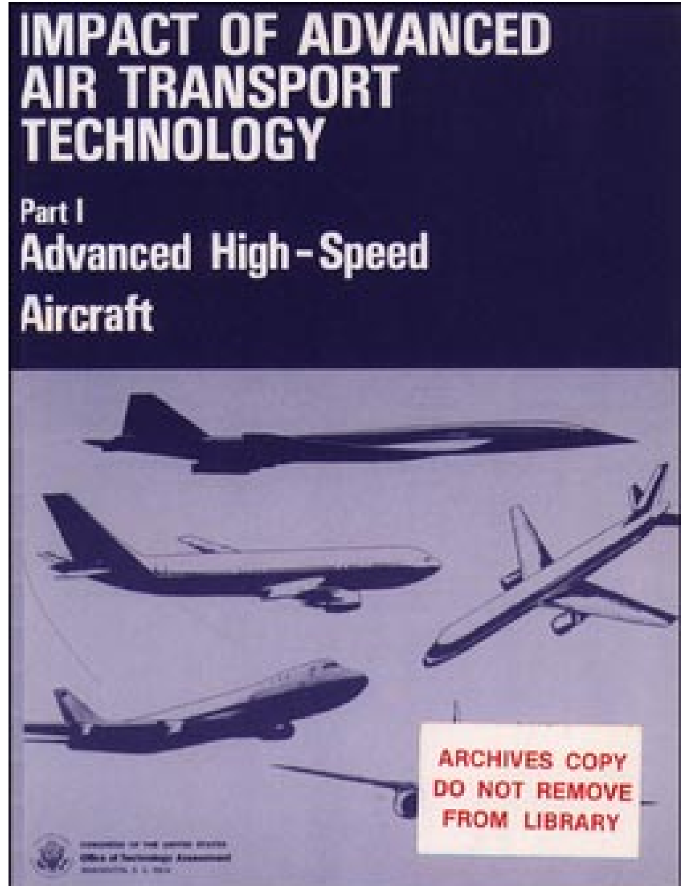
Advanced High-Speed Aircraft

April 1980

NTIS order #PB83-110585



Library of Congress Catalog Card Number 80-600060

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 Stock No. 052-003 -00745-2

Foreword

In April 1978, the House Science and Technology Committee requested that the Office of Technology Assessment perform a technology assessment “to provide a fresh look at the impact of eventual widescale introduction of advanced high-speed aircraft. ” The specific issue raised was whether the potential benefits of advanced supersonic transport aircraft—or second generation supersonic transports—justify increases in the levels of Federal funding for generic research and development in supersonic cruise technology. This request was subsequently endorsed by the Senate Committee on Commerce, Science, and Transportation.

Responding to this request, OTA proposed a broad and long-term study to examine the potential for advanced air transport technology, both passenger and cargo. The objectives of this study were to examine the economic, environmental, energy, societal, and safety impacts of advances in the technology of high-speed aircraft, commuter aircraft, and air cargo. To bring the scope of the assessment within manageable bounds, we focused strictly on the aircraft technologies and excluded the examination of such areas as the airport and terminal area capacity and the air traffic control process, all of which could affect the convenience, efficiency, and safety of our future airport system.

This report is the first in a series and deals solely with advanced high-speed aircraft, including both subsonic and supersonic. Three other reports to be published in the near future comprise the remaining parts of this assessment. They are: “Financing and Program Alternatives for Advanced High-Speed Aircraft, ” “Air Service to Small Communities, ” and “Air Cargo. ”

In conducting this assessment, OTA was assisted by an Advisory Panel and a Working Group each comprised of representatives from Government agencies, the aerospace industry, public interest groups, financial institutions, and universities. The contributions of these individuals and members of their respective organizations were significant and extremely important to the outcome of this study.

John H. Gibbons

JOHN H. GIBBONS
Director

Impact of Advanced Air Transport Technology Advisory Panel

Robert W. Simpson, *Chairman*
Director, Flight Transportation Laboratory, Massachusetts Institute of Technology

Jane H. Bartlett
President
Arlington League of Women Voters

Ray E. Bates
Vice President
Douglas Aircraft Co.

