shelf from other countries, has resulted in relatively low development costs, steady progress, and enhanced reliability. According to the Japanese Technology Evaluation Center propulsion panel, Japan is clearly positioned to be a world leader in advanced propulsion technology for aerospace planes by the year 2000. Japanese government officials said Japan does not have any intention of gaining such a position and Japan is only studying aerospace plane concepts to make an appropriate contribution in this field.

According to a U.S. expert in hypersonic propulsion, Japan is pursuing a very deep and broad-based research and development program in hypersonic propulsion. The expert said that although the United States is ahead of Japan in NASP propulsion technology, Japan may be ahead of the United States in air-breathing hypersonic propulsion technology for several other important applications, including two-stage-to-orbit space launch vehicles and high-speed commercial transport aircraft. The Japanese are building and testing components and complete engines using a variety of propulsion cycles that are suitable for a variety of applications. The expert said no other country is pursuing such a comprehensive program in hypersonic propulsion. According to the expert, the United States has placed essentially all of its hypersonic technology in the NASP Program. The expert added that although the NASP propulsion system may be a good choice for a single-stage-to-orbit accelerator-type vehicle, the NASP propulsion concept is very inefficient for a future operational high-speed commercial transport aircraft in the Mach 3 to 6 speed range. Japan's air-turboramjet experimental engine (a composite cycle engine concept using a hydrogen-cooled inlet with an expander-cycle air-turboramjet) would have three to four times the specific impulse from Mach 0 to 6 as would the NASP propulsion system. In addition, according to the expert, the Japanese engine is being developed on the ground using existing facilities. The Japanese are not only developing this engine but are building and testing a variety of other hypersonic propulsion concepts, including liquid air rockets, liquid air turboramjets, and scramjets.

One U.S. expert in hypersonic propulsion believes that Japan intends to be in a position early in the 21st century to become the world leader in high-speed commercial transport aircraft capable of achieving speeds above Mach 3. The expert indicated the Japanese believe they cannot compete with U.S. and European aircraft manufacturers in the near-term for high-speed (supersonic) commercial transport aircraft. However, the Japanese intend to be ready to compete in the Mach 3 and above (hypersonic) transpacific transport aircraft market, which the Japanese believe will become viable in the next century. The expert said the Japanese are doing everything a prudent nation would do if that were its goal. Japan may be in a position to leapfrog over the U.S. aerospace industry in the next 5 to 10 years, according to the expert.

Advanced Materials

The second most critical enabling technology is advanced materials. The weight of an aerospace vehicle must be reduced as much as possible to minimize the fuel and thrust required by the engine. Also, hypersonic flight causes extremely high temperatures due to air resistance on the vehicle's surfaces and within the engine. For example, the X-30's nose cone could reach more than 5,000 degrees Fahrenheit, and the leading edges of the wing and tail could reach almost 3,500 degrees Fahrenheit. Therefore, materials must be developed that are able to withstand extremely high temperatures and are high-strength, lightweight, and reusable. Advanced materials include carbon-carbon, titanium-based alloys, beryllium-based alloys, fiber composites, and titanium aluminide produced either conventionally or by rapid solidification technology.

According to the Department of Defense, ongoing research and development in Japan in the following areas indicate a moderate technical capability with possible leadership in some niches of advanced materials technology and a potential capability for making important contributions to meeting U.S. challenges and goals in advanced materials:

- development of composite materials capable of retaining structural properties at high temperatures;
- development of improved nondestructive evaluation techniques for advanced composites; and
- improvements in modeling and prediction of life-cycle failure.

According to the Department of Defense, trend indicators show that Japan's capability to develop composite materials is increasing at a rate faster than that of the United States. Trend indicators also show that Japan's capability to develop improved nondestructive evaluation techniques for advanced composites and improve modeling and prediction of life-cycle failure is increasing at a rate similar to the United States.

Japanese research and development in two other areas indicate a general lagging behind the United States but a potential capability for making contributions in selected areas to meeting U.S. challenges and goals in advanced materials, according to the Department of Defense:

- application of structural composites to reduce observables and
- improvements in characterization of composite material response to weapon effects.

Japan has active materials development programs and may lead the United States in selected aspects of materials research. However, according to the Department of Defense, the United States has the overall lead in the design and effective use of advanced composite materials in specific military applications. Primary opportunities for cooperation will occur with Japan in the area of fibers and ceramics. Critical technological advances are being made in carbon-fiber technology developed in Japan. According to the Office of Technology Assessment, most officials of U.S. ceramic companies that they interviewed believe Japan is the world leader in advanced ceramic research and development.

The use of composites is now well established in Japan. Japan may lead the United States in some commercial applications. Japan has also become an important supplier to the United States. For example, Kyocera, the largest ceramics firm in the world, has established subsidiaries and a research and development centers in the United States.

According to the Department of Defense, Japan is ahead of Europe and the Soviet Union and second only to the United States in materials and structures research and development.

Japan is also embarking on a major initiative in materials to support development of next-generation air transports. In 1987 the Japanese Ministry of International Trade and Industry began research on metal composite, ceramic composite, advanced carbon-carbon, and carbon-fiber materials. The Ministry concluded that development of advanced materials able to withstand high temperatures is a priority. In 1989 the Ministry initiated an 8-year program to develop new heat-resistent materials for a spaceplane and other purposes. The Ministry expects that advanced materials for use at temperatures up to 2,200 degrees Celsius will be available by the year 2000.

According to the Department of Defense's Critical Technologies Plan,[10] the United States is judged to be the world's leader in composite materials. However, the U.S. lead in composite materials is being rapidly eroded by a combination of industrial technology transfer, such as aircraft composite technology, and strong research and development efforts by foreign countries, including Japan. For example, according to the Office of Technology Assessment, Japanese fiber producers could abrogate existing agreements and sell directly in the U.S. market. Also, the Japanese could use technology gained from joint ventures with a U.S. aircraft manufacturing firm to launch its own commercial aircraft industry.

Although Japan is the world's largest producer of carbon fiber (a key ingredient in advanced composites), it has only been a minor participant to date in the worldwide application of advanced composites. One reason is that Japan has not developed a domestic aircraft industry—the industrial sector that currently uses the largest quantities of advanced composites. Another reason is that Japanese companies have been limited by licensing agreements from participating directly in the U.S. market.

The National Space Development Agency of Japan is conducting research and development of titanium alloys and advanced carbon-carbon fiber polyimides, reinforced carbon-carbon composites, and thermal protection systems for HOPE. Agency contractors are conducting extensive tests on carbon-polyimide materials for use in HOPE's structure. The Agency is also studying carbon-carbon coated with silicon-

[10]The third Annual Defense Critical Technologies Plan is a plan for developing the 21 critical technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of U.S. weapon systems and to outline an investment strategy to manage and promote the development of these technologies. See Critical Technologies Plan, Washington, D.C.: Department of Defense, 1991.

carbide and titanium and ceramic tiles for HOPE's thermal protection system. Samples of these materials will be mounted and tested on the Orbiting Reentry Experimental Vehicle scheduled to be launched in 1993. Mitsubishi managers at the company's Nagoya plant told us they have mastered the autoclave bonding processes for forming HOPE structural components from all the candidate materials.

The Agency is also conducting research and development of a thermal protection system using ceramic tiles. The Agency's test results have demonstrated that its tiles have the same thermal protection as tiles used on the U.S. space shuttle.

The National Aerospace Laboratory is investigating fiber-reinforced metals and plastics and an advanced carbon-carbon thermal protection system.

Fuji has a wide range of advanced materials capabilities, including carbon-carbon composites and reinforced carbon-carbon composites. Fuji is conducting research on superplastic forming, diffusion bonding, and electron beam-welding processes. Fuji is also studying molding processes of thermoplastic composites and carbon-polyimide, evaluating composite material characteristics under a space environment (e.g., electron beam radiation and thermal cycles), and developing various thermal protection systems. However, Fuji is not conducting research on titanium aluminides and does not have rapid solidification technology production capability.

Mitsubishi has developed superplastic forming, diffusion bonding, and electron beam-welding processes. Its composite laboratory in Nagoya is conducting research on autoclave molding of titanium foil, studying advanced fabrication of carbon-carbon, studying molding processing for thermoplastic composites, and evaluating the thermal properties of composites. Thermal protection systems being studied include carbon-carbon composites, ceramic tiles, and metallic thermal protection systems.

Kawasaki has tested carbon-carbon composite material to 1,700 degrees Celsius for 10 6-minute cycles. According to NASP Joint Program Office Fact Finding Group officials, Kawasaki officials stated their carbon-carbon material is one of the best in the world. NASP Program officials and U.S. industry representatives were impressed with Kawasaki's carbon-carbon composite material and had no reason to doubt Kawasaki's claim. However, they questioned whether Kawasaki could produce carbon-carbon composite materials in sufficient quantities to build an aerospace plane.

Advanced structural materials industries have become increasingly international in character through acquisitions, joint ventures, and licensing agreements. According to the Department of Defense, this trend has important consequences for the United States: one can no longer assume that the United States will dominate the advanced structural materials technologies and their applications. According to the National Research Council, the United States is already lagging behind other nations in applying advanced materials to manufacturing processes. Also, the rate of technology flow among companies and between countries is likely to grow due to the increasingly multinational character of the materials industries.

Some of the key technologies for a future Japanese spaceplane are being developed in nonaerospace industries. For example, titanium-aluminide used in the manufacturing of turbocharger rotors for motorcycle engines by Kawasaki could have spaceplane applications. Members of the Fact Finding Group cautioned that relatively small levels of investment in the development of enabling technologies in Japan (compared with investment levels in the United States) does not mean that significant research and development is not being conducted. Technology developed by nonaerospace industry in Japan is applicable to developing and building a spaceplane.

Assessment of Advanced Materials Work in Japan

According to U.S. government and university materials experts who were members of the Japanese Technology Evaluation Center panel on advanced composites, the Japanese believe that technological superiority in space structures and launch systems, and particularly in hypersonic vehicles, will allow Japan to become a dominant force in the aerospace market. An enabling technology is advanced materials, one of three areas selected by the Ministry of International Trade and Industry for major national development investment.

Many Japanese government and industry programs are long-term efforts geared to the future at the expense of short-term gains. For example, the Ministry's program to develop new heat-resistent materials for a spaceplane and other purposes is scheduled to last for 8 years—a longer time than would be possible in the United States. Parallel approaches to advanced materials research and technology are encouraged and supported by the Japanese. These approaches often involve overlapping activities between several groups with a sharing of information at the precompetitive stage, according to panel members. In contrast, the United States often tries to select one best approach initially and then frequently finds that other options are needed.

According to panel members, requirements for Japanese government programs are usually set at a modest, realistic, and attainable level. In this way, Japanese government and public support can be maintained. Unlike the United States, the goals are not driven by requirements for a specific system. Also, in comparison to the United States, direct Japanese government funding for new materials is quite small, since it usually does not include personnel costs. Japanese government funding focuses on areas of national interest. According to panel members, a strong national unity drives Japanese industry to make much larger contributions to the support of new materials research and technology.

According to the Japanese Technology Evaluation Center panel, some Ministry of International Trade and Industry materials programs have led to new consumer markets and ultimately to substantial returns on the Japanese government's investment. The Japanese have learned manufacturing skills and have formed technical teams within and across industries, which remain intact for the long periods of time required to develop and exploit the market. However, the new high temperature materials program is quite different. Although these materials may be an enabling technology for an aerospace plane and hypersonic transport aircraft, they may only be produced in small quantities. Japanese companies that only produce materials may have to reexamine the question of national commitment versus profit. A large, well-funded, and vertically integrated Japanese company may be able to produce the materials and aircraft structures internally.

Panel members noted that a strong fiber and carbon industry makes Japan the leader in carbon fiber technology and that this technical base should allow Japan to not only match U.S. carbon fiber technology but also introduce lower cost manufacturing methods. However, panel members did not see any research in Japan on innovative approaches to oxidation protection. Although ceramic and intermetallic matrix composites are not being actively pursued in Japan at this time, they may be in the near future. Monolithic ceramic research and development activity is still at a high level. High-temperature monolithic intermetallic research is just beginning, although some products consisting of titanium aluminides have been manufactured. Panel members noted a novel Japanese approach in matrixless ceramic composites. Finally, technologies for high-temperature composites fabrication exists in Japan but large numbers of panels or parts have not yet been produced. A decrease in the interest of Japanese companies in aluminum matrix composites that have lower temperature capabilities is due to the lack of a commercial market and not the availability of technology.

Computational Fluid Dynamics and Supercomputers

Computational fluid dynamics—the use of advanced computer programs to solve a set of mathematical equations with a high-speed digital computer—is extensively used in aerospace vehicle programs to simulate air flows, high temperatures, and pressure contours around various design configurations of an aerospace plane and within advanced propulsion systems at high Mach speeds. These calculations are used in the design of the vehicles' airframe and engine.

Computational fluid dynamics is also used to simulate aerospace vehicle performance between speeds of Mach 8 and 25, where ground test facilities or capabilities are not adequate in terms of velocity duplication and actual test data are limited. Computational fluid dynamics computer programs must also be validated by actual test data at lower speeds, which are then compared to the theoretical calculations. Modifications to the computer programs are then made where appropriate.

Advances in supercomputers over the past several years have allowed extensive used of computational fluid dynamics in Japanese aerospace vehicle research and development programs. Use of supercomputers has resulted in more accurate and faster air flow calculations.

Three of the five supercomputer manufacturers in the world are Japanese: Fujitsu, Hitachi, and Nippon Electric Corporation. The other two, both U.S. companies, are Cray Research and Cray Computer Corporation. According to U.S. officials, growth in computational capability in Japan has been impressive, and Japan's national laboratories have the computing power to perform state-of-the-art computations on aircraft and propulsion systems. Further improvements in storage and performance are currently underway.

The United States currently has a commanding lead in computational fluid dynamics, according to the Department of Defense. However, strenuous efforts are being made in Japan to develop a competitive capability, since computational fluid dynamics is recognized worldwide as a critical technology. Computational fluid dynamics is a powerful tool for modifying designs and solving problems, and its use by the U.S. aerospace industry for the design of the next-generation commercial aircraft is expected to help maintain the current U.S. dominance.

According to the Department of Defense's Critical Technologies Plan, ongoing research and development in Japan in the following areas indicate a general lagging behind the United States but a potential capability of making contributions in selected areas in meeting U.S. computational fluid dynamics challenges and goals:

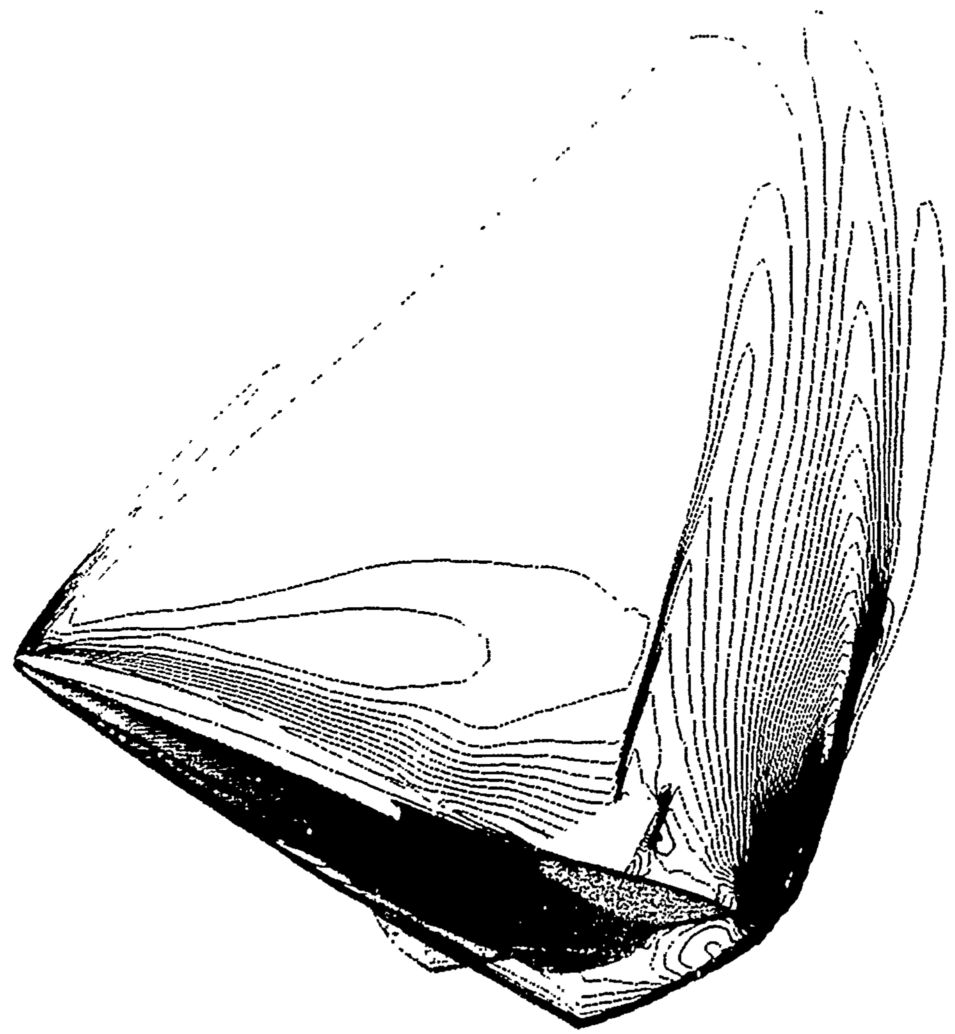
- to improve the application of computational fluid dynamics to complex three-dimensional aerothermodynamic analyses (including characterization of chemical reactions);
- to empirically validate codes for three-dimensional analysis of material response to high-strain/high-deformation rates; and
- to develop algorithms and programming tools to exploit massively parallel computing architectures.

Japan is one of the world's leaders in supercomputers and has, through research on its aerospace plane programs, continued at a growing rate to develop the validated data bases and sophisticated algorithms necessary to use computational fluid dynamics as a design tool. According to the Department of Defense, Japan has recently demonstrated competent efforts in three-dimensional flow mixing as well as the sophisticated design of two-dimensional jet engine inlets.

Formal exchange of information about computational fluid dynamics is limited; however, much of the computational fluid dynamics research into numerical techniques and algorithms is conducted in the academic environment, whose results are published in widely available journals. However, many of the empirically validated computational fluid dynamics codes that can be used for practical applications are proprietary. Among the U.S. military services, the U.S. Air Force is the primary proponent for computational fluid dynamics exchanges. The field of computational fluid dynamics is also expected to benefit at least indirectly from many of the exchange programs in propulsion and materials.

Computational fluid dynamics propulsion research is being conducted at the National Aerospace Laboratory and at several universities for physical phenomena for aerodynamics and propulsion. The Laboratory has been active in numerical simulation research since 1960. Since the development and installation in 1977 of a prototype of Japan's present supercomputers, the Laboratory's Numerical Simulator System has achieved excellent computational fluid dynamics results. For example, figure 4.2 shows the shock wave and surface pressure distribution of an aerospace plane configuration computed by the Laboratory using advanced computational fluid dynamics techniques.

Figure 4.2: Computational Fluid Dynamics Supercomputer Simulation of Shock Waves and Surface Pressure Distributions



Source: National Aerospace Laboratory.

The Numerical Simulator System at the Laboratory has been used since 1987 to investigate the flow field around an aerospace plane through its propulsion system. Simulation of hypersonic flow around an aerospace plane, surface pressure contours, and shock waves using various Navier-Stokes computational fluid dynamics codes illustrate the advanced state of computational technology in Japan. U.S. engineers stated detailed resolution of flow fields produced at the Laboratory indicate Japanese capability to compute real gas effects and hydrogen engine injection processes. The Laboratory is currently conducting computational fluid dynamics temperature and pressure assessments for HOPE. Another major computational fluid dynamics effort is to solve flow field calculations for the Orbiting Reentry Experimental vehicle.

The University of Osaka is working with the Laboratory to develop computational fluid dynamics techniques for scramjet applications. In addition, attention at the University of Nagoya is focused on shock wave capturing using Euler, thin layer Navier-Stokes, and parabolized Navier-Stokes computational fluid dynamics codes.

According to the NASP Program's Chief Scientist, the Japanese demonstrated they can compute aerodynamics for an aerospace plane using Euler and Navier-Stokes computational fluid dynamics codes. National Aerospace Laboratory engineers were able to show in detail both the computed and measured correlation of an airflow around an aerospace plane. The computed flow was conducted using Navier-Stokes computational fluid dynamics codes and a supercomputer, and the measured airflow was conducted in the Laboratory's hypersonic wind tunnel. The Japanese have captured chemical or real gas effects in their computational fluid dynamics external flow codes for three-dimensional complex configurations. The Chief Scientist said the Japanese have been able to quickly grasp important technical issues in computational fluid dynamics and are achieving impressive results. He believes the United States has a 1- to 2-year lead in computational fluid dynamics due to the NASP Program. In terms of computer hardware, he believes Japan is already at parity with the United States.

According to Japanese Technology Evaluation Center propulsion engineers, the Japanese routinely include real gas effects and complex reaction kinetics in their flow field analyses, and their codes are based on the latest algorithms. Japan's visualization and postprocessing capabilities are also at the leading edge. The propulsion engineers concluded that Japan clearly has the appropriate computational fluid dynamics capabilities to enable it to move rapidly in this aspect of advanced propulsion development. According to the Director for Space Transportation Research in the Science and Technology Agency, in Japan, real gas effects and complex reaction kinetics are generally not included in flow field analyses. However, National Aeronautics and Space Administration officials are seeing more and more analyses in Japan involving real gas effects.

Technological Challenges

Japanese industry and government officials identified several areas as of November 1988 in which more research or technology maturation is required to develop various aerospace vehicles. The basic problem facing Japan is simply a lack of experience in hypersonics. Also, test facilities in Japan are inadequate for full-scale development of an aerospace plane. Japanese aerospace test facilities and their capabilities are discussed in chapter 6.

National Space Development Agency of Japan officials told us the key technological challenges facing HOPE are hypersonic aerodynamics, aerodynamic heating (real gas effects), thermal protection system characteristics and validation, kinetic effects (chemical reaction with materials), a space station docking system, flight control, and anti-oxidation carbon-carbon. Also, the availability of the U.S. Navstar Global Positioning System for HOPE's guidance, navigation, and control is a key issue.

National Aerospace Laboratory engineers said the most challenging technologies for future Japanese aerospace plane development are air-breathing propulsion and advance materials. They identified other critical technological challenges as problems associated with supersonic mixing in a combustion chamber, aerodynamic configuration, slush hydrogen, and fuel tank structure. Institute of Space and Astronautical Science officials mentioned hypersonic aerodynamics and integration of the engine and airframe as technological challenges.

U.S. and Japanese Investment in Aerospace Vehicle Research and Technological Development Efforts

Although directly comparable data for U.S. and Japanese investment in aerospace vehicle research and technological development efforts are not available, funding levels and the number of people involved indicate that U.S. investment in the NASP Program in these areas far exceeds that of Japan in its aerospace vehicle programs. Moreover, planned funding and personnel levels indicate that U.S. investment in the NASP Program will continue to exceed that of Japan in its programs.

U.S. Investment in the NASP Program

The NASP Program is expected to cost more than $5 billion between fiscal years 1986 and 1997, according to the NASP Joint Program Office. The United States has spent about $1.8 billion in the NASP Program between fiscal years 1986 and 1990. Of this amount, the U.S. government has invested about $1.1 billion and U.S. industry about $736 million. According to the NASP Joint Program Office, more than 5,500 people in government, industry, and academia are working on the NASP Program.

The U.S. government also plans to spend about $864 miilion on the NASP Program from fiscal years 1991 to 1993—and a considerably larger amount in subsequent years if a decision is made to build and flight test the X-30. However, planned funding for Phase III of the NASP Program (fiscal years 1993 to 1999) to build and flight test the X-30 experimental vehicle has not yet been determined. As of September 1991, no total NASP Program cost figure was available. However, the NASP Joint Program Office is conducting a cost estimate of Phase III and expects to report that figure to the Congress in March 1992.

Future U.S. industry contributions, however, are expected to be marginal, according to a NASP Interagency Office official, since a national contractor team[1] has been established and companies are no longer in competition.

[1]In May 1990 the Department of Defense and National Aeronautics and Space Administration approved a proposal by the five NASP prime contractors to form a single NASP team. The national contractor team consists of General Dynamics Corporation (airframe development), McDonnell Douglas Corporation (airframe development), Rockwell International Corporation's North American Aviation Division (airframe development), Rockwell International Corporation's Rocketdyne Division (engine development), and United Technology Corporation's Pratt & Whitney (engine development). The National Program Office was also established to integrate the contractor team's work and serve as a single point-of-contact for the government with the contractor team on contractual and technical matters.

Japanese Government, Industry, and University Investment

The Japanese government has spent about $127.9 million and Japanese industry has provided an additional $22.5 million on aerospace vehicle research and development efforts between Japan fiscal years 1982 and 1990.

The Japanese government plans to spend about $3.4 billion between Japan fiscal years 1988 and 1999 on aerospace vehicle research and development. This figure includes about $2.73 billion for the HOPE spaceplane. Between Japan fiscal years 1990 and 1996, an additional $41.8 million is expected to be provided by Japanese industry.

According to National Aerospace Laboratory officials, foreign government and industry officials have a perception that Japan has almost unlimited resources for developing a spaceplane and that the Japanese are working on many spaceplane programs simultaneously. According to Laboratory officials, current Japanese government and industry funding for spaceplane research and development is limited. Current spaceplane proposals are viewed by the Japanese government ministries that must approve them as being too expensive. The three Japanese spaceplane programs are concept or system studies conducted in national space agencies, institutes, and laboratories. Moreover, only the research phase for HOPE has been authorized. HIMES and the single-stage-to-orbit aerospace plane concept have not been approved by the Japanese government.

Funding for spaceplane research and development in Japan over a 15-year period between 1986 and 2000 represents only 5 to 6 percent of the Japanese government's planned investment in all space activities. Preliminary and informal discussions have taken place within the Science and Technology Agency's Spaceplane Study Group regarding the funding of various Japanese spaceplane projects over a 15-year period from 1986 to 2000. According to the Science and Technology Agency, all Japanese spaceplane projects over this 15-year period could cost between $2.3 billion and $3.1 billion.

According to a 1987 study prepared by the Japanese Consultative Committee on Long Term Policy for the Space Activities Commission, Japanese government investment in research and development of all Japanese space activities between 1986 and 2000 could total about $46.8 billion. Agency officials explained in addition to developing operational spaceplanes, these activities include development of rocket boosters, tracking and data acquisition stations, Japanese participation in the planned U.S. space station, low earth orbit manned platforms and co-orbiting platforms, a space factory, a space telescope, an orbital service vehicle, polar orbit earth observation satellites, a polar orbiting platform, an orbital transfer vehicle, geostationary meteorological satellites, communication and broadcasting satellites, a geostationary platform, data relay tracking satellites, and a deep space probe (see fig. 2.1). The study also estimates Japanese industry will probably invest about $24 billion over the same 15-year period. Thus, Japanese government and industry investment in Japan's entire space infrastructure could total about $70.8 billion between 1986 and 2000.

The Director for Space Transportation Research in the Science and Technology Agency stressed that the purpose of the study by the Japanese Consultative Committee on Long Term Policy was to predict future Japanese space activities with cost estimates—and not to prescribe future Japanese space activities. The High Commissioner of the Space Activities Commission said the content of the study's report, including future plans and cost estimates, has not affected Japanese space policy, since the nature of the study's report was only to predict future Japanese space activity. The High Commissioner and Director said no Japanese government organization, including the Space Activities Commission, has ever officially indicated cost estimates for future Japanese space activities.

National Space Development Agency of Japan

The National Space Development Agency of Japan has an annual budget of about $1 billion. Although its budget has increased about 10 percent annually since Japan fiscal year 1987, Space Development Agency officials believe even a 10-percent annual increase is not enough to complete its future projects.

The Director of the Space Activities Planning Division at the Science and Technology Agency indicated the Space Development Agency has invested about $3.7 million between Japan fiscal years 1986 and 1988 in the HOPE program. He estimates the total HOPE program will cost about $2.3 billion. HOPE program managers, on the other hand, estimate the spaceplane program through its first scheduled flight in 1998 could cost about $3 billion. HOPE's total cost has not yet been officially determined.

The Space Development Agency's budget in Japan fiscal year 1990 is almost $1.1 billion, of which about $905 million, or about 82 percent, is funded by the Science and Technology Agency. This figure includes about $156 million from other quasi-government agencies. The Space Development Agency requested about $1 billion for Japan fiscal year

1991 from the Science and Technology Agency and about $124 million from other government sources, for a total of about $1.1 billion. The Science and Technology Agency provided about $3.1 million in Japan fiscal year 1990 to the Space Development Agency's budget for HOPE.

In 1988 the Space Development Agency had 938 personnel, including 468 staff at its Tokyo headquarters. As of November 1988, 30 full-time people were working on spaceplane studies at the Agency's Tsukuba Space Center. The Agency's research and development centers include the Tanegashima Space Center, Tsukuba Space Center, the Kakuda Propulsion Center, and the Earth Observation Center.

The Tanegashima Space Center is Japan's major launch facility. The Takesaki range handles small rocket launches, the Osaki range is used for H-I satellite launches, and the Yoshinobu Launch Complex (currently under construction) will be used for future H-II launches of satellites and the HOPE spaceplane. Other space center facilities include the Masuda tracking data acquisition station, Nogi radar station, and Uchugaoka radar station. The Center also conducts combustion tests for solid rocket motors and liquid rocket engines.

The Tsukuba Space Center, with 232 Space Development Agency employees and 150 contractor personnel as of November 1988, is responsible for research and development of space technologies and engineering tests of satellites and launch vehicles. The Kakuda Propulsion Center develops and tests propulsion systems for launch vehicles. The Earth Observation Center receives and processes remote sensing data transmitted from earth observation satellites.

Institute of Space and Astronautical Science

The Institute of Space and Astronautical Science budget for Japan fiscal year 1989 totaled about $150 million. This figure represents about 13.6 percent of the $1.1 billion total space development budget in Japan. Institute officials would like the Institute's share of the Japanese government's budget allocated to science increased to about 15 percent. However, several researchers in the Institute commented that the Institute is a "maverick" institution and its relative modest budget and academic profile allow it to plan its missions on scientific rather than political requirements.

Between Japan fiscal years 1982 and 1988, the Institute spent about $16.9 million on research and development of a winged vehicle. Of this amount, about $6.7 million was spent on the winged vehicle configuration and about $10.2 million on the propulsion systems. The Institute spent about $4 million between Japan fiscal years 1989 and 1990 on these activities for HIMES. At the time of our visit, Institute officials said they expected to spend about $20 million during each of the next 6 Japan fiscal years (or about $120 million between Japan fiscal years 1989 and 1995) on HIMES until its first scheduled flight in 1997. As of March 1991, however, this plan had not yet been approved. This investment includes propulsion system development. Researchers in the Institute commented they are still requesting funding to build a HIMES prototype.

The Institute is investing about $24 million for construction of new test facilities. These include transonic and supersonic wind tunnels at its Sagamihara facility.

The Institute is headquartered in Sagamihara and, as of 1989, had a total of 291 staff members, including 30 professors, 27 associate professors, 23 visiting professors and associate professors, 49 research associates, and 162 administrative staff and technicians. In addition, the Institute had 97 graduate students and 8 research students. The Institute operates the Kagoshima Space Center, the Noshiro Testing Center, Sanriku Balloon Center, Usuda Deep Space Center, and Space Data Analysis Center and Space Utilization Research Center at Sagamihara.

National Aerospace Laboratory

The National Aerospace Laboratory's total budget for Japan fiscal year 1990 was about $68.8 million. Its aeronautical and space technology budget for Japan fiscal year 1989, for example, was about $69.6 million, of which about $22.3 million was allocated for research, about $21.6 million for personnel, and about $25.9 million for facilities. Although the Laboratory's overall budget has been relatively flat since Japan fiscal year 1982, Laboratory officials expect significant near-term growth. The amount allocated for facilities has shown a major increase since Japan fiscal year 1982.

The Laboratory invested about $15.8 million in research and development of enabling technologies for an aerospace plane between Japan fiscal years 1987 and 1989. This includes about $10.6 million for materials, about $4.2 million for propulsion, about $600,000 for aerodynamics, about $100,000 for control, about $300,000 for systems, and about $100,000 for numerical simulation. In Japan fiscal year 1989, the Laboratory requested about $11.9 million for its Innovative Aerospace Transportation Research and Development program.

In Japan fiscal years 1989 and 1990, the Laboratory spent about $10.2 million on technology development and about $15.7 million on system definition work for a Japanese aerospace plane. Laboratory managers said they will seek to double Japanese government funding to about $67 million in Japan fiscal year 1991 and double it again to about $133 million in Japan fiscal year 1992. Most of the Laboratory's funding for aerospace plane research since Japan fiscal year 1987 has been spent on assessing composite materials, advanced propulsion systems, and aerodynamics.

According to U.S. industry officials, the Laboratory plans to spend about $357 million between Japan fiscal years 1988 and 1998 on its program to develop and build a 10-metric ton unmanned hypersonic experimental aircraft. The experimental vehicle would be used as a flying test bed for air-breathing engines.

The Laboratory is headquartered in Chofu and, as of 1990, had about 450 people. This includes about 330 to 340 research personnel; about 60 conduct research on enabling technologies for an aerospace plane. Personnel are organized around key aerospace technologies such as aerodynamics, materials, computational fluid dynamics, and propulsion.

The Laboratory's facilities include the Kakuda Branch, which is used primarily for research and tests on rocket and air-breathing propulsion systems. Japan's major scramjet combustion test facility is located at the Kakuda Branch. The Laboratory's Chofu Airfield Branch is responsible for aircraft research, structural tests, and wind tunnel facilities.

The Ministry of International Trade and Industry

In April 1989 the Ministry of International Trade and Industry announced an 8-year program from Japan fiscal years 1989 to 1996 totaling about $30.9 million to integrate industry research under one government program to develop Japanese high-speed (supersonic and hypersonic) commercial transport aircraft. Of the $30.9 million, the Ministry plans to spend about $20.1 million from Japan fiscal years 1989 to 1996 on a combined-cycle (turbojet/ramjet) supersonic commercial transport propulsion system and about $10.8 million on materials. Both programs are in the basic research and development stage and consist mainly of component research. According to the Ministry, the programs are not a project to develop a propulsion system for a commercial aircraft.

The Ministry brought under its authority airframe and propulsion research being conducted by the National Aerospace Laboratory and Japanese aerospace companies. In Japan fiscal year 1989, the Ministry allocated only about $3 million to the program. Of this amount, it allocated about $473,000 for airframe research, $233,000 for propulsion, and about $2.3 million for composite materials. The Science and Technology Agency provided about $7.9 million to the National Aerospace Laboratory for construction of a ramjet test chamber high-temperature system. This project is expected to last 4 years.

Ministry officials reviewed proposals in 1988 and 1989 for the construction of supersonic and hypersonic test facilities. They are not optimistic that Japanese government funding will be forthcoming. The Ministry estimated that about $6.2 billion would be required for all Japanese government test facility projects. This included wind tunnels; test chambers for heat-resistant structures, high-altitude operations, and ramjet engines; a high-speed simulator; a supersonic aircraft prototype; and a flight test facility with a 11,000-foot runway. As of March 1991, the Ministry had no proposals for the construction of supersonic and hypersonic test facilities.