Norman Bradburn
Director
National Opinion Research Center

Frederick Bradley, Jr.
Vice President
Citibank, N.A.

John G. Borger
Vice President of *Engineering*
Pan American World Airways, Inc.

Secor D. Browne
Secor D. Browne Associates, Inc.

F. A. Cleveland
Vice *President, Engineering*
Lockheed Aircraft Corp.

Elwood T. Driver
Vice Chairman
National Transportation Safety Board

James C. Fletcher
Burroughs Corp.

William K. Reilly
President
The Conservation Foundation

David S. Stempler
Chairman, Government Affairs Committee of *the Board of Directors*
Airline Passengers Association, Inc.

Janet St. Mark
President
SMS Associates

John Wild
Executive Director
National Transportation Policy Study Commission*

Holden W. Withington
Vice *President, Engineering*
Boeing Commercial Airplane Co.

Michael Yarymovych
Vice President, Engineering
Rockwell International

Observers:

Charles R. Foster
Associate Administrator for Aviation Standards
Federal Aviation Administration

James J. Kramer**
Associate Administrator for Aeronautics and Space Technology
National Aeronautics and Space Administration

*Commission was dissolved Dec. 31, 1979.
** Resigned from panel during conduct of study after leaving NASA.

Advanced High-Speed Aircraft Project Staff

Eric H. Willis, *Assistant Director, OTA*
Science, Information, and Transportation Division

Robert L. Maxwell, *Transportation Program Manager*

Lemoine V. Dickinson, Jr., *Project Director*
Jerry D. Ward, *Co-Project Leader*

Yupo Chan Larry L. Jenney Jacquelynne Mulder
David Seidman Paula Walden Arthur L. Webster

Contractors

F. Edward McLean, *Technical Advisor to Advanced High-Speed Aircraft Working Group*
William E. Howard, *Editor*

Advanced High-Speed Aircraft Working Group

Richard Alpagh
Chief, Nonhighway Transportation Branch
Department of Energy

Jane H. Bartlett
President
Arlington League of Women Voters

Richard D. Fitzsimmons
Director, Advanced Program Planning
Douglas Aircraft Co.

Jack I. Hope
Manager
HAECO Inc.

William Sens
Pratt and Whitney Engine Co.

Armand Sigalla
Chief, Technology Preliminary Design
Boeing Commercial Airplane Co.

John Wesler
Director of Environment and Energy
Federal Aviation Administration

Bruce R. Wright
Lockheed California Co.

Publishing Office

John C. Holmes, *Publishing Officer*
Kathie S. Boss Debra M. Datcher Joanne Heming

Contents

Contents—continued

LIST OF TABLES

LIST OF FIGURES

Contents—continued

Chapter I

SUMMARY OF FINDINGS

The following are the major findings of the OTA assessment on advanced high-speed aircraft—both subsonic and supersonic types—in the context of major uncertainties over world energy supplies:

- **Barring some** major disruption in the growth of the world **economy and assuming reasonable success in coping with increasingly costly energy, the total market for air travel and commercial aircraft should continue to expand in the future.** Growth in passenger-miles and airline route miles over the next **30** years will be closely tied to the price and availability of fuel. Accordingly, the demand for advanced long-range aircraft could vary from 2,200 to 3,300 units. This would represent sales by manufacturers on the order of $150 billion in 1979 dollars. (See table 1.)

Table 1.—World Requirements-New Aircraft

	1980 thru 2010	Potential sales 1979 dollars
Short and medium range (up to 2,700 nautical miles)	6,500-8,500[a]	$235 billion
Long range (over 2,700 nautical miles)	2,200-3,300[a]	$150 billion

[a]Estimates exclude U S S R and the People's Republic of China.