The Ministry has several small laboratories that conduct space-related work, but its primary role is in the promotion of future space commercial applications. Its current focus is on the development of high-speed commercial transport aircraft through international collaboration. Ministry officials told us seven people in the Ministry's Space Industry Division are involved full-time in spaceplane work. Several other Ministry employees are involved part-time.

Ministry of Education, Science, and Culture

In Japan fiscal years 1989 and 1990, the Japanese Ministry of Education, Science, and Culture funded a $130,000 study on scramjets involving 20 professors at four Japanese universities. In addition, the University of Tokyo receives about $20,000 annually from the Ministry for similar research on scramjets.

Fuji Heavy Industries

Fuji received about $3.63 million in contracts from the National Space Development Agency of Japan for HOPE development activities from Japan fiscal years 1986 to 1990. The company also received what Fuji officials described as "small contracts" from the National Aerospace Laboratory for study related to a single-stage-to-orbit aerospace plane. Fuji has invested about $3.5 million of its own funds between Japan fiscal years 1986 and 1990 in research on all aerospace plane development work, excluding facilities. During that period, the company also invested about $15 million on test facilities that can be used for a variety of purposes in addition to aerospace plane research and development. Fuji also plans to build a hypersonic wind tunnel that could cost about $7.8 million.

As of February 1991, Fuji had 15,358 employees, of which 2,768 worked in the Aerospace Division. Only 20 engineers are working full-time on the HOPE project and on an aerospace plane. Another 40 engineers, working part-time, support them in functional areas.

Ishikawajima-Harima Heavy Industries

Ishikawajima-Harima has what company officials described as two "very small contracts" with the National Aerospace Laboratory and the Institute of Space and Astronautical Science to conduct studies on the single-stage-to-orbit aerospace plane concept. Although Ishikawajima-Harima investment information was proprietary, company officials indicated that Ishikawajima-Harima's own investment in aerospace plane research and development is greater than its Japanese government contracts. Company officials said National Aerospace Laboratory contracts were evenly divided among four companies (Fuji, Ishikawajima-Harima, Kawasaki, and Mitsubishi) and that the Institute of Space and Astronautical Science contracts totaled "several million yen" (tens of thousands of dollars) divided among the four companies.

Ishikawajima-Harima officials did not indicate how many people were working on aerospace plane-related propulsion research and development.

Kawasaki Heavy Industries

Kawasaki officials at the company's Gifu Works said the company had spent about $4 million between Japan fiscal years 1986 and 1989 on fundamental research for an aerospace plane. Company officials also said fundamental research is conducted in several different groups within the company. They added that Kawasaki plans to spend about $34 million on in-house research and development for an aerospace plane between Japan fiscal years 1990 and 1996.

Kawasaki established a new organization within the company in August 1988 to conduct aerospace plane research and development. System study and research and development works for subsystems (such as aerodynamics, advanced materials, guidance and control, and thermal control) are carried out within this newly organized team. Kawasaki officials at the company's Tokyo headquarters told us about 25 engineers were "deeply involved" full-time in conducting research and development work on HOPE and other spaceplanes, including a single-stage-to-orbit aerospace plane. Company officials at the Gifu Works told us the 25 engineers in the design team are supported by 100 people in many other functional areas. Research and development for an air-turboramjet and scramjet is underway at Kawasaki's Kobe Works.

Mitsubishi Heavy Industries

Mitsubishi received about $3.4 million in contracts from the National Space Development Agency of Japan between Japan fiscal years 1987 and 1989 for work on HOPE. U.S. officials reported problems with the LE-7 turbopump (developed by Ishikawajima-Harima) could use all of Mitsubishi's budget for aerospace plane engine development in Japan fiscal year 1990. Mitsubishi expected to receive a small contract of about $123,000 in Japan fiscal year 1989 from the National Aerospace Laboratory for work on a single-stage-to-orbit aerospace plane.

Mitsubishi anticipates receiving future contracts from the Space Development Agency totaling about $702 million out of the $1.56 billion total development cost of the H-II launch vehicle. In addition, company officials expect to receive about half of the $117 million for each of four planned H-II operational vehicles, including launch operations for a total of about $234 million.

According to Mitsubishi officials, as of November 1988, 60 company engineers were participating in the HOPE program. Only a few people were involved in aerospace plane activities.

Japanese National Universities

Direct research efforts of the Japanese national universities are funded through an annual base budget for research activities. These funds are divided among faculty at each institution and are discretionary regarding research topics. According to Japanese Technology Evaluation Center panel members, direct financial support to individual professors in Japan for aerospace plane research is quite small. However, this can be misleading because, unlike in the United States, faculty and student salaries in Japan are generally separated from research grants. For example, each faculty member in the Aeronautics Department at the University of Tokyo receives about $20,000 annually in research grants. A group of 20 professors at four Japanese national universities, including the University of Tokyo, received a grant of $130,000 for Japan fiscal years 1989 to 1991 to study hypersonic reactive flows in scramjets. This grant was to encourage them to funnel their base research grants into hypersonics. Panel members commented that despite the small size of the grant, Japanese faculty indicated it was a major help in building a strong research effort in hypersonics.

Japanese Aerospace Test Facilities and Their Capabilities

Plans for the development of Japanese aerospace vehicles, such as the National Space Development Agency of Japan's HOPE spaceplane, Institute of Space and Astronautical Science's HIMES vehicle, and the National Aerospace Laboratory's air-breathing single-stage-to-orbit aerospace plane concepts, have significantly increased Japanese interest in hypersonics. Also, the NASP Program is substantially responsible for this increased interest in Japan in a field that had been relatively dormant in the United States and Europe for about 20 years. However, research and development of Japanese aerospace vehicles and concepts require not only adequate test facilities and a comprehensive understanding of hypersonics but also experienced and trained personnel.

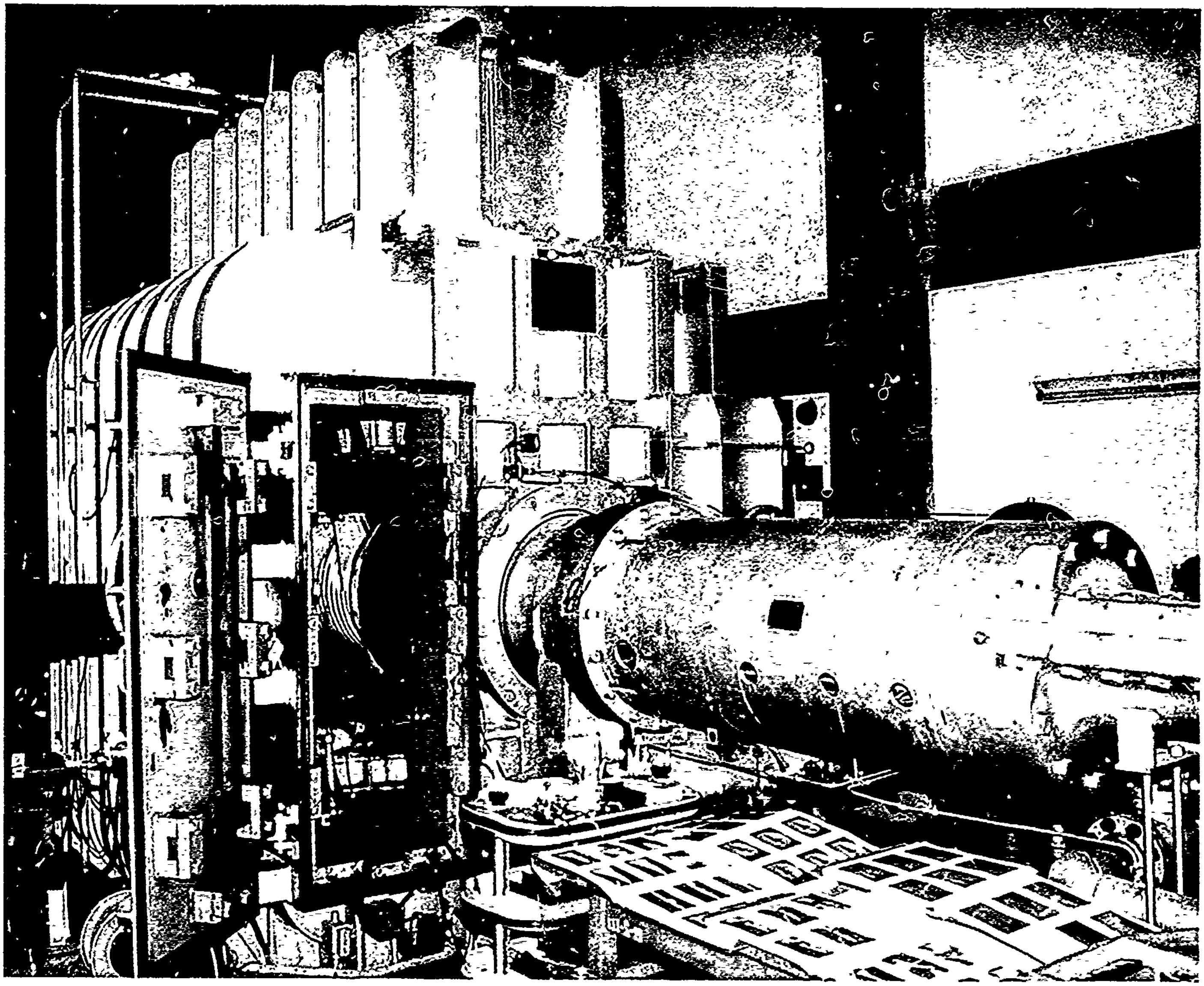
This assessment of Japanese aerospace test facilities and their capabilities includes wind tunnels and air-breathing propulsion test cells; advanced materials research, development, production, and fabrication laboratories; supercomputer facilities; and Japanese facilities needed to test future aerospace vehicles.

Wind Tunnels and Air-Breathing Propulsion Test Cells

Japanese wind tunnel facilities are generally small, modeled after U.S. facilities, and adequate only for limited subscale testing. Japanese government and industry officials told us existing test facilities in Japan are not adequate for large-scale testing or developing an aerospace plane.

The National Aerospace Laboratory's 50 centimeter Hypersonic Wind Tunnel is currently the only hypersonic wind tunnel in Japan. Figure 6.1 shows the test section of the National Aerospace Laboratory's 50 centimeter Hypersonic Wind Tunnel at Chofu.

Figure 6.1: National Aerospace Laboratory's 50 Centimeter Hypersonic Wind Tunnel



Source: GAO.

The Laboratory plans to invest about $26.3 million between Japan fiscal years 1991 and 1993 to construct a new test leg for its 50 centimeter Hypersonic Wind Tunnel. The new test leg is designed to have a 1.27-meter exit diameter Mach 10 nozzle parallel to the existing 50-centimeter test section. This size was determined by the maximum capability of existing wind tunnel facilities to provide detailed aerodynamic data during HOPE's development phase. The size was also determined by an analysis of U.S. hypersonic tests conducted during development of the U.S. space shuttle.

The National Aerospace Laboratory's Ram/Scramjet Combustor Test Facility, built at the Kakuda Branch in 1977 and upgraded in 1983, is an intermittent, blowdown engine/propulsion component facility. The facility is capable of conducting direct-connect tests of ramjet and scramjet combustors up to speeds of Mach 2.5. However, the facility is primarily a small research facility.

According to Laboratory officials, the Laboratory does not have a good combustion test facility for a scramjet. Moreover, its large vacuum test chamber is inadequate for large engine component testing.

The National Aerospace Laboratory's Ram/Scramjet Engine Test Facility will be an intermittent blowdown hypersonic wind tunnel. The facility is being built at the Laboratory's Kakuda Branch by Kobe Steel in cooperation with FluiDyne Engineering Corporation. The facility is now scheduled to be placed in operation in 1993.

The types of tests being conducted in Japanese facilities is also an important indicator of not only their capabilities but also of their intentions. Specific examples of the types of tests and applications of Japanese wind tunnels are discussed in our June 1990 report on foreign test facilities.[1]

Limitations in Ground Test Capabilities

Adequate ground test capabilities and facilities to test future air-breathing aerospace vehicles above speeds of Mach 8 for sustained periods do not exist. In fact, no single facility or group of facilities is capable of creating the combination of velocities, temperatures, and pressures necessary to simulate these aerospace vehicles' actual flight conditions. Therefore, flight demonstrators are being developed, or being considered for development, by the United States, Soviet Union, Germany, and Japan as "flying test beds" to validate the required technologies at speeds between Mach 8 and 25.

[1]This report provides technical data and information on principal Japanese wind tunnels and air-breathing propulsion test cells, including performance characteristics (i.e., technical parameters describing the facility's principal capabilities and operating range), cost information, and the number and type of staff required to operate the facility. This catalogue of foreign aerospace test facilities also provides narrative information describing each facility, its testing capabilities, planned improvements, unique characteristics, and current programs.

Computational Fluid Dynamics

Although Japanese aerospace vehicle programs depend heavily on numerical aerodynamic simulation, they still rely on wind tunnels to validate new designs, refine design configurations, establish data bases, and validate computational fluid dynamics simulations. Fundamental research in hypersonics for HOPE, HIMES, and single-stage-to-orbit aerospace plane concept and system studies will also rely heavily on the Japanese hypersonic wind tunnel and instrumentation.

Advanced Materials Research, Development, Production, and Fabrication Laboratories

The National Space Development Agency of Japan's Tsukuba Space Center has facilities for research and development of structure and thermal protection technology for its launch vehicles and HOPE. The National Aerospace Laboratory is building a new structural materials laboratory at its Chofu Airfield Branch, to be completed in 1991, that will test thermal properties and strength of aerospace plane structures and materials. The Institute of Space and Astronautical Science's Research Division for Space Transportation at Sagamihara has research sections for vehicle structures and high-strength materials. Recent activities have included, for example, research on the fracture of metallic materials at high temperatures.

The Japan Ultra-high Temperature Materials Research Center was established in Yamaguchi Prefecture and the Japan Ultra-high Temperature Materials Laboratory in Gifu Prefecture in March 1990 to achieve rapid progress in research and development of ultra-high temperature materials. These facilities were established under the basic research improvement plan of the New Energy and Industrial Technology Development Organization.

Fuji's advanced materials laboratories in Utsunomiya have a wide range of advanced materials capabilities, including carbon-carbon composites and reinforced carbon-carbon composites. Fuji has facilities for superplastic forming, diffusion bonding, and electron beam-welding processes. Fuji is also studying molding processes of thermoplastic composites and carbon-polyimide, evaluating composite material characteristics under a space environment (e.g., electron beam radiation and thermal cycles), and developing various thermal protection systems. Fuji also has extensive composite material lay-up facilities and autoclaves for composite material manufacturing. However, Fuji does not have rapid solidification technology production capability.

Mitsubishi's composite materials laboratory in Nagoya has facilities for developing superplastic forming, diffusion bonding, and electron beam-welding processes. Its laboratory is conducting research on autoclave molding of titanium foil, studying advanced fabrication of carbon-carbon, studying molding processing for thermoplastic composites, and evaluating the thermal properties of composites. It has the capability to conduct thermal protection system analyses on carbon-carbon composites, ceramic tiles, and metallic thermal protection systems. It also has an organic matrix composites manufacturing capability.

Supercomputer Facilities

The National Aerospace Laboratory has been conducting numerical aerodynamic simulation since 1960 and, with a loosely coupled multi-processor system with two supercomputers, established an innovative research facility in 1987 at its Chofu Airfield Branch. The facility has a Fijitsu FACOM[2] VP-400 supercomputer with a peak processing speed of 1.14 gigaflops and a 1-gigabyte main memory and a Fijitsu FACOM VP-200 supercomputer with a peak processing speed of 570 megaflops and a 128-megabyte main memory. The Laboratory has 40 to 50 people working on computational fluid dynamics codes, including full Navier-Stokes computational fluid dynamics codes.

The Institute of Space and Astronautical Science has a Fijitsu VP-200 supercomputer at its Sagamihara headquarters.

Japanese aerospace industry generally uses intermediate-class computers (an older mainframe computer that is not as fast as a mini-supercomputer), but has access to the National Aerospace Laboratory's Fijitsu VP-400 supercomputer at user's or reasonable cost. Japanese industry is using full Navier-Stokes computational fluid dynamics codes in their aerospace plane research.

The privately owned Institute for Computational Fluid Dynamics near Tokyo employs 27 people, including 16 engineers. Its computational hardware includes a Hitachi S8-20/80 supercomputer acquired in 1990 that has a 2-gigaflop processing rate and 512 megabytes of memory. In 1986 the Institute acquired a Fijitsu VP 200 supercomputer with a 570-megaflop processing rate and 256 megabytes of memory. In 1987 the Institute acquired a Nippon Electric Corporation SX2 supercomputer with a 1.3-gigaflop processing rate and 256 megabytes of memory. In 1989 the Institute acquired a Fijitsu VP-400E supercomputer with a 1.3-gigaflop processing rate and 512 megabytes of memory.

[2] In Japan, Fijitsu supercomputers are commonly identified by the acronym FACOM, which stands for Fijitsu Automatic Computer.

Japanese universities, according to the advanced supercomputer liaison scientist with the Office of Naval Research in Tokyo, generally have the best supercomputers in Japan. As of August 1990, for example, the University of Tokyo's Hongo Campus had the latest and fastest Japanese supercomputer: a Hitachi S8-20. This supercomputer has a maximum processing speed of 3 gigaflops and a 512-megabyte main memory. The University of Hokkaido also has the Hitachi S8-20. Kyoto University has a Fijitsu VP-400E—the top of the line Fijitsu supercomputer. The University of Osaka and Tohoku University in Sendai each have the 256-megabyte memory Nippon Electric Corporation SX2 supercomputer.

In Japan, the number of people performing large-scale computations (such as computational fluid dynamics research on an aerospace plane) is significantly less than in the United States, according to the Office of Naval Research liaison scientist. For example, as of March 1991, Kawasaki has the most in Japanese industry (six to seven people).

Japanese Facilities Needed for Testing Future Aerospace Vehicles

Space Development Agency officials said Japan will need to construct new hypersonic wind tunnels; a shock tunnel with a 1.5-meter test section at the National Aerospace Laboratory or at the Space Development Agency; high-enthalpy wind tunnels; a guidance, navigation, and control facility; and a landing facility for HOPE. The Institute of Space and Astronautical Science is proposing scramjet test facilities at the National Aerospace Laboratory, but funding is a problem. Ishikawajima-Harima is planning to build an engine test facility at Kakuda.

According to U.S. Department of Commerce officials in Osaka, the Chubu region is conducting a conceptual study to build a world class aerospace research center in Chubu, Japan, known as the Chubu Aerospace Institute. Although still in its preliminary stages, this project is significant, according to U.S. officials, and demonstrates Japan's desire to play a central role in international cooperative development of hypersonic and supersonic transport aircraft.

According to the Chubu Industrial Advancement Center, the Chubu Aerospace Institute is expected to cost about $577 million for a facility with a supersonic wind tunnel or about $1.9 billion for a facility with a hypersonic wind tunnel. Japanese officials have not yet determined a site or timetable for completion of the project. However, the Institute is expected to have a research staff of 120 with an additional 30 support employees to conduct studies on aircraft and space projects. The planned Institute is also expected to have laboratories for engines, aerodynamics and air power, systems and materials, and aircraft systems. U.S. Department of Commerce officials said the creation of such a center could serve as an enticement for international collaboration on the HOPE spaceplane.

International Cooperation

Japan is not participating with other governments on air-breathing aerospace research and development efforts. Japan currently has no plans for international cooperation. However, Japanese government and industry officials believe that developing an aerospace plane will ultimately require an international effort. Japan wants to first raise its technology level to international standards before seeking international cooperation.

Japanese government officials and industry representatives expressed interest in cooperating with the United States on the NASP Program. They also expressed reservations about cooperative ventures with the United States based, in part, on barriers that include Japan's lack of experience in hypersonics, Japan's constitutional prohibitions against the military use of space, fundamental differences in U.S. and Japanese aerospace plane programs, and strict U.S. export controls on the transfer of technology. Currently, NASP Program officials do not anticipate seeking international cooperation in developing and demonstrating the X-30. However, according to U.S. government and industry officials, areas in which Japanese technology might be incorporated in the NASP Program include advanced propulsion and advanced materials.

The United States is ahead of Japan in developing the technologies for an air-breathing single-stage-to-orbit aerospace plane. However, a significant international collaborative effort to build an aerospace plane involving Japan, France, Germany, the United Kingdom, and/or the Soviet Union could be competitive with the NASP Program.

U.S./Japanese Cooperation

The High Commissioner of the Space Activities Commission believes space development inherently requires international cooperation and that Japan will promote international cooperation through an appropriate contribution. The High Commissioner indicated Japan is not developing its aerospace plane technology base independently. One U.S. hypersonics expert suggested Japan is first developing the technology for a broad range of applications before seeking international cooperation.

The High Commissioner of the Space Activities Commission told us that development of a Japanese aerospace plane will be an international effort, and not purely a Japanese effort, due to the lack of Japanese technology and funding. A Ministry of International Trade and Industry official said it would be in the best interest for Japan and the United States to join in the development of an aerospace plane and share the benefits of cooperative development. Several Japanese government officials stated the burden on any one country to have its own aerospace plane development program would be too great, even for the United States. The National Space Development Agency of Japan's Director for Program Planning told us if Japan wants to be an equal partner in building an aerospace plane, then it will need to develop an experimental aerospace plane by itself for proper contribution to the partnership so that Japan will not be treated as a minor partner.

Ministry officials said Japan is ready to collaborate with the United States and other countries on a Mach 2 to 5 supersonic transport aircraft in the areas of technology, manpower, and funding. The Japanese believe the cost of developing the next-generation commercial supersonic and hypersonic transport aircraft will also require an international consortium. Japan plans to play a major role in any future consortium and has already begun research and development on advanced materials and propulsion as two areas in which Japan could make significant contributions.

Although the United States continually assesses the possibility and desirability of international cooperation in developing and building the X-30, NASP Program officials have not developed a formal strategy or written policy regarding international cooperation. NASP Program officials have not actively sought international cooperation. However, in September 1988 the NASP Program Director stated that program officials have begun exploring collaboration with foreign countries and that it is very clear the United States is in the lead in technology.

In September and October 1988, members from the NASP Joint Program Office Fact Finding Group representing the NASP Joint Program Office, Office of Science and Technology Policy, McDonnell Douglas Corporation, and Rockwell International Corporation visited France, Germany, the United Kingdom, and Japan to (1) exchange information about the status of and plans for spaceplane development in Europe, Japan, and the United States, (2) understand the problems and technical barriers to spaceplane development, and (3) explore specific technical areas for possible use on NASP or for possible collaborative development. After these visits, and based on other assessments, the NASP Program Director ruled out joint development of the X-30 with any one country.

Currently, no discussions are being held on international collaboration for designing and developing the X-30. U.S. officials believe the United States is still ahead in developing enabling hypersonic technologies, some of which may have significant commercial applications in the future. The Acting Director of the Office of Science and Technology Policy stated in July 1989 that any sharing of technology will be judged on how the technology would benefit the parties, not on whether the technology would reduce costs. The National Space Council considered the possibility of international cooperation on the NASP Program. However, most Council members believe NASP should remain a national program, since aerospace technology is one of the few remaining areas in which the United States has a positive balance of trade (about $26.9 billion in 1990 and an estimated $37.1 billion in 1991, according to the Department of Commerce). As of September 1991, the NASP Program Director did not anticipate that the NASP Program would seek international partners.

The National Aeronautics and Space Administration has frequent contacts with foreign aerospace vehicle program managers, scientists, and engineers. It utilizes foreign expertise and monitors foreign programs through existing data exchange agreements.

NASP airframe contractors do not favor international cooperation. They believe the United States is far ahead in hypersonics and that Europe and Japan would have little to offer. However, some subcontracting has occurred with Japanese companies through traditional partnerships. If U.S. government funding for the NASP Program diminishes, then U.S. industry may reconsider seeking foreign support, according to U.S. industry representatives. Germany and Japan are considered the most probable possibilities by U.S. industry, since their commitment to hypersonic programs appears strong. If U.S. government funding for NASP diminishes, U.S. industry officials are concerned that any collaborative agreement may be difficult to achieve because of U.S. export controls on the transfer of technology.

According to U.S and foreign government officials and industry representatives, advantages of international cooperation in the NASP Program include the sharing of technical data and information, expertise, and approaches; having access to greater resources, such as test facilities; sharing costs; reducing or eliminating duplication; and increasing the market size. Disadvantages include inherent difficulties in different program goals and objectives, concepts, and size; sharing technology; sharing ownership; difficulties in integrating diverse national bureaucracies; delays in reaching decisions due to differing political and legal systems; complications resulting from different decision processes, priorities, and competencies; political inertia, which may make projects hard to start and even harder to stop; competition for funding with countries' other national and international commitments; a tendency to undertake low-priority projects only; conflicts between cooperation and competition; and a decreasing market share.

Barriers to Cooperation With the United States

According to Japanese government officials and industry representatives, barriers to Japanese cooperation with the United States on the NASP Program include Japan's lack of experience in hypersonics; the perception that NASP is a military program; Japan's constitutional prohibitions against the military use of space; potential military applications of a future NASP-derived operational vehicle; differences in the objectives, size, schedule, and level of technology maturation of U.S. and Japanese aerospace plane programs; a reluctance by the United States to share its technology, most recently demonstrated during negotiations on U.S.-Japanese codevelopment of the Support Fighter (FS-X) experimental airplane;[1] and strict U.S. export controls on the transfer of technology.

National Space Development Agency of Japan officials told us the Japanese constitution as well as a Japanese Diet (Parliament) resolution states that "Japan will only pursue space activities for peaceful purposes." Japanese government officials interpret this prohibition as meaning no military activities in space development. U.S. officials suggested this prohibition means no offensive weapons in space.

Kawasaki officials expressed concern that U.S. test facilities may not be available due to scheduling conflicts and heavy use by the NASP Program. Mitsubishi program managers expressed concern that the X-30 is a Department of Defense-funded program incorporating technology that has both military and commercial use. The Japanese government would have great difficulty politically participating in a program that has both civilian and military applications, since space activities in Japan are strictly limited to civilian use. However, they stressed this is a problem primarily for the Japanese government. This is also a problem for Japanese industry due to legal restrictions on exports.

Mitsubishi is prepared to participate in the NASP Program if a framework for cooperation is developed. The company would prefer to cooperate

[1]Under a 1989 agreement with the United States, Mitsubishi leads a consortium to jointly develop an F-16 derivative fighter aircraft. The FS-X project will give Japanese companies experience in several new technologies, such as manufacturing sophisticated radars and wings from composite materials Some U.S. government officials and industry representatives believe that this exchange of technology could pose a future commercial threat to the United States.

with the United States. However, if that were not possible, then the company would cooperate with European countries.

According to U.S. government and industry officials, areas in which Japanese technology might be incorporated in the NASP Program include advanced propulsion and advanced materials.

Japanese Cooperation With Europe and the Soviet Union

Mitsubishi and Daimler Benz are discussing possible Japanese cooperation on Germany's Saenger II two-stage-to-orbit space launch vehicle concept.[2] France's two government-owned propulsion companies, Societe Nationale d'Etude et de Construction de Moteurs d'Aviation, or National Company for the Study and Construction of Aviation Engines, and the Societe Europeenne de Propulsion, or European Propulsion Company, reported they would consider joining forces with the Japanese government to develop the propulsion system for the next-generation supersonic transport aircraft. In 1989 the Japanese Ministry of International Trade and Industry invited the United Kingdom and France to participate in a project to build a Mach 5 supersonic transport. Four Japanese manufacturers and five European manufacturers committed $17 million to an initial research effort.

The Ministry opened its National Research and Development Program to foreign companies beginning in Japan fiscal year 1989. The New Energy and Industrial Technology Development Organization and four foreign companies discussed a contract concerning their participation in the research and development of a supersonic and hypersonic transport propulsion system. This effort is one of the Large-Scale Projects supported by the Ministry. A recent agreement between the Organization and the foreign companies will contract some of the research and development work to the foreign companies. According to the Ministry, the technical results of this Japanese government-funded project will be shared among the foreign companies and contribute to technology development in the field of aeroengines. Finally, according to the Ministry, this project is expected to set a precedent that will further international collaboration in the development of innovative technologies.

Science and Technology Agency and European Space Agency administrators meet annually to discuss Japanese and European space activities. According to National Space Development Agency of Japan

[2] Germany's Advanced European Space Transportation System Saenger II is discussed in our report on aerospace investment in Europe.

officials, these meetings resulted in the formation in 1987 of a Working Group on Space Transportation Systems. The Science and Technology Agency has overall coordination responsibility for the Working Group. The Japanese provide the Europeans with information about H-II and HOPE activities, while the Europeans share information with the Japanese on the European Space Agency's Ariane 5 and Hermes.

Soviet officials visited Japan in July 1989 to discuss cooperative space ventures, including joint development of an aerospace plane. Representatives from the Soviet space agency GLAVKOSMOS,[3] the Space/Industry Corporation, and the Technology Export-Import Corporation met with officials from the Society of Japanese Aerospace Companies and the National Space Development Agency of Japan. The Soviets are interested in cooperating on hypersonic technology leading toward the development of a single-stage-to-orbit aerospace plane. According to a Space Development Agency official, the Japanese were not interested in cooperating with the Soviets, since this type of joint program would violate multilateral export control agreements on the transfer of Western technology to the Soviet Union.

Currently, Japan and the Soviet Union are not cooperating on the development of enabling technologies for an aerospace plane. However, Japan and the Soviet Union jointly conduct a computational fluid dynamics conference every other year.

International Collaboration Among Foreign Aerospace Plane Programs

Although the United States is ahead of Japan in developing the technologies for an air-breathing single-stage-to-orbit aerospace plane, a significant international collaborative effort in hypersonics involving Japan, France, Germany, the United Kingdom, and/or the Soviet Union could be competitive with the NASP Program. The combined convergence of national interests, expertise, approaches, funding, and sharing of test facilities in such a cooperative effort could, in the long term, seriously challenge U.S. leadership and preeminence in hypersonics.

Japan has been pursuing joint ventures in aeronautics and aerospace for a number of years. To date, cooperation between Japan and Europe has not been significant. According to a National Aeronautics and Space Administration Ames Research Center official, the Soviet Union appears

[3]GLAVKOSMOS is a Russian acronym that stands for Soviet Main Administration for the Development and Utilization of Space Technology for the National Economy and Research It was established in 1985 to (1) exploit space technology, (2) facilitate commercialization, (3) coordinate space operations, and (4) promote international cooperation.

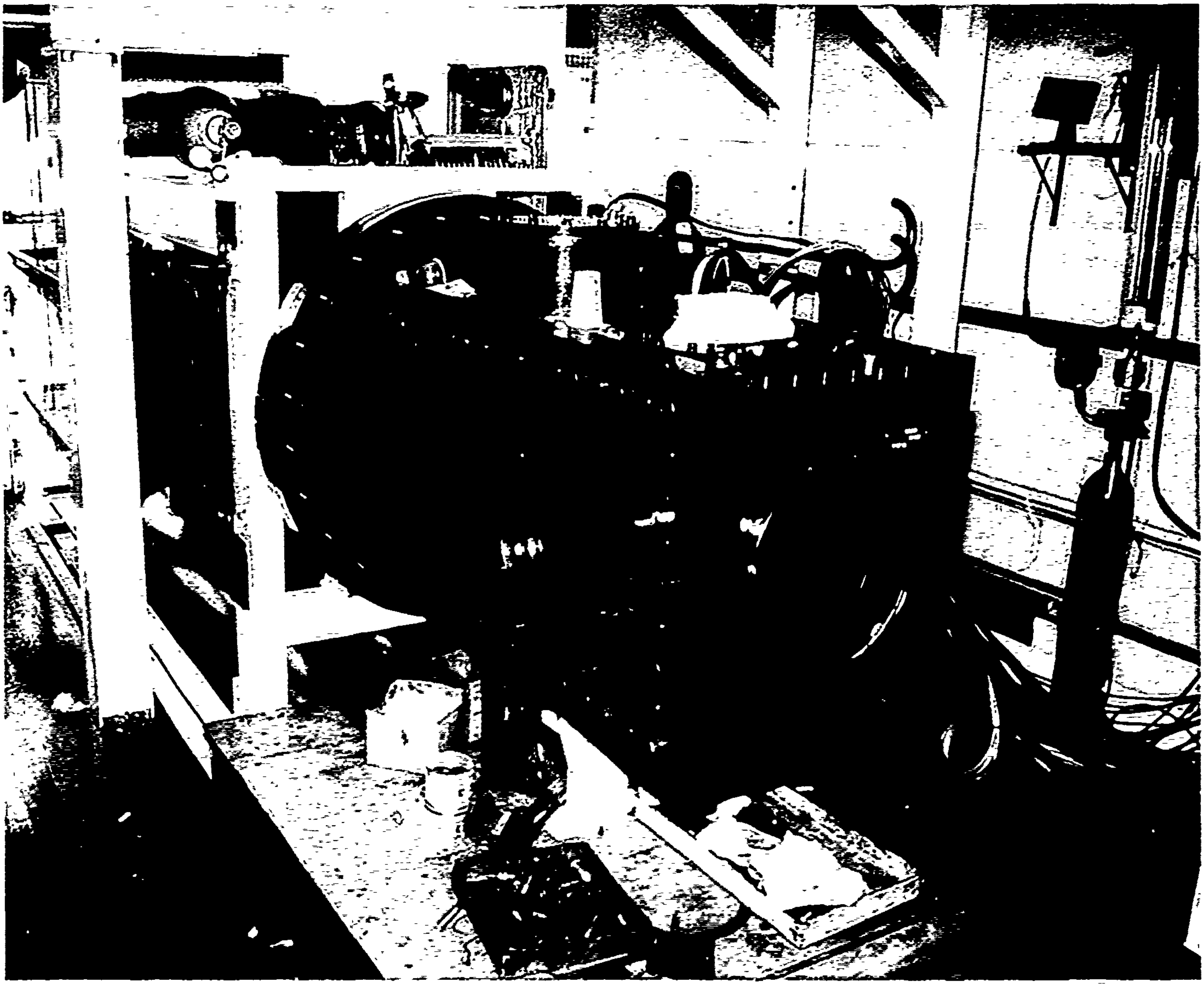
to be aggressively developing joint efforts with European countries. The official said if the ongoing Interim Horizontal Takeoff and Landing (HOTOL)[4] vehicle project between British Aerospace and the Soviet Ministry of Aviation Industry is successful, then further Soviet collaboration in hypersonics with European countries and/or Japan may be more likely. This collective capability could serve to significantly erode U.S. leadership in hypersonics in a very short time. The official also noted that the combination of European and Soviet skills, experimental test facilities, and Japanese supercomputers could possibly lead to the development of a European/Soviet aerospace plane that would constitute an awesome challenge to the United States. Prospects for international collaboration with the United States are not imminent.

Another National Aeronautics and Space Administration Ames Research Center official said the Japanese and Europeans will follow whatever decision the United States makes regarding an aerospace plane. If the United States decides to build NASP, then the Japanese and Europeans will immediately initiate a program of their own, probably a collaborative program. The official added the aerospace plane programs the Japanese and Europeans currently have will allow them to initiate a collaborative program.

[4]An interim version of HOTOL is being designed to be air-launched by the Soviet Union's Antonov An-225 heavy-lift transport aircraft. Both HOTOL and Interim HOTOL are discussed in our report on aerospace investment in Europe.

said they overcame this problem by using a longer compression tube for the free piston compressor in the T-4 Shock Tunnel. The piston travels approximately 26 meters during the driver compression stroke in the T-4 Shock Tunnel, compared to just 6 meters for the T-3 Shock Tunnel's piston. Figure 8.3 shows the test section of the University of Queensland T-4 Shock Tunnel.