SOURCE Off Ice of Technology Assessment

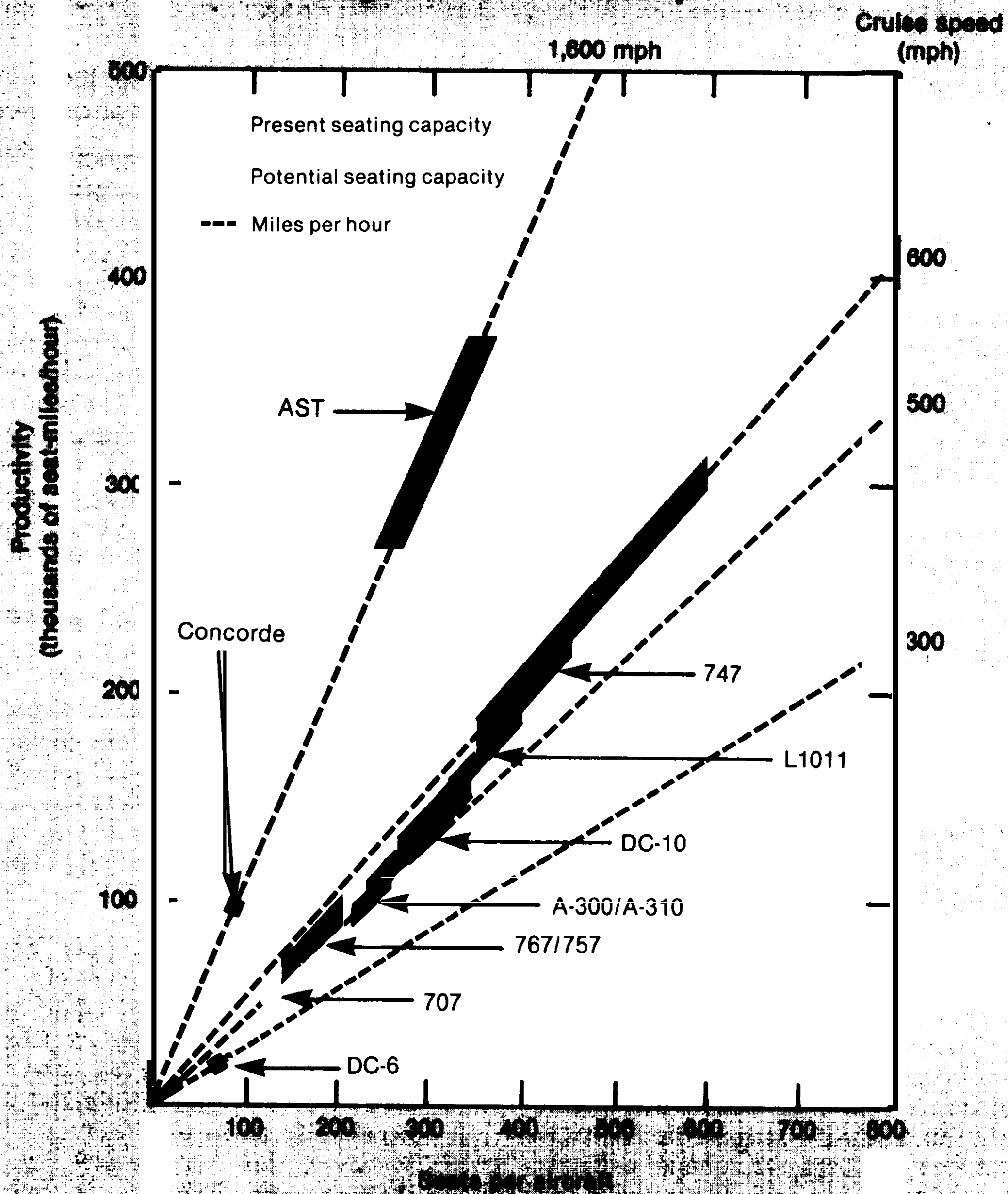
- **While supersonic aircraft might satisfy a portion of this long-range market, it is expected that the market will be dominated by subsonic aircraft—at least in this century.** Substantial improvements in technology for subsonic aircraft may provide the incentive for new designs. To offset rising fuel costs, manufacturers already are developing subsonic aircraft with more energy-efficient engines, such as the Boeing 767 and 757. This trend probably will continue and will most likely be fed by more technical advances in aerodynamic efficiency, lighter materials, and still more efficient engines. These could help lower operating costs, energy usage, and aircraft emissions.