Figure 8.3: University of Queensland T-4 Shock Tunnel



Source: GAO

Australia's principal aerospace company is British Aerospace Australia. The company is conducting research on an instrumentation system for a hypersonic vehicle. It also manages testing of aerospace plane concepts and components for European companies in Australian test facilities.

Australian companies such as Hawker de Havilland and AUSPACE have capabilities for the design and manufacture of commercial and noncommercial spacecraft, while organizations such as MITEC, AWA (formerly known as Amalgamated Wireless Australasia), Phillips, British Aerospace Australia, Nippon Electric Corporation (Australia), and the Commonwealth Science and Industrial Research Organization have capabilities and experience in satellite communications technology.

Aerospace plane testing is being conducted in shock tunnels at The Australian National University in Canberra and at the University of Queensland in Brisbane. The University of Sydney is conducting research on scramjet combustion.

Australian Space Policy and Aerospace Goals and Objectives

Although the Australian government is not involved in developing air-breathing aerospace plane technology, the former Australian Space Board considered a proposal from British Aerospace Australia to jointly develop an instrumentation system for a hypersonic vehicle. The high-velocity Re-entry Air Data System would allow the aerodynamic parameters of a space shuttle orbiter (such as its angle of attack, angle of sideslip, free stream dynamic pressure, and Mach number) to be determined in real time during black out periods when the orbiter reenters the atmosphere at hypersonic velocities.

The Australian Space Board turned the proposal down, since Australia does not have an avionics industry capable of developing a reentry air data system and no market exists for the instrumentation system in Australia. British Aerospace Australia, however, is still actively pursuing the proposal and has presented the Re-entry Air Data System to the National Aeronautics and Space Administration for its consideration. The Australian government is also considering establishing a research consortium with industry to test foreign aerospace plane development concepts and components.

Australia wants to create spinoffs from space activities to its manufacturing and services sectors and provide a focus for innovation in a number of industries. The Australian government selects space projects that are likely to have significant benefit for other industries and promotes collaboration in international spacecraft research.

Australian Participation in Foreign Aerospace Vehicle Programs

Australia currently participates in international aerospace plane development efforts by testing British, French, German, and U.S. spaceplane concepts and components in its shock tunnel test facilities.

Tests for British Aerospace on geometry for the HOTOL vehicle concept were conducted in 1987 at the Australian National University's T-3 Shock Tunnel. In 1988 tests for Avions Marcel Dassault-Breguet Aviation on the European Space Agency's proposed Hermes spaceplane were also conducted at the T-3 Shock Tunnel. In 1988 tests for Messerschmitt-Boelkow-Blohm were conducted at the T-3 Shock Tunnel to verify computational fluid dynamics codes for the German Saenger II aerospace plane concept.

The head of the Department of Physics and Theoretical Physics at The Australian National University said a cooperative program with the National Aeronautics and Space Administration's Langley Research Center on scramjet combustion efficiency is being established. British Aerospace Australia is also testing the development of the Re-entry Air Data System to measure and control flight parameters and fuel injectors for an air-breathing aerospace plane in the T-3 facility and at the University of Queensland's T-4 Shock Tunnel.

Australian Investment in Aerospace Vehicle Research and Technological Development Efforts

The Australian government invested about $55,000 in 1988 for the Re-entry Air Data System feasibility study by British Aerospace Australia, and industry spent about $9.4 million from 1987 to 1989 on a feasibility study of an international spaceport on the Cape York Peninsula.

British Aerospace Australia has invested about $702,000 in aerospace research and development between 1983 and 1988. The company planned to invest about $234,000 in 1989 and about $468,000 in 1990. It has five people working on the Re-entry Air Data System. British Aerospace Australia has a $1.2 million contract for HOTOL Phase I and II testing, a $350,000 contract from Messerschmitt-Boelkow-Blohm for Saenger II testing, and a $117,000 contract from Avions Marcel Dassault-Breguet Aviation for Hermes testing.

The Australian National University has received an annual grant of about $1 million from the Australian Department of Education since 1963 to operate its T-3 Shock Tunnel facility. In 1989 the University received a $40,000 contract from British Aerospace for HOTOL testing and a $80,000 contract from Avions Marcel Dassault-Breguet Aviation for Hermes testing. The University also received $132,000 annually from the National Aeronautics and Space Administration from 1986 to 1988 for scramjet combustion mixing testing.

The University of Queensland receives a $109,000 annual grant from the Australian Research Council through the Australian Department of Science to operate its T-4 Shock Tunnel facility. In 1988 it received small fee-for-service contracts for HOTOL and Hermes testing. It also received about $1.3 million in grants from the National Aeronautics and Space Administration since 1985 for NASP scramjet research. According to an official at the Department of Mechanical Engineering at the University of Queensland, about $787,000 has been invested in the T-4 Shock Tunnel facility.

The University of Queensland received a total of about $380,000 in grants from the Australian Research Council for 1991. This amount included $153,000 for shock tunnel studies, $110,000 for shock tunnel instrumentation, $57,000 for layer-induced fluorescence in shock tunnels, and $60,000 for pilot expansion tube studies (over 2 years).

Australian Test Facilities and Their Capabilities

Research in Australia to build facilities to allow hypersonic testing at speeds up to orbital velocity resulted in development of a free piston shock tunnel. With the development of this type of facility, a method is now available for aerodynamic testing at speeds up to orbital velocity for reusable launch vehicles.

The United States, Germany, France, and Japan are constructing or planning construction of free piston shock tunnels based on the Australian Stalker Tube design. However, these facilities are not in operation, and the only two shock tunnels that currently allow testing of high-speed aerodynamic effects on launch vehicles are both located in Australia. These facilities provide the basis for Australian participation in international aerospace plane development projects.

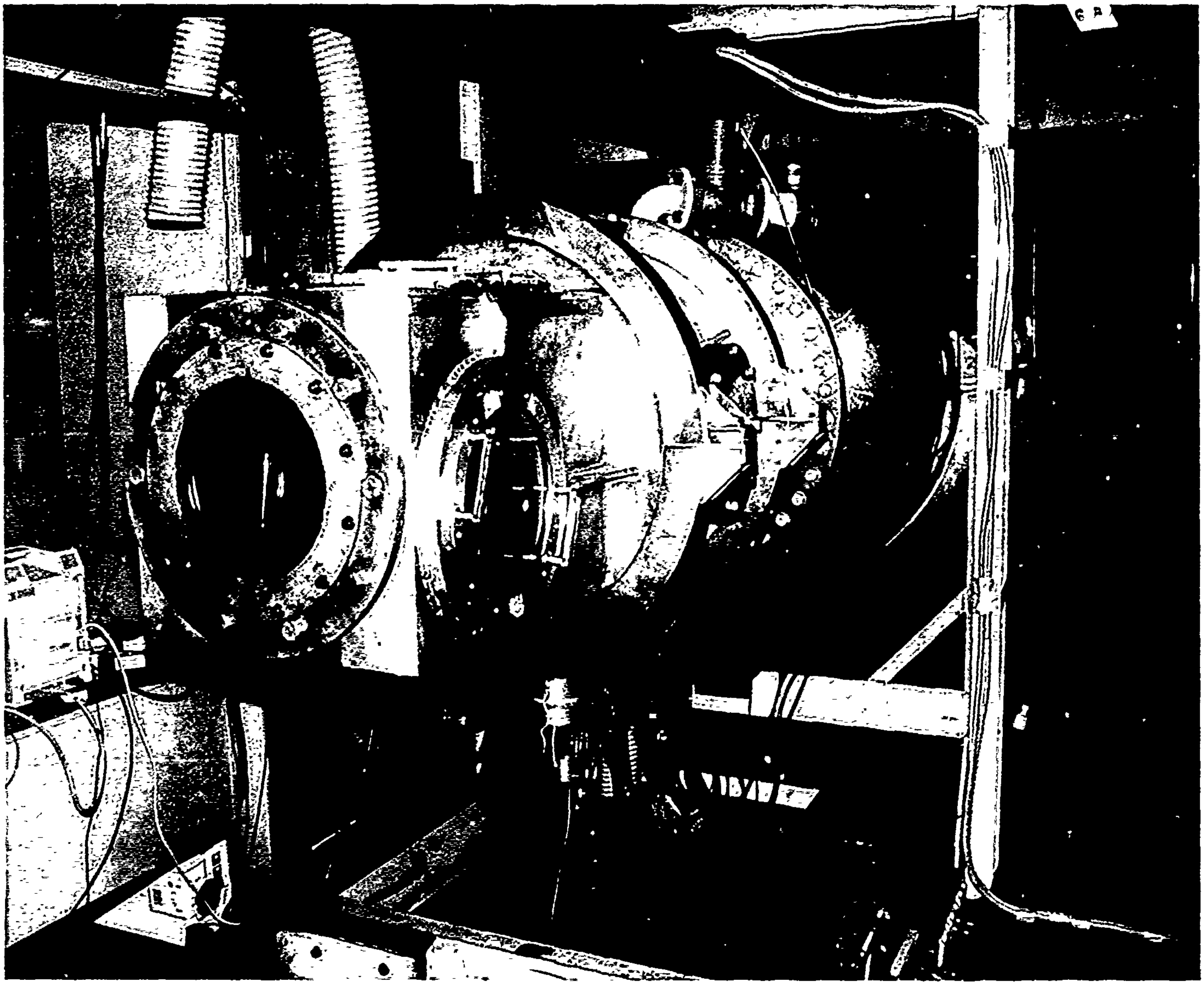
The Australian National University T-3 hypervelocity short-duration shock tunnel facility was designed for research into hypervelocity flight. According to University officials, the facility is only one of two shock tunnels in the world (the other is the T-4 Shock Tunnel at the University of Queensland in Brisbane, Australia) that allows simulation of real gas effects, which occur in the flow about a vehicle traveling at hypersonic speeds.

This capability is a result of the combination of stagnation enthalpy, test section density, and hypersonic Mach number. Currently, this combination can only be achieved in these shock tunnels. University officials said this combination of parameters is required for simulation of real gas effects in the flow about a spaceplane model.

The T-3 Shock Tunnel can measure equilibrium and non-equilibrium real gas effects at speeds up to Mach 19.1, corresponding to an equivalent flight velocity of Mach 23.5. The facility is capable of conducting scale model tests, heat transfer rates, pressure distribution measurements, schlieren photography and Mach-Zehnder interferometry, mass spectrometry, and coherent anti-Stokes Raman scattering to determine rotational and vibrational temperatures and molecular species concentrations. It also uses other optical diagnostic techniques and laser facilities. The T-3 Shock Tunnel is operated by eight people at an annual operating cost of about $830,000.

One feature that makes this facility design unique is its free-piston driver technique where the compression of gas is effected by a single stroke of a heavy piston. This technique raises the pressure and the temperature of the gas immediately before rupture of the main shock tube diaphragm. Another characteristic of T-3 is the prior steady flow technique. This technique allows the prior establishment of steady flow in a hypersonic nozzle to be used to ensure rapid starting of a subsequent shock initiated flow, which produces hypersonic flows exceeding orbital escape velocities. Figure 8.1 shows the test chamber of The Australian National University T-3 Shock Tunnel.

Figure 8.1: The Australian National University T-3 Shock Tunnel

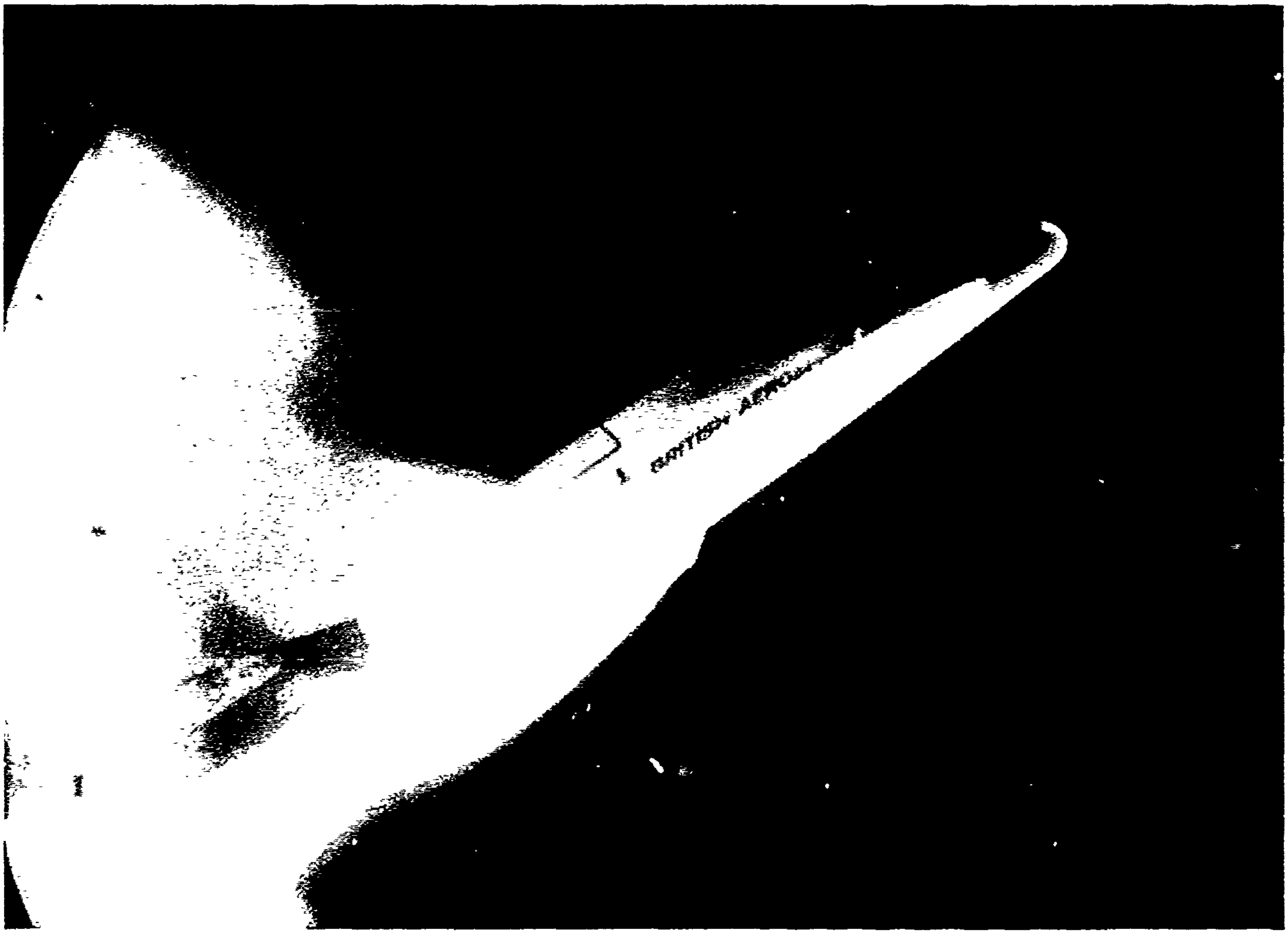


Source: GAO

Currently the T-3 Shock Tunnel is being used to test the European Space Agency's Hermes spaceplane for Avions Marcel Dassault-Breguet Aviation, HOTOL surface catalysts for British Aerospace, computational fluid dynamics code validation for Messerschmitt-Boelkow-Blohm, and scramjet diagnostics and biconic geometry work for the National Aeronautics and Space Administration's Langley Research Center. The

Australian National University is also planning to use the T-3 Shock Tunnel to calibrate the Re-entry Air Data System for British Aerospace Australia. Figure 8.2 shows a reentry test on a model of HOTOL in the T-3 Shock Tunnel.

Figure 8.2: Reentry Test on a Model of HOTOL in The Australian National University T-3 Shock Tunnel

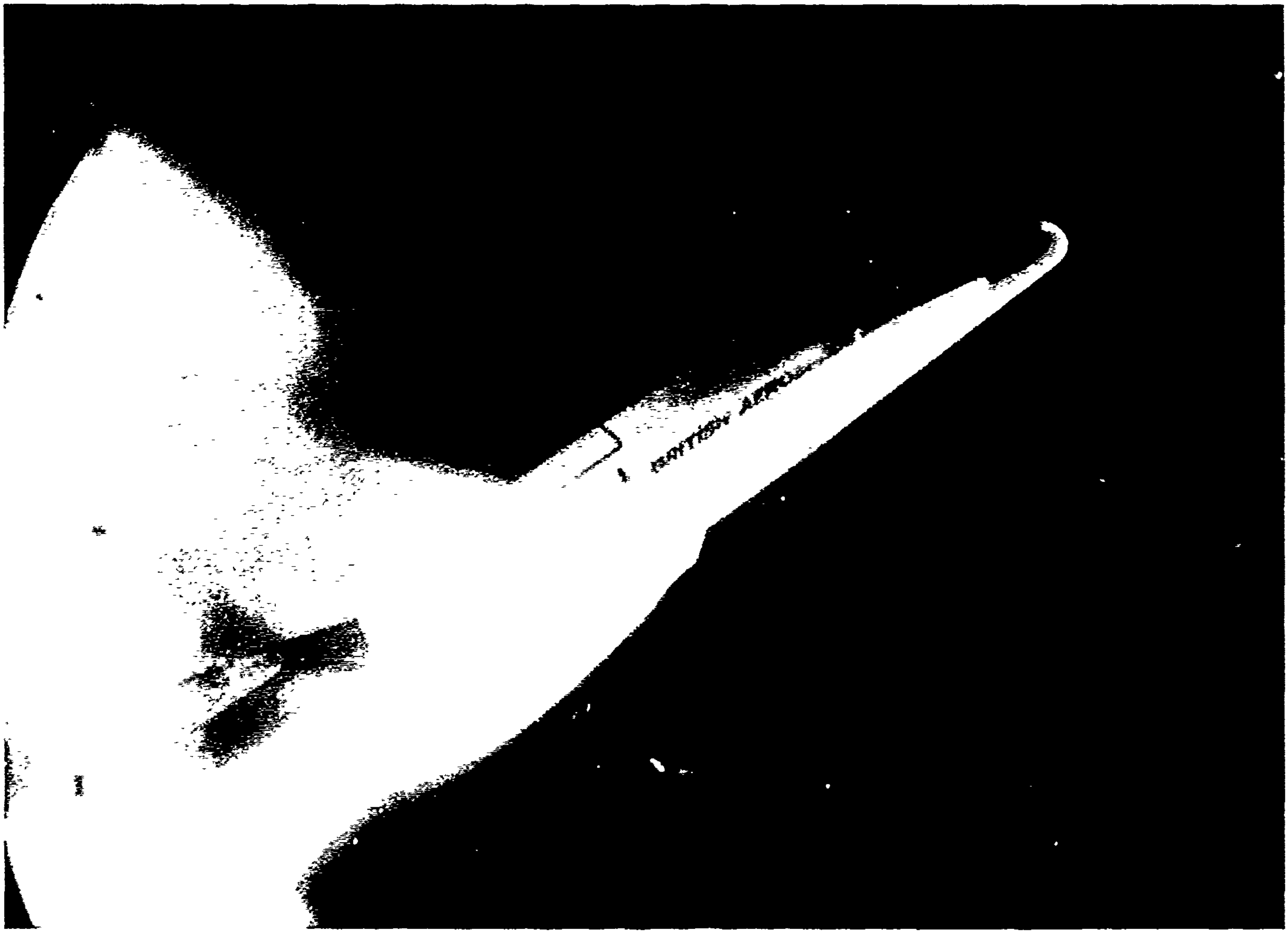


Source: British Aerospace.

The University of Queensland T-4 Shock Tunnel is the latest in a series of Australian shock tunnels; the first three were constructed at The Australian National University beginning in the 1960s. According to the Australian engineer that designed the shock tunnel, a disappointing feature of T-3 is the pressure loss in its shock tube. Australian engineers

Australian National University is also planning to use the T-3 Shock Tunnel to calibrate the Re-entry Air Data System for British Aerospace Australia. Figure 8.2 shows a reentry test on a model of HOTOL in the T-3 Shock Tunnel.

Figure 8.2: Reentry Test on a Model of HOTOL in The Australian National University T-3 Shock Tunnel



Source: British Aerospace.

The University of Queensland T-4 Shock Tunnel is the latest in a series of Australian shock tunnels; the first three were constructed at The Australian National University beginning in the 1960s. According to the Australian engineer that designed the shock tunnel, a disappointing feature of T-3 is the pressure loss in its shock tube. Australian engineers

The T-4 Shock Tunnel was built specifically to test scramjets and keep Australia in the forefront of hypersonic testing. However, according to University of Queensland engineers, it has not yet reached its designed operating levels. The T-4 Shock Tunnel has a useful test time of 1.1 milliseconds at Mach 14 and 0.24 milliseconds at Mach 22.

The T-4 Shock Tunnel has been used to support U.S.-sponsored fundamental research on scramjet combustion similar to that conducted in the T-3 facility. This research has (1) addressed the behavior of flush wall injectors, (2) demonstrated measurement techniques, including direct measurement of local skin friction and overall aerodynamic force (a first in pulse-type facilities, according to a National Aeronautics and Space Administration official), and (3) gathered data on an annular injector model. This model was identical to a model tested at Mach 17 flight conditions in the National Aeronautics and Space Administration-owned HYPULSE hypervelocity expansion tube facility located at the General Applied Sciences Laboratory in Ronkonkoma, New York. The experiment on the annular injector model provides direct assessment of the effects of contamination (in the form of oxygen dissociation) on combustion in the reflected shock tunnels T-3 and T-4 compared to the clean (undissociated) air stream produced by the U.S. hypervelocity pulse facility at the same flight conditions.

The T-4 Shock Tunnel is also currently being used for upper surface flows and shock boundary layer interaction on the European Space Agency's Hermes spaceplane for Avions Marcel Dassault-Breguet Aviation and scramjet combustion testing for the National Aeronautics and Space Administration. As of March 1991, a cooperative program was also underway with British Aerospace in the United Kingdom on flow studies on a model of the U.S. space shuttle orbiter.

An Australian consortium, WBM-Stalker-Bechtel, headed by the designer of both the T-3 and T-4 Shock Tunnels is consulting with Rocketdyne and the Deutsche Forschungsanstalt fuer Luft- und Raumfahrt, or German Aerospace Research Establishment, for building free-piston shock tunnels. The Rocketdyne Hypersonic Flow Laboratory shock tunnel, originally expected to be constructed at Rocketdyne's Burro Flats site at its Santa Susana Field Laboratory near Los Angeles, California, would be the world's largest and most advanced shock tunnel. It would be three times larger and use 40 times as much energy as the T-4 Shock Tunnel. The shock tunnel would be more than 300 feet long and weigh approximately 1.6 million pounds.

Initially, the shock tunnel was to have been used to provide test conditions simulating inflight characteristics over the Mach 12 to 24 range for a full-scale, direct-connect NASP scramjet combustor. The facility has been designed to conduct nozzle and leading edge tests and to accommodate airframe tests. In late 1987, Rocketdyne began to design and construct the facility. In 1989 the Australian consortium was awarded a $16-million contract from Rocketdyne. Construction of the facility was scheduled to begin in July 1990 and be completed in May 1991; however, construction was delayed due to lack of funding. As of September 1991, construction of the Rocketdyne facility remained at a standstill due to a reevaluation of the contractor team, escalating costs, a diminishing need, and the availability of other test facilities. Although most of the components were built[1] and stored, there are no plans at this time to complete the facility. According to Rocketdyne officials, about $18 million has already been spent on the facility and another $20 million to $25 million would be required to complete the facility. Rocketdyne officials said the shock tunnel could be operational by 1995 or 1996 if a decision is made to complete the facility and funding is available.

The German Aerospace Research Establishment's Hoch-Enthalpie-Kanals Goettingen, or Goettingen High-Enthalpy Tunnel, is scheduled to become operational in 1991. This facility is a Mach 7 free-piston shock tunnel that will produce flow velocities up to 7 kilometers per second with testing times of 1 millisecond.

Smaller contracts to design the T-5 shock tunnel for the Graduate Aeronautical Laboratory at the California Institute of Technology in Pasedena, California, and modify an expansion tube at the General Applied Sciences Laboratory were awarded in 1988. University of Queensland officials said the Japanese are also interested in building a free-piston shock tunnel for combustion tests at the University of Tohoku in Sendai, Japan. A pilot tunnel is being constructed at the University to develop free-piston driver technology.

Potential research applications for the T-3 and T-4 Shock Tunnel facilities include testing of instrumentation for air data systems, which measure the flight altitudes and control the flight parameters of the vehicle, and development of fuel injectors for air-breathing engines. Development of suitable subsystems, such as fuel injectors, could be enhanced

[1]According to Rocketdyne officials, some of the facility's larger components were manufactured in Japan, since no U.S. company had the capability to build the components due to the size of the casting required.

by aerodynamic testing in the facilities to determine distribution and burning patterns. Also, tests of measurement and flow variations for engine performance could be established.

Cape York International Spaceport

Australia's planned Cape York International Spaceport, located at 12 degrees latitude south of the equator on the east coast of Queensland's Cape York Peninsula, would be the world's first private enterprise space launch facility dedicated to serving the commercial market. The estimated $500 million project is being funded without financial assistance from the Australian government.

In 1988 two Australian consortia, the Cape York Space Agency and the Australian Spaceport Group each conducted feasibility studies of the Cape York International Spaceport proposal at the request of the Queensland government. The Australian Spaceport Group consisted of Australian Domestic Communication Satellite, Broken Hill Proprietary, Bond Corporation, Comalco, and Martin Marietta Corporation. The initial Cape York Space Agency consortium included businessmen in the state of Queensland, the Shimizu Corporation of Japan, and some of the world's major aerospace companies. The Cape York Space Agency enlisted the help of United Technologies Corporation, General Dynamics Corporation, Messerschmitt-Boelkow-Blohm, McDonnell Douglas Corporation, and a consortium of Japanese companies for its study on the commercial potential of the Cape York facility.

In June 1989 the Australian Spaceport Group announced the abandonment of its proposal for the project based on commercial considerations. At the same time, the Cape York Space Agency announced it had a commercially viable proposal for the project and that it proposed to proceed with further studies.

In October 1989 the Cape York Space Agency, now fully owned by Essington, an Australian property developer, submitted a proposal to the Australian and Queensland governments outlining its plan for a spaceport on the Cape York Peninsula and requesting the two governments to formally announce support of the project subject to compliance with statutory obligations. The plan included the purchase of the Soviet Zenit launch vehicle for launch by the Australian spaceport operator. The government considered the proposal in December 1989 and advised the Cape York Space Agency that it had no objection in principal to the use of Soviet rockets. The government's final endorsement of the project was conditional upon the satisfactory resolution of a range of issues, including technology transfer, international relations, security arrangements, environmental impact, and Aboriginal concerns.

In November 1990 the Cape York Space Agency's owner, Essington, stated its intention to sell the Agency but, as of April 1991, had not announced a new owner. The Australian government is now waiting for the emergence of a commercial organization or consortium possessing the managerial, technical, and financial resources to develop the project. According to the Australian Space Office, the necessary resources are likely to be available only in a substantial Australian company or a consortium. As part of this process, the Australian Space Office has hired a consultant to review the project parameters, prepare an investment memorandum, and negotiate with qualified interested parties to complete the next phase of the spaceport's development.

The restructuring of the project is viewed by the Australian government essentially as a commercial matter. Australian government officials stressed that the current actions do not signal a change in the government's position that the venture would need to proceed without government investment or subsidy.

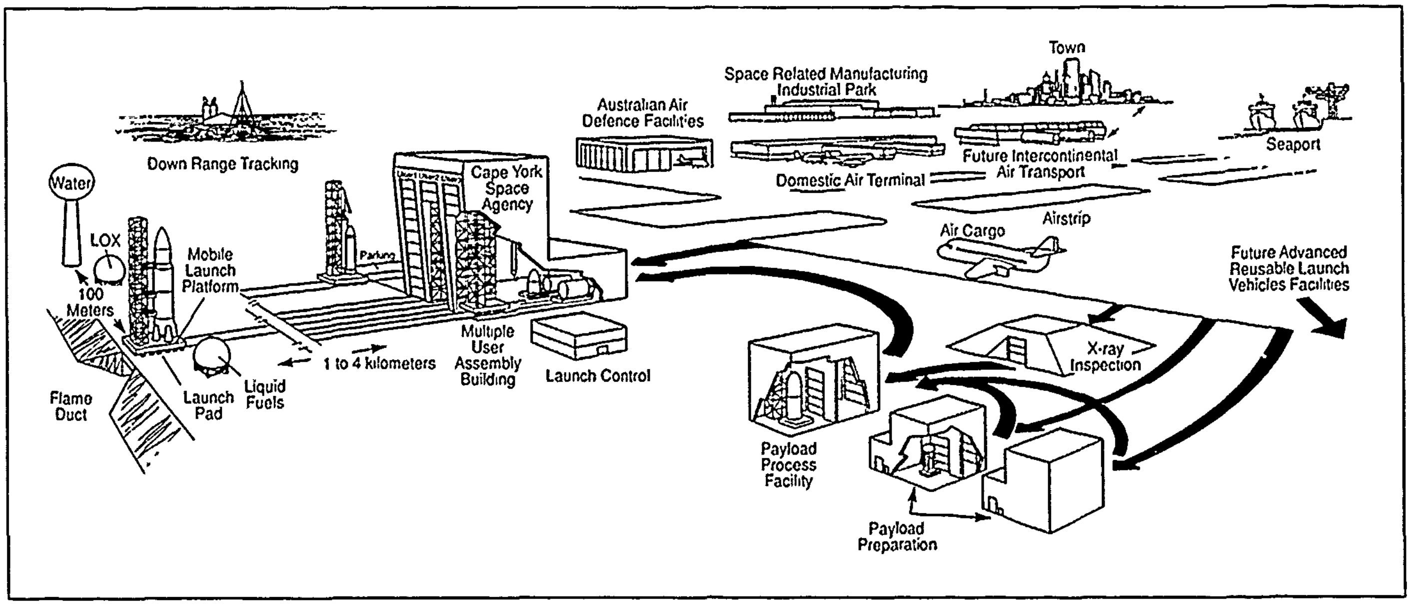
The site would be a satellite launch center for the entire Pacific Rim region and could serve initially as a hub for long-haul flights by future hypersonic transport aircraft linking Asia, the Pacific Islands, and Australia to Europe, North and South America, and Africa. Another long-range possibility would be the expansion of the Cape York International Spaceport for future shuttle spacecraft or aerospace planes, such as Hermes, HOPE, HOTOL, Saenger II, or a future operational NASP-derived aerospace plane. Cape York Space Agency awarded the construction contract in 1990. Environmental studies are expected to be completed by late 1992, and construction would begin in 1993. Initial commercial launch operations are expected to begin in 1996.

The spaceport would be built at Bromley Holding near Temple Bay on the east coast of the Cape York Peninsula. The Cape York Space Agency plans to construct an airport and harbor facilities, including a barge ramp for landing cargo brought in by sea. Booster components would be shipped by sea to the deep water ports of Cairns or Townsville in northeastern Australia and then taken by barge to Temple Bay. Satellite payloads and personnel would arrive by airplane at a new airport.

A major obstacle to construction of a spaceport is the Cape York Space Agency's selection of land on Temple Bay, which has been the subject of several Aboriginal territory disputes. According to the Australian Space Office, the spaceport proposal, in common with other industrial developments proposed for the Cape York Peninsula, must achieve resolution of Aboriginal territorial claims over the land in question. In the case of the proposed location of the spaceport at Temple Bay, two local Aboriginal tribes claim to have had traditional association with that land. Even though they do not have legal title, the Cape York Space Agency is holding discussions with these groups to identify their concerns and reach an acceptable arrangement.

Long-range development plans may involve using larger boosters for launches into low earth and polar orbits. The Japanese may consider using the Cape York International Spaceport for launching the H-II booster. Figure 8.4 shows a schematic drawing of the Cape York International Spaceport.

Figure 8.4: Cape York International Spaceport



Source. Commonwealth Science and Industrial Research Organization, Office of Space Science and Applications.

The Cape York Space Agency considers the prospects good for development of a market for commercial launch services in Asia and the Pacific Rim. A Cape York Space Agency assessment concluded that a new spaceport will be required in the Pacific Basin to serve the international market for commercial space transportation. Officials at Cape York

Space Agency said the Japanese aerospace community is a particularly strong supporter of a spaceport concept to serve the needs of its future supersonic and hypersonic transport aircraft and spaceplanes.

As discussed in chapter 3, other proposed spaceplane landing sites in the Pacific region may include Kagoshima, the Hokkaido Space Center, and Iwate Prefecture Spaceport in Japan; Kiritimati Island in Kiribati; Hawaii; Vandenberg Air Force Base and Edwards Air Force Base in California. The Cape York International Spaceport could be competitive with these and other sites (such as Kourou, French Guiana, and Florida) because of a number of factors. These factors include its proximity to the equator, good meteorological conditions, access to both polar and equatorial orbits, Pacific Rim location, availability of large land areas, and political stability in Australia. Launches from the Cape York Peninsula also would have the advantage of improved rocket performance because of the site's proximity to the equator (12 degrees south latitude). The Ariane 5 complex at Kourou, French Guiana, is the only existing launch site positioned closer to the equator (6 degrees north latitude).

Foreign Participation in the Cape York International Spaceport

Shortly after the government of Queensland concluded its feasibility study in 1987, Cape York Space Agency's manager discussed the Cape York International Spaceport proposal with a delegation from GLAVKOSMOS, the Soviet space agency. GLAVKOSMOS officials gave Cape York Space Agency a firm commitment in 1989 to participate in its spaceport plans to find some profitable use for its Zenit boosters. The Chinese have also expressed interest in using a Cape York Peninsula launch facility. United Space Boosters, a subsidiary of United Technologies Corporation, was selected by the Cape York Space Agency to provide its expertise in aerospace procurement and launch pad management.

United Space Boosters' application for an export license for services prompted a high-level U.S. government review of defense and trade policy as a result of Soviet participation in the Cape York International Spaceport project. The Department of State's Office of Munitions Control concluded in 1989 that technology transfer concerns were adequately addressed by the government of Australia and the Cape York Space Agency. In 1990 the President gave the Secretary of State the authority to grant United Space Booster's application as long as it meets the guidelines in a proposed commercial space launch policy developed by the National Space Council. As of March 1991, this license is still under review.

Other concerns regarding U.S. participation were expressed by U.S. rocket manufacturers that foreign subsidized launch vehicles would have an unfair advantage over those sold by U.S. firms. The Departments of Commerce and Transportation were initially concerned that the Cape York International Spaceport venture could cut into the American commercial market. However, the new policy includes provisions to help protect the U.S. domestic industry. The proposed policy would require all U.S. government payloads to be launched on U.S. vehicles.

According to the Australian Space Office, the U.S. government has also indicated its wish to reach agreements to ensure free and fair trade in the international space launch market. The primary emphasis is on "rules of the road" and permissible subsidization. Further discussions on these subjects are anticipated.

International Cooperation

Australia has commercial contracts with European countries, the United States, the People's Republic of China, and Japan. In 1987 it signed a Space Research Cooperation Agreement with the Soviet Union. Australia also operates a number of tracking facilities for foreign organizations, such as the National Aeronautics and Space Administration and the European Space Agency, on a contract basis. Since the primary thrust of the Australian space program is industry development, Australia prefers participation in foreign aerospace research and development efforts to solely service-for-fee testing at its shock tunnel facilities. According to the Australian Space Office, Australia represents no commercial threat to the United States in aerospace vehicle development.