- **The most compelling argument for an advanced supersonic transport (AST) is improved aircraft productivity—seat-miles generated by an aircraft per unit of time.** Since the advent of jets, major productivity improvements have resulted almost entirely from increases in size. (See figure 1.) But the potential for further productivity gains through scaling up aircraft size is not as impressive as in the past. Thus, while aircraft may be further stretched, the market for larger subsonic jets will be constrained by the number of airline routes with sufficiently high passenger densities to warrant placing them into service.

  Increased speed offers another avenue for major productivity improvement. An aircraft able to fly at better than 1,600 mph (Mach 2 +) can transport twice as many passengers a day on long-distance flights (more than 2,700 nautical miles) as a subsonic aircraft of equivalent size. This higher speed provides a significant timesaving for the passenger on these long-distance journeys.

- The drawback in the past from pursuing speed-derived productivity has been cost. The productivity could have been achieved, but at too high a proportionate increase in total operating costs (TOC). In other words, **higher productivity does not necessarily mean profitability.** Over time, however, this cost penalty has been decreasing—the difference in the potential cost of supersonic aircraft compared to subsonic aircraft has been shrinking. While rising energy costs could slow the trend, it is reasonable to expect that through technological improvements this convergence will continue. To **the extent that it does, the economic penalty of supersonic cruising aircraft will become less. (See figure 2.)**

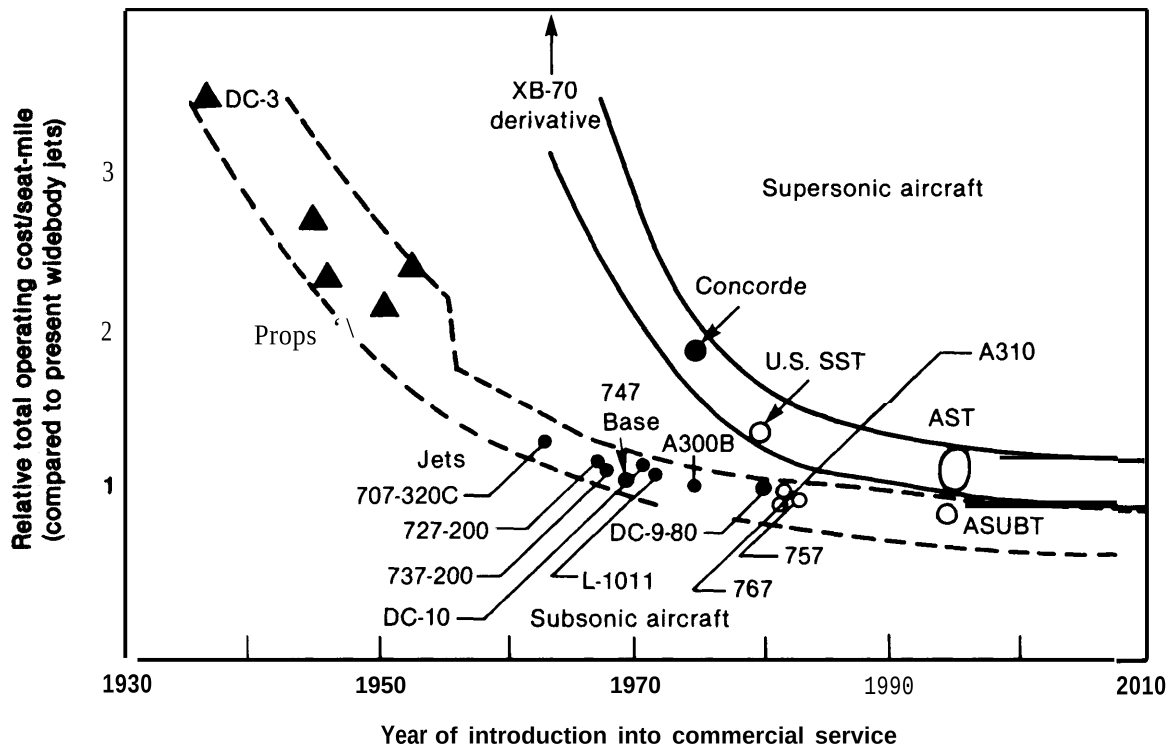
Figure 1.—Aircraft Productivity



$$\text{Cost per seat-mile} = \frac{\text{Total cost}}{\text{productivity}}$$

SOURCE: Office of Technology Assessment, based on industry data.

Figure 2.—Relative Total Costs of Supersonic and Subsonic Aircraft



SOURCE: Office of Technology Assessment based on industry data.

- **Assuming that an economically viable and environmentally acceptable AST could be developed in the 1990-2010 period, its greater productivity could command sales of about 400 aircraft worth about $50 billion in 1979 dollars.** This would represent approximately one-third of the total sales anticipated for the long-range market through 2010. AST sales would mean fewer sales of subsonic aircraft. It is estimated that 400 ASTs could replace approximately 800 subsonic aircraft.

- **While the market outlook for an AST appears to be inviting, the actual development, production, and operation of such an aircraft are clouded by major uncertainties.** Two principal uncertainties are fuel price and availability and the technical feasibility and cost of satisfying increased community sensitivity to noise around airports.

—**Fuel price and availability:** There are great unknowns as to the future price and availability of fuel. However, given that an AST would have fuel consumption rates at least 1.5 to 2 times greater per seat-mile than equivalently sized subsonic transports, it would be more sensitive to fuel price increases than a subsonic aircraft. Therefore, future fuel price increases could have a larger impact on the total operating cost of an AST than on a subsonic transport and could be a significant factor in determining its future viability.

Further, fuel for transport aircraft must be available on a worldwide basis. Examination of alternative fuels such as synthetics or liquid hydrogen or methane should be continued.