The Australian government also has a policy that requires foreign companies and organizations awarded contracts for Australian purchases to invest in other economic sectors through collaborative offset arrangements. According to the Australian Space Office, this offset policy would not be applicable to Australian participation in the NASP Program.

Although Australian government officials and industry representatives expressed interest in the NASP Program, potential barriers include (1) the Australian government ban on participation in the U.S. Strategic Defense Initiative Program or nuclear weapons programs and (2) the perception that a future operational NASP-derived vehicle would have Strategic Defense Initiative applications. Another potential barrier is strict U.S. export controls on the transfer of technology. Concerns about technology transfer to the Soviet Union were raised during U.S. policy debates about U.S. participation in the Cape York International Spaceport project. Australia is a member of the Coordinating Committee for Multilateral Export Controls, and according to Australian government officials, it adheres closely to the Coordinating Committee's policies and procedures. Australia is also a full party to the Missile Technology Control Regime.[2]

[2]The Missile Technology Control Regime is a set of identical, national policies announced in 1987 by the United States, France, the United Kingdom, Germany, Japan, Italy, and Canada to limit the availability and transfer of certain systems, equipment, and technologies necessary for the development of nuclear-capable missiles. Spain and Australia subsequently became members of the Missile Technology Control Regime.

Conclusions

The United States is ahead of Japan in hypersonic technology. However, U.S. leadership and superiority in aeronautics face increasing competition from Japanese efforts to develop operational aerospace vehicle technologies. Japan has not officially approved any plan to build an aerospace plane. The United States also has not approved a plan to build an aerospace plane. Although Japan does not have an established national research and development program to build an aerospace plane, Japanese government and industry are conducting feasibility studies and developing the technologies needed for various concepts of operational aerospace vehicles through various programs to secure independent manned access to space, reduce the cost of launching payloads into orbit, and ensure a competitive role in future high-speed commercial transport markets.

Japan is conducting research and development on three different but coordinated spaceplane programs. Japanese aerospace vehicle development programs are essentially concept or system studies and consist of fundamental research on enabling technologies. Japan is coordinating various national aerospace vehicle development programs in a step-by-step approach to achieve its goal of demonstrating the technology for an air-breathing single-stage-to-orbit aerospace plane.

Japan does not appear likely to develop and build an aerospace plane by itself because of the extensive technology and funding requirements and lack of adequate test facilities. Building any future operational Japanese aerospace vehicle would require an international effort.

Japan is the only other country besides the United States, the Soviet Union, and France that is studying a single-stage-to-orbit aerospace plane using scramjet air-breathing propulsion—the most technologically challenging aerospace plane concept. The United States, through the NASP Program, is advancing hypersonic technology further than Japan. The United States is the only country that has gone beyond the initial design phases and tested major components of an air-breathing aerospace vehicle.

Although the Japanese are making a determined effort to challenge U.S. superiority in hypersonics, the United States is ahead of Japan in developing the three enabling technologies considered critical for an aerospace plane: air-breathing propulsion, advanced materials, and computational fluid dynamics. However, Japan is making progress in the development of enabling technologies, particularly in advanced air-breathing propulsion and advanced materials.

Japan has conducted the necessary preliminary work on a wide variety of advanced propulsion systems for various aerospace plane concepts and other applications. Japan's approach is state of the art and the results are plausible and realistic. Also, Japan's research and development schedule is ambitious, but achievable.

A Japanese systems study comparing engines concluded that the two best combined-cycle engine concepts are the air-turboramjet/scramjet/rocket and the liquid air cycle engine/scramjet—the same two combined types of engines the United States determined were the best 30 years ago. Japan now has an engineering basis for selecting these two engines for further development. Moreover, Japanese duplication of U.S. engine tests and the ability to achieve the same results provide Japan with something it lacks: experience in hypersonics.

Currently, Japanese advanced propulsion research and development is behind that of the United States, but they are making rapid progress in selected systems. The Japanese enjoy a high level of project consistency and continuous funding. Japan's aerospace plane development has been evolutionary in nature, while the U.S. program has placed greater emphasis on revolutionary advances achieved primarily through technological breakthroughs.

Japan is developing several important aerospace plane propulsion systems that the United States has either abandoned or is not working on at the present time. These systems include the liquid air cycle engine, air-turboramjet experimental engine, and high-pressure expander-cycle engine. Japanese projects are generally smaller than those in the United States and focus on incremental advances in technology. The Japanese have good success in applying proven technology to new projects as seen in these engine programs. This evolutionary approach, coupled with an ability to obtain technology off the shelf from other countries, has resulted in relatively low development costs, steady progress, and enhanced reliability. Japan is clearly positioned to be a world leader in advanced propulsion technology for aerospace planes by the year 2000.

Japan is pursuing an intensive and comprehensive research and development program in hypersonic propulsion. Although the United States is ahead of Japan in propulsion technology for a single-stage-to-orbit accelerator-type aerospace vehicle, Japan may be ahead of the United States in hypersonic propulsion technology for several other important applications, including two-stage-to-orbit space launch vehicles and high-speed commercial transport aircraft. Whereas the United States has placed essentially all of its emphasis on a scramjet propulsion system for the X-30, Japan is building and testing components and complete engines using a number of propulsion cycles that are suitable for a variety of applications. No other country is pursuing such a comprehensive program in hypersonic propulsion. The Japanese are not only developing an air-turboramjet experimental engine but are building and testing a variety of other hypersonic propulsion concepts, including liquid air rockets, liquid air turboramjets, and scramjets.

Japan may be in a position early in the 21st century to become the world leader in high-speed commercial transport aircraft at speeds above Mach 3. Although Japan may not be able to compete with the United States and Europe in the near-term for supersonic commercial transport aircraft, it may be very competitive in the Mach 3 and above transpacific hypersonic transport aircraft market. Japan is doing everything a prudent nation would do if that were its goal. Given this approach, Japan may be in a position to leapfrog over the U.S. aerospace industry in the next 5 to 10 years.

Japan has active materials development programs and may lead the United States in selected aspects of materials research. Japan's capability to develop composite materials is increasing at a rate faster than that of the United States. However, the United States has the overall lead in the design and effective use of advanced composite materials in specific military applications. Critical technological advances are being made in carbon-fiber technology developed in Japan. Japan may be the world leader in advanced ceramic research and development. Primary opportunities for cooperation will occur with Japan in the area of fibers and ceramics. Japan is ahead of Europe and the Soviet Union and second only to the United States in materials and structures research and development.

The United States is the world's leader in composite materials. However, the U.S. lead is being rapidly eroded by a combination of industrial technology transfer and strong research and development efforts by Japan and other countries. The use of composites is now well established in Japan and it may lead the United States in some commercial applications. Japan has also become an important composite material supplier to the United States.

Some of the key advanced materials for a future Japanese spaceplane are being developed in nonaerospace industries. Relatively small levels of investment in the development of enabling technologies in Japan (compared with investment levels in the United States) often lead to significant research and development being conducted. Technology developed by nonaerospace industry in Japan is applicable to developing and building a spaceplane.

Many Japanese government and industry programs are long-term ventures geared to the future at the expense of short-term gains. The Japanese encourage and support parallel approaches to advanced materials research and technology. Requirements for Japanese government programs are usually set at a modest, realistic, and attainable level to maintain Japanese government and public support. Moreover, the goals are not driven by requirements for a specific system as seen in the United States. Also, direct Japanese government funding for new materials is quite small and focuses on areas of national interest. Japanese industry, driven by strong national unity, makes much larger contributions to the support of new materials research and technology.

The United States currently has a commanding lead in computational fluid dynamics. However, strenuous efforts are being made in Japan to develop a competitive capability, since computational fluid dynamics is recognized by Japan (and worldwide) as a critical technology. Supercomputer hardware represents no problem for Japan, since three of the five supercomputer manufacturers in the world are Japanese. Growth in computational capability in Japan has been impressive, and Japan's national laboratories have the computing power to perform state-of-the-art computations on aircraft and propulsion systems.

No Japanese aerospace vehicle program compares to the scope of the NASP Program in terms of the amount of funding or number and type of people working on the program. Levels of investment in air-breathing aerospace vehicle research and technological development efforts by Japanese government and industry to date are significantly less than U.S. government and industry investment in the NASP Program. Also, planned U.S. government and industry investment in the NASP Program are substantially greater than planned Japanese government and industry investment.

According to foreign government officials and industry representatives, Japanese test facilities (such as wind tunnels and air-breathing propulsion test cells) are adequate for fundamental research and the current level of effort in Japan, but the facilities are not adequate for large-scale testing or development of an aerospace plane. The United States is ahead in terms of facility size, productivity, and use of testing techniques. Japan's rate of progress in refurbishing and modifying old facilities and building new ones is significant.

Japan wants to first raise its technology level to international standards before seeking international cooperation. Japanese government officials and industry representatives expressed interest in cooperating with the United States on the NASP Program but also had some serious reservations. These reservations are based, in part, on barriers that include Japan's lack of hypersonic experience, Japan's constitutional prohibitions against the military use of space, fundamental differences in U.S. and Japanese aerospace plane programs, and strict U.S. export controls on the transfer of technology.

According to U.S. government and industry officials, areas in which Japanese technology might be incorporated in the NASP Program include advanced propulsion and advanced materials.

Although Australia does not have an aerospace vehicle research and technological development program, Australian industry and universities are developing competence in selected subsystems and play a significant role in testing foreign aerospace vehicle concepts and components. Currently, the only two shock tunnel facilities in the world that can test real gas effects on space launch vehicles are located in Australia. This unique capability keeps Australia in the forefront of hypersonic testing.

According to U.S. government and industry officials, the NASP Program could benefit from the use of Australian test facilities. Once larger U.S. and German shock tunnel facilities become operational, the Australian facilities could serve in a supporting role or provide a back-up capability. Australia's planned Cape York International Spaceport would be the world's first commercial facility designed to accommodate future horizontal takeoff and landing aerospace planes.

Major Contributors to This Report

National Security and International Affairs Division, Washington, D.C.

Norman J. Rabkin, Associate Director
Robert L. Pelletier, Assistant Director
Mark A. Pross, Evaluator-in-Charge
John S. Townes, Senior Evaluator

Glossary

Aeroballistic
The flight characteristics of projectiles or high-speed vehicles in the atmosphere.

Aerothermodynamic
A branch of thermodynamics relating to the heating effects associated with the dynamics of a gas, particularly the physical effects produced in the air flowing over a vehicle during launch and reentry.

Air-Breathing
An aerodynamic vehicle engine that requires air for combustion of its fuel.

Air-Breathing Propulsion Test Cell
A ground test facility used to test an aircraft engine that requires air for combustion of its fuel.

Airflow
A flow or stream of air.

Air-Turboramjet
An air-breathing engine similar to a ramjet except that the air is compressed in an axial flow fan before being mixed with hydrogen (or some other hydrocarbon fuel) and burned in the ramburner. Combustion products are passed through a heat exchanger, which heats the hydrogen fuel, and then are expanded through the exhaust nozzle, creating the thrust. The heated hydrogen passes through an axial flow turbine, which drives the fan, and then is injected into the ramburner, where the heated hydrogen is burned. Temperature limitation caused by turbine blade materials is avoided, since combustion products are not passed through the turbine. Air-turboramjets can perform well from Mach 0 to 6. The term air-turboramjet is a misnomer resulting from the apparent inadvertent contraction of air-turborocket/ramjet.

Air-Turborocket
A combined-cycle engine in which the initial acceleration propulsion mode involves a compressor or fan driven by a turbine. The turbine's motive power is not obtained from fuel combustion in the compressed airstream (as in a turbojet) but rather from either fuel-rich bipropellant combustion or exothermic monopropellant decomposition. The (usually) fuel-rich turbine exhaust is then combusted in the compressed airstream and the products exhausted through a nozzle.

Air-Turborocket/Ramjet	A combined-cycle engine that utilizes an air-turborocket initial mode followed by a conversion to subsonic combustion ramjet mode for high-speed acceleration and cruise. The term air-turboramjet is a misnomer resulting from the apparent inadvertent contraction of air-turborocket/ ramjet.
Algorithm	A step-by-step procedure for solving a mathematical problem.
Ambient Temperature	The temperature of the gas around a test model, which is unaffected by the model's presence.
Angle of Attack	The acute angle between the direction of the relative airflow and the chord (i.e., the straight line joining the leading and trailing edges of an airfoil) of the test model.
Angle of Sideslip	The acute angle between the direction of the relative airflow in a lateral plane and the chord (i.e., the straight line joining the leading and trailing edges of an airfoil) of the test model.
Autoclave	An airtight vessel constructed of thick-walled steel alloy for carrying out chemical reactions under pressure and high temperatures. Autoclaves are used for the industrial processing of composite materials.
Autoclave Molding	A method of curing reinforced plastics that uses an autoclave with 50 to 100 pounds per square inch steam pressure to set the resin.
Biconic Geometry	Two cone structure configuration.
Blowdown Wind Tunnel	An open-circuit wind tunnel in which gas stored under pressure is allowed to expand through a test section to provide a stream of gas or air to test a model. The gas then escapes into the atmosphere or into an evacuated chamber. Test times are finite and usually last from a few seconds to minutes.

Boundary Layer	A region of the flow of a retarded viscous fluid near the surface of a body that moves through a fluid or past which a fluid moves.
Canard	An aerodynamic vehicle in which horizontal surfaces used for trim and control are forward of the wing or mainframe lifting surface.
Carbon-Carbon	A material that consists of 100-percent carbon fibers in a carbon matrix. The material does not contain any binders or epoxy and is coated with a ceramic material. Carbon-carbon is extremely lightweight and is being considered for use on aerospace plane thermal protection systems.
Carbon-Fiber	Material made by pyrolyzing any spun, felted, or woven raw material to a char at temperatures from 700 degrees to 1,800 degrees Celsius. Carbon-fiber is used as a reinforcing material with epoxy or polyester resins to form composites, which have a higher strength/weight ratio than metals.
Celsius	A temperature scale in which the freezing point of water at standard atmospheric pressure is 0 degrees Celsius and the corresponding boiling point is 100 degrees Celsius. Zero degrees Celsius equals 273.16 degrees Kelvin.
Coherent Anti-Stokes Raman Scattering	A phenomenon observed in the scattering of light as it passes through a transparent medium. The light undergoes a change in frequency and a random alteration in phase due to a change in rotational or vibrational energy of the scattering molecules.
Columbium	A platinum-gray, ductile metal with brilliant luster that is used in alloys, especially stainless steels. Columbium is also known as the element niobium.
Combined-Cycle Engine	Engine concepts using some combination of air-breathing and rocket components which are integrated into a single propulsion system.

Composite Materials	Structural material made of two or more different materials such as carbon-fiber reinforced epoxy resin.
Computational Fluid Dynamics	A tool for predicting the aerodynamics and fluid dynamics of air around flight vehicles by solving a set of mathematical equations with a computer. Also known as numerical aerodynamic simulation, computational fluid dynamics is used in aerospace vehicle research and development programs to improve the understanding of hypersonic flow physics and as an aerospace vehicle design tool.
Cryogenic	Operating at extremely low temperatures.
Diffusion Bonding	A solid-state process for joining metals by using heat and pressure to achieve atomic bonding.
Dynamic Pressure	The pressure of a fluid resulting from its motion when brought to rest on a surface. It is also known as impact pressure, stagnation pressure, and total pressure.
Electron Beam Welding	A technique for joining materials in which components to be welded are heated by a concentrated beam of high-velocity electrons in vacuo.
Enabling Technology	A critical technology that makes development and demonstration of an aerospace vehicle possible. Enabling technologies may include an air-breathing propulsion system; advanced materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; use of computational fluid dynamics and supercomputers for aerodynamic, structural, and propulsion system design; and efficient use of hydrogen both as a fuel and to actively cool the airframe.
Enthalpy	The total energy (heat content) of a system or substance undergoing change from one stage to another under constant pressure. Enthalpy is expressed as the sum of the internal energy of a system plus the product of the system's volume multiplied by the pressure exerted on the system

by its surroundings. Enthalpy is also known as heat content, sensible heat, and total heat.

Euler Codes	Computer software that is a mathematical representation of the motion of a fluid whose behavior and properties are described at fixed points in a coordinate system.
Expander Air-Turboramjet	A combined-cycle propulsion system of the air-turborocket/ramjet type in which the compressor or fan element used in the air-turborocket mode is driven directly (or through a gear train) by a turbine. The turbine is powered by the flow of high-temperature, high-pressure gas (usually hydrogen). The gas is previously pumped to high pressure as a liquid and then heated in a heat exchange rather than in a direct combustion process.
Expander Bleed-Cycle Engine	Also known as the open expander-cycle engine, the expander bleed-cycle engine uses heat exchange-heated propellant to drive its turbopump. However, unlike the closed expander-cycle engine, a small amount of propellant (usually hydrogen) is "bled" from the high-pressure (pumped) thrust chamber supply to drive a low-flow, high pressure-ratio turbine. Exhausted from the turbine at relatively low pressures, this bleed-flow is discharged overboard (rather than being injected into the thrust chamber for combustion, since its pressure is too low for combustion). The Japanese LE-5A engine for the H-II launch vehicle (currently under development) is an example of an expander bleed-cycle engine.
Expansion Tube	A wind tunnel for conducting tests at hypervelocity speeds in which fluid (such as air or some other test gas) at high pressure, usually involving rapid combustion to increase energy, is released by rupturing a diaphragm and accelerating through an evacuated working section (test chamber) containing the model. The major difference between a shock tube and an expansion tube is that in an expansion tube the isentropic flow is exact.
Fairing	A structure or surface on an aircraft or rocket that reduces drag, such as the streamlined nose of a satellite-launching rocket.