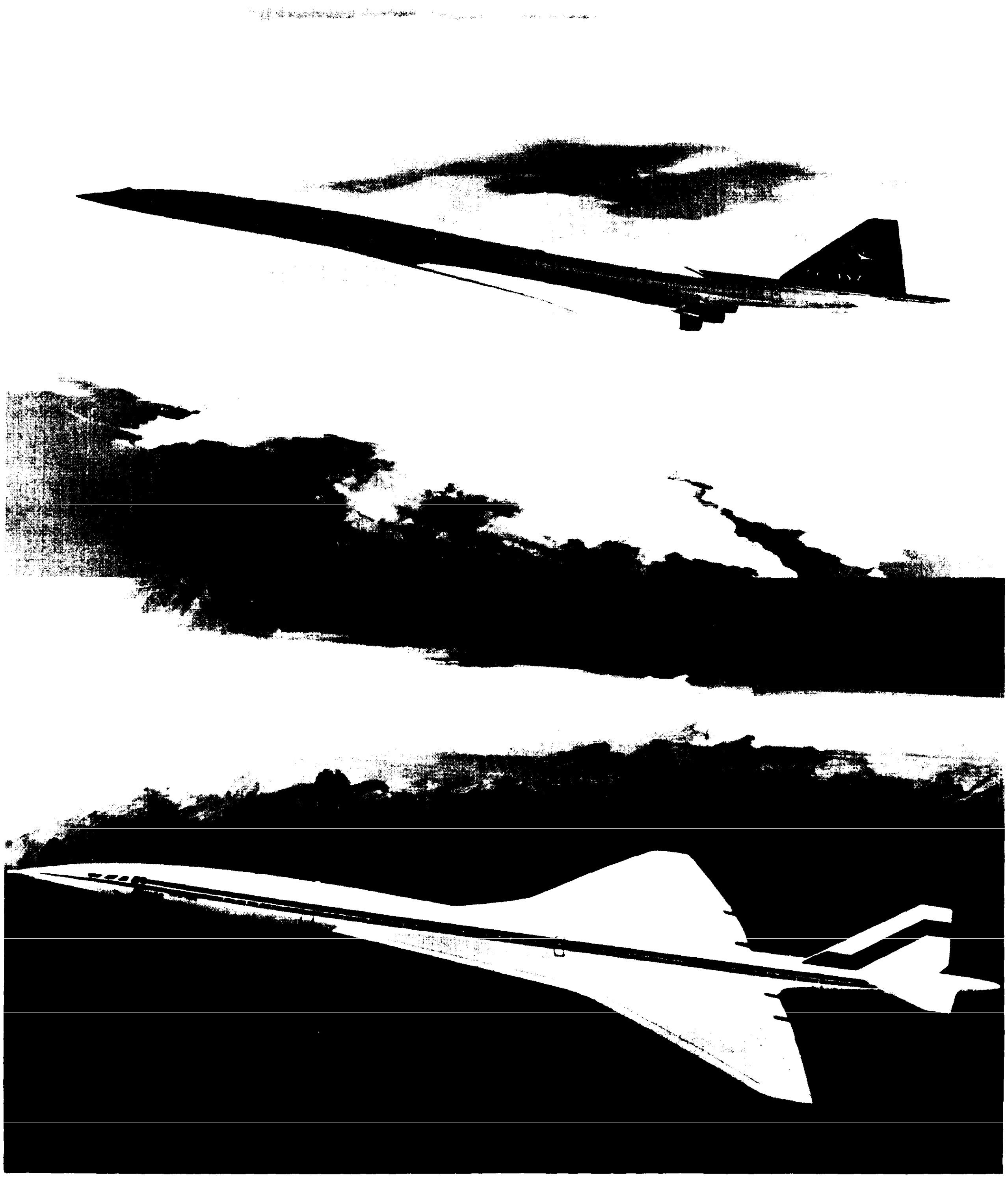
—**Noise:** One of the greatest obstacles appears to be the ability of an AST to cope with diminishing public tolerance toward noise, especially in the vicinity of airports. Public attitudes are likely to bring about more stringent noise standards in the future, affecting both supersonic and subsonic aircraft as well as airport operations. While present supersonic work by the National Aeronautics and Space Administration (NASA) indicates the possibility of meeting the Federal Aviation Administration (FAA) (FAR part 36, stage 2) noise regulations, more research and technology development, at further expense, would be needed to meet more stringent regulations. Until the uncertainty over changes in the regulations is resolved and the uncertainty about supersonic aircraft noise is reduced, aircraft manufacturers may be reluctant to commit themselves to a new supersonic aircraft program. The investment would be too large to risk failure of not meeting a more stringent noise standard.

- **The Supersonic Cruise Research (SCR) program conducted by NASA since the American supersonic transport (SST)* was canceled by Congress in 1971 has identified and made advances in several technology areas—aerodynamics, structures, propulsion, and noise reduction on takeoff and landing.** Significant improvements may be achieved with further work, but even if these technology advances are validated there can be no guarantee that the aerospace industry would act on them. The cost of applying this technology to the design and development of a suitable aircraft could run to $2 billion in 1979 dollars. Tooling up and starting production could require at least an additional $5 billion to $7 billion–sums believed to be far beyond the resources of any one company. **The financial risk could be reduced by the formation of a domestic consortium of two or more aerospace companies, or perhaps by an international consortium that would include foreign manufacturers. Formation of a corporation similar to that of COMSAT is another alternative which may be applicable for undertaking such a program. ***
- Foreign manufacturers are moving ahead in the subsonic field. Their willingness to embark on an AST appears to be tempered by the same uncertainties as those facing the U.S. industry. However, the supersonic area does present them with another opening where they could alter the longstanding U.S. competitive advantage in the sale of long-range aircraft. **Thus, given the probability of an expanded market for air transportation in the future and the importance to our domestic economy and our international trade balance of sustaining U.S. leadership in commercial aviation, it appears that it would be in our national interest to keep our options open in the supersonic field.**
- **Accordingly, it appears appropriate to carry out a generic R&D** program to preserve the supersonic option.** This program should be adequate to maintain the skills and knowledge from which a future development project could be effectively initiated and should produce more factual information to reduce the technical uncertainties. The objectives of this generic R&D program should be carefully defined to yield information that would facilitate a decision on whether or not to proceed with an AST at a later date. The financial risks also need to be more fully understood. **If Congress wishes to maintain the U.S. SST option, then the existing level of Federal support is not considered adequate to accomplish this. R&D, however, will not shed light on those external factors governing the viability of an AST—the increasing sen-**