Free-Piston Driver Technique	A technique in which a single stroke of a heavy piston in a shock tunnel compresses the driver gas to raise its pressure and temperature before rupturing the main shock tube diaphragm. When helium driver gas is used, this technique allows routine operation of the shock tunnel in the reflected shock mode with test section stagnation enthalpy values approaching orbital velocities (8 kilometers per second).
Gas Generator Air-Turboramjet	A combined-cycle propulsion system of the air-turborocket/ramjet type in which the compressor or fan element used in the air-turborocket mode is driven directly (or through a gear train) by a turbine. The turbine is powered by the flow of high-temperature, high-pressure gas produced in a bipropellant, monopropellant, or solid propellant combustion-type gas generator.
Gas Generator-Cycle Rocket	A pump-fed liquid-propellant rocket engine in which a low-flowrate, high pressure-ratio pump-drive turbine is powered by a bipropellant (or monopropellant) gas generator. The low-pressure exhaust is expelled overboard through separate ducts or through the exit section of the main exhaust nozzle, since its pressure is too low to admit it into the combustion chamber. Examples of the gas generator-cycle rocket engine include the Aerojet TechSystems liquid engines for the Titan 4 booster (LR-87 and LR-91), the European Vulcain rocket engine for the Ariane 5 launch vehicle, and the Japanese LE-5 engine for the H-I launch vehicle.
Geostationary	A satellite orbit traveling from west to east at speeds that allow it to remain fixed over a given place on the earth's equator at approximately 22,300 miles in altitude. A geostationary satellite makes one revolution in 24 hours, synchronous with the earth's rotation.
Gigabyte	One billion bytes.
Gigaflop	One billion floating-point operations per second. Gigaflop is used as a measurement of the processing capability of very large computers.
Global Positioning System	A positioning or navigation system designed to use 18 to 24 satellites, each carrying atomic clocks, to provide a receiver anywhere on earth

with extremely accurate measurements of its three-dimensional position, velocity, and time.

Graphite-Polyimide Composites	A composite material composed of a mixture of whisker-thick graphite fibers that add stiffness and an organic (polyimide) resin matrix, which has more heat resistance than conventional epoxies.
Heat Exchanger	Any device that transfers heat from one fluid to another or to the environment.
Heat Transfer	The transfer or exchange of heat by radiation, conduction, or convection within a substance and between the substance and its surroundings.
High-Pressure Expander-Cycle Engine	Generically, a liquid propellant rocket engine that usually uses hydrogen for its fuel. Its turbopump is powered by a high-pressure propellant flow that is heated by propellant heat exchange in the thrust chamber cooling jacket. The turbine-drive flow is then injected into the thrust chamber where combustion takes place. The Japanese high-pressure expander-cycle engine augments the conventional jacket heat pickup in the turbine-drive propellant (hydrogen) with an adjunct cylindrical heat exchanger inserted directly into the combustion volume of the thrust chamber. Thus, the engine is able to achieve higher chamber pressure levels than could otherwise be achieved. In the 1950s, Pratt & Whitney developed a prototype of a unique hydrogen-fueled air-breathing engine (Model 304) based on this expander-cycle.
Hypersonic	A range of speed that is five times or more the speed of sound in air.
Hypersonics	A branch of aerodynamics that deals with the flow of air and other gaseous fluids at speeds greater than five times the speed of sound in air. Hypersonics may also refer to the technologies associated with aerospace vehicles flying at such speeds.
Hypervelocity	A range of speed that is about 12 times or more the speed of sound in air.

Interferometry

The design and use of optical interferometers to conduct, for example, precise measurements of wavelength, very small distances and thickness, and indices of refraction, and to study the hyperfine structure of spectral lines.

Intermittent Wind Tunnel

A wind tunnel in which energy is stored, usually as compressed air, and then released suddenly to force a large quantity of air through the small throat of the nozzle and over the test model in the test section in a short period of time. The test gas is then captured in a vacuum dump tank or released into the atmosphere.

Isentropic

Constant entropy or without change in entropy (a measure of the unavailability of energy).

Kinetics

A branch of science that deals with the effects of forces on the motion of material bodies or with changes in a physical or chemical system.

Liquefaction

A change in the phase of a substance to the liquid state. Liquefaction usually involves a change from the gaseous to the liquid state, especially of a substance that is a gas at normal pressure and temperature.

Liquid Air Cycle Engine

Basically a rocket engine in which the oxidizer is liquid air obtained by liquefaction of the air entering the air-breathing inlet. The heat sink capacity of liquid hydrogen is used in a heat exchanger to liquefy the flow of air. The liquid air is then pumped to a conventional rocket combustion chamber, which is used to burn the liquid hydrogen. This engine has variations in the method used to obtain the power to pump the air and hydrogen to high pressures. Theoretically, this engine can perform well from Mach 0 to 8. A liquid air cycle engine is the same as a liquid air rocket engine.

Liquid Air Rocket

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Mach Number
A number representing the ratio of the speed of an object to the speed of sound in the surrounding atmosphere. An object traveling at the local speed of sound is traveling at Mach 1.

Mach-Zehnder Interferometry
The design and use of a type of optical interferometer that depends on amplitude splitting of the wavelength. It is used mainly in measuring the spatial variation of the index of refraction of a gas. The device has two semitransparent mirrors and two wholly reflecting mirrors at alternate corners of a rectangle. Half the beam of light travels along each side of the rectangle. The major application of the Mach-Zehnder interferometer is studying the airflow around models of aircraft, missiles, and projectiles.

Magnetic Levitation
A train or sled launch vehicle that travels at high speed at some distance above an electrically conducting track or magnetic field by means of levitation (the use of physical force that does not involve physical contact to balance gravity).

Mass Spectrometry
An analytical technique for identification of chemical structures, determination of mixtures, and quantitative elemental analysis, based on application of the mass spectrometer.

Massively Parallel Computing
The simultaneous computation of several parts of a problem on a computer that can carry out more than one logic or arithmetic operation at one time. The computer usually consists of 100 or more processors.

Megabyte
One million bytes. A megabyte is a unit of information content equal to 1,048,576 bytes.

Megaflop
One million floating-point operations per second. Megaflop is used as a measurement of the processing capability of very large computers.

Microgravity	The condition of near weightlessness induced by free-fall or unpowered space flight. It also refers to the scientific discipline concerned with the evaluation of the processes in a near-zero gravity environment, particularly those of fluid physics, life, and material sciences.
Microsecond	One-millionth of a second.
Mini-Supercomputer	Basically a vector-architecture supercomputer with relatively few central processing units capable of attaining performance levels that are 30 to 70 percent of the largest supercomputer systems, or about 100 to 300 megaflops (for the 1990 to 1991 time frame). Mini-supercomputers are sometimes referred to as "departmental" supercomputers, in contrast to larger "corporate" systems.
Navier-Stokes Codes	Computer software that contains the mathematical equations of motion for a viscous fluid.
Nozzle	The exit duct of a wind tunnel or exhaust duct of an engine used for accelerating a fluid and producing a desired direction, velocity, or shape of discharge. The fluid's pressure decreases as it leaves the nozzle. The nozzle usually has an increasing cross-section in the direction of the flow.
Observables	Characteristics of a flight vehicle (such as distance, speed, and shape) that can be seen electronically, optically, or thermally. Composite materials can absorb radar waves, thus reducing the returned radar signal.
Parabolized Navier-Stokes Codes	Computer codes that use detailed equations for predicting viscous flows in which the equations have been simplified to act on the supersonic outer inviscid flow and with no reverse-flow in the viscous regions on the body.
Piston-Driven	A type of shock tunnel in which energy is created by a piston being fired (or driven) down a cylinder, compressing the test gas ahead of it. The pressure and temperature of the test gas is increased, creating a shock.

Platelet Technology

Very small and intricate passages for transporting a cooling fluid through a hot aerospace vehicle component by constructing the component from a series of very thin sheets of the desired material. Each sheet is photoetched to create the holes or passages desired. The sheets are then placed on top of one another and fused together. The advantage of this technique, particularly for development and experimental work, is that the designs can be easily modified and a new part can be made very quickly. Platelet technology is being considered for use in aerospace vehicles as a thermal control system.

Polyimides

Natural or synthetic fibers composed of natural or synthetic polymers (a material built up from a series of smaller units) having the same imide group repeated along the chain.

Pre-Burner Cycle Cryogenic Engine

Also known as the staged-combustion and topping cycle engine, this class of rocket engine features a turbopump drive in which some (or all) of the propellants undergo combustion at conditions considerably above thrust chamber combustion pressure (and at acceptable turbine inlet temperature conditions). The propellants pass through the turbine driving the pumps and are then injected into the thrust chamber where maximum cycle temperatures are achieved. Like the expander-cycle engine, and unlike the gas generator-cycle rocket engine and expander bleed-cycle engine, the pre-burner cycle cryogenic engine has no separate low-pressure turbine exhaust discharge.

Prior Steady Flow Technique

A technique whereby the prior establishment of steady flow in a hypersonic nozzle is used to ensure rapid starting of a subsequent shock-initiated flow. This technique is used to allow operation of a free-piston shock tunnel in the non-reflected shock mode. It also permits high-stagnation enthalpy shock tube flows that can be produced with the free-piston driver resulting in a hypersonic flow. Thus, test section stagnation enthalpies exceeding orbital escape velocity (11 kilometers per second) can be produced.

Ramjet

An air-breathing engine that compresses (or rams) the high-speed air entering the inlet by efficiently slowing it down to subsonic speeds, at which time it is burned with the fuel in a combustion chamber (ramburner). High-temperature combustion gases are expanded through an exhaust nozzle at high speed, creating the thrust. A ramjet is capable of efficient operation at supersonic speeds of about Mach 2 to 6.

Ram-Rocket

A rocket engine in which an air-breathing inlet and duct system are added, permitting atmospheric air to be introduced at the exit of the rocket combustion chamber. By operating the rocket engine with more fuel than necessary to use the rocket's oxidizer, the rocket's hot combustion products can be mixed with the atmospheric air where the excess fuel is burned, creating additional high-temperature combustion products. A ram-rocket engine provides high thrust at subsonic and supersonic conditions while retaining the rocket's ability to produce thrust at static (Mach 0), hypersonic, and orbital conditions.

Rapid Solidification Technology

A process in which molten metals such as titanium and aluminum are transformed into a very fine powder, which is then solidified. The resulting alloy (ti-aluminide) demonstrates much higher strength and stiffness at high temperatures compared to conventional titanium alloys. Moreover, ti-aluminide has one-half the weight of the material previously used at these high temperatures.

Real Gas Effects

A gas behavior or phenomena resulting from the interactions of gas molecules.

Reynolds Number

A dimensionless number used as an indication of scale of fluid flow. It is significant in the design of a model of any system in which the effect of viscosity is important in controlling the velocities or the flow pattern of a fluid. Reynolds Number is equal to the density of a fluid times its velocity times a characteristic length divided by the fluid viscosity.

Rockoon

A high-altitude sounding system consisting of a small solid-propellant research rocket carried aloft and launched by a large balloon.

Schlieren

An optical technique that detects density gradients occurring in a fluid flow. Schlieren is a German word that means "striations." It refers to various shadowgraphic techniques for optical investigations. Variations in density in flow through shock waves and supersonic flow, for example, are sharply visible in tonal gradations.

Scramjet	A supersonic combustion ramjet air-breathing engine in which air flows through the combustion chamber at supersonic speeds. Hydrogen is injected into the combustion chamber where it is ignited by the hot air. At very high flight speeds (Mach 6 and above), the supersonic speeds in the combustor reduce the internal pressures and temperatures, allowing efficient combustion of the hydrogen fuel and a reduction in the weight of the combustor. The hot gases are further accelerated through the exhaust nozzle, creating the thrust. Theoretically, scramjets provide efficient operation at hypersonic speeds of about Mach 4 to 25 (orbital velocity).
Shock Tube	A wind tunnel for conducting tests at hypervelocity speeds in which fluid (such as air or some other test gas) at high pressure, usually involving rapid combustion to increase energy, is released by rupturing a diaphragm and accelerated through an evacuated working section (test chamber) containing the model.
Shock Tunnel	A hypervelocity wind tunnel in which a shock wave generated in a shock tube ruptures a second diaphragm in the throat of a nozzle at the end of a tube. Gases emerge from the nozzle over the model in the test chamber and into a vacuum dump tank. Speeds achieved in a shock tunnel typically range from Mach 6 to 25.
Shock Wave	A fully developed compression wave of large amplitude, across which density, pressure, and particle velocity change drastically.
Slush Hydrogen	A mixture of liquid and frozen hydrogen that is denser than liquid hydrogen.
Slush Oxygen	A mixture of liquid and frozen oxygen that is denser than liquid oxygen.
Sonic (Velocity)	The speed of sound in air (761.5 miles per hour at sea level).
Sounding Rocket	A rocket that carries aloft equipment for making observations of or from the upper atmosphere.

Specific Impulse	A performance parameter of a rocket propellant, expressed in seconds, equal to the thrust in pounds divided by the weight flow rate in pounds per second.
Stagnation Enthalpy	The total energy or heat content of a system generated when the flow is brought to rest (zero velocity) isentropically at a stagnation point.
Subsonic	A range of speed below the speed of sound in air.
Supercomputer	A computer with the highest processing speed in any given period of time. A supercomputer is part of a high-performance computing system that is at the forefront of the computing field in terms of computational power, storage capability, input/output bandwidth, and software. These systems include high-speed vector and pipeline machines, special purpose and experimental systems, scalable parallel architectures, and associated mass storage systems, input/output units, and systems software.
Superconducting Magnets	An electromagnet whose coils are made of a type II superconductor with a high transition temperature and extremely high critical field.
Supersonic	A range of speed between about one and five times the speed of sound in air.
Telemetry	Transmitting the readings of instruments to a remote location by means of wires or radio waves.
Test Cell	A horizontal test stand for an air-breathing or rocket engine surrounded on three sides by a shelter providing protection from weather and limited protection from an accidental explosion.
Test Chamber	The test section of a wind tunnel.

Thrust

The force exerted in any direction by a fluid jet.

Torch Igniter Module

A self-igniting flame device used to ignite the fuel-air mixture in a combustor region of a ramjet-type engine.

Transonic

A range of speed between about 0.8 and 1.2 times the speed of sound in air.

Turbofan

An air-breathing engine, similar to a turbojet, in which a portion of the compressed air bypasses the combustor and turbine. The remaining compressed air enters the combustor. The compressed air is then mixed with the fuel, burned, and expanded through the turbine. The power from the turbine is used to drive the compressor. Hot gases exiting from the turbine and compressed bypass air can be mixed and expanded through an exhaust nozzle or separate exhaust nozzles to produce the thrust. When fuel is added and burned downstream of the turbine, a turbofan engine can operate efficiently from Mach 0 to 2.5.

Turbofan-Ramjet

An air-breathing engine consisting of a turbofan engine mounted within a ramjet duct. At low speeds, the engine operates as a turbofan. Between Mach 1 and 2, the ramburner begins to operate, providing a greater portion of the thrust until the turbofan is shut down at speeds of approximately Mach 3. At that point, the ramjet provides all of the thrust. During all operating modes, the high-temperature combustion gases are expanded through the exhaust nozzle to produce the thrust. A turbofan-ramjet engine provides the efficiency of a turbofan during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6).

Turbojet

An air-breathing engine in which air is compressed by a compressor before it enters a combustor. Air is then mixed with fuel, burned, and expanded through a turbine. The power from the turbine is used to drive the compressor. Hot gases exiting from the turbine are expanded through an exhaust nozzle to produce thrust. When fuel is added and burned downstream of the turbine, a turbojet engine can operate efficiently from Mach 0 to 3.

Turbojet-Ramjet	An air-breathing engine consisting of a turbojet engine mounted within a ramjet duct. At low speeds, the engine operates as a turbojet. Between Mach 1 and 2, the ramburner begins to operate and provides a greater portion of the thrust until speeds of approximately Mach 3.5, when the turbojet is shut down and the ramjet provides all of the thrust. During all operating modes, high-temperature combustion gases are expanded through the exhaust nozzle to produce thrust. A turbojet-ramjet engine provides the efficiency of a turbojet during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6).
Turboramjet	An air-breathing engine consisting of a turbojet engine mounted within a ramjet duct. Intake air is compressed at low speeds by a compressor driven by a turbine and at high speeds by the ram effect of the engine moving through the air. At low speeds, the engine operates as a turbojet. Between Mach 1 and 2, the ramburner begins to operate and provides a greater portion of the thrust until speeds of approximately Mach 3.5, when the turbojet is shut down and the ramjet provides all of the thrust. During all operating modes, high-temperature combustion gases are expanded through the exhaust nozzle to produce thrust. Like the turbojet-ramjet, the turboramjet engine provides the efficiency of a turbojet during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6). A turboramjet engine is the same as a turbofan-ramjet engine or turbojet-ramjet engine.
Turborocket	A combined-cycle engine in which hot gases from a rocket operating with excess fuel are used to energize a turbine, which, in turn, drives a compressor for operation at speeds of Mach 0 to approximately 5. Gases exiting the turbine are mixed with air from the compressor, which burns the excess fuel. The resulting high-temperature gases are expanded through an exhaust nozzle, causing the thrust. A turborocket engine significantly reduces the need to carry oxidizer, thus reducing the weight of propellant needed to accelerate a vehicle to high Mach numbers and altitudes. A turborocket engine is a variant of an air-turboramjet engine.
Vacuum Test Chamber	A pressure vessel, typically spherical or cylindrical, that can be pumped down to a near vacuum. A vacuum test chamber can be used in engine testing to provide a low-pressure reservoir for receiving discharged engine exhaust.

Wind Tunnel

A ground test facility used to test flight characteristics of an aircraft by directing a controlled stream of air around a scale model and measuring the results with attached instrumentation.

Related GAO Products

Aerospace Plane Technology: Research and Development Efforts in Europe (GAO/NSIAD-91-194, July 25, 1991).

Aerospace Technology: Technical Data and Information on Foreign Test Facilities (GAO/NSIAD-90-71FS, June 22, 1990).

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National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30 (GAO/NSIAD-88-122, Apr. 27, 1988).