'Throughout, the abbreviation SST refers only to the U.S. supersonic transport program that was begun in 1963 and terminated in 1971.

● An analysis of these alternatives is reported in a soon to be published OTA report entitled "Financing and Program Alternatives for Advanced High-Speed Aircraft ."

•● In this report, generic R&D is that process of verifying and validating technologies leading to a state of "technology readiness" for development of a specific product. At a state of "technology readiness, " R&D activities can move from the generic to the specific. Specific R&D is that part of the process where a product or a family of products is defined. When the term "research" is used in this report, it refers to generic R&D.



Illustrations Courtesy of McDonnell Douglas and Boeing Aircraft Co

Artists' concepts of advanced supersonic transport

60-285 0 - 80 - 2

sitivity of the public to aircraft noise, the price and availability of adequate fuel supplies, and the availability of financing for such a major capital commitment.

DISCUSSION

This study examines the prospects for introducing new types of large, long-range aircraft—subsonic, supersonic, and hypersonic, beyond the next generation of scheduled aircraft such as the Boeing 767 and 757—into commercial service over the next 30 years and weighs the financial and other risks inherent in acquiring the technology for developing these advanced transports. Traditionally, the generic R&D from which subsequent generations of commercial aircraft have evolved has been supported by the Department of Defense, by NASA, and by the U.S. aerospace industry. In the subsonic field, this trend seems likely to continue, although NASA's role may become comparatively greater than the military's in the pursuit of more fuel-efficient and quieter transport aircraft to satisfy future environmental concerns.

Generic R&D leading to an AST that is safe, economical, and environmentally acceptable involves a different supporting structure. Because the military is not aggressively pursuing a supersonic cruise aircraft, no suitable engine or airframe is expected to emerge from the Department of Defense R&D programs. Since the cancellation of the U.S. SST program in 1971, technological development at a low level of effort has been carried out by NASA and the aerospace industry. It is generally agreed that considerable additional technological development would be necessary to reduce the technical risks of embarking on an AST to a level acceptable to private investors.

Therefore, a central purpose of this assessment is to identify for Congress the positive and negative impacts of future commercial supersonic transports. These will need to be taken into account in considering the level of Federal Government funding of NASA's generic R&D leading to possible development of an AST, a second-generation aircraft with performance capabilities beyond the British-French Concorde. In this perspective, our assessment is not a market study of the prospects for a specific supersonic aircraft design. It is rather an evaluation of whether technological research toward a class of possible future supersonic aircraft seems sensible in the long run and whether mastery of supersonic technology in this country will be an important factor in our international competitiveness in the future.

In looking at the overall issue of supporting further research into supersonic cruise aircraft—and what might be gained from it—this study assesses where the technology stands now and examines the directions it might take. The real issue now is whether the long-term promise of some kind of supersonic transport—to be designed perhaps in 5 to 10 years—is sufficient to justify getting the technology ready. If we keep with past practice, the burden of financing such research would fall in large measure on the public treasury, which is why the question was originally put to OTA.

CURRENT STATE OF TECHNOLOGY

Present supersonic technology is not likely to produce an aircraft during the time frame considered in this study that would be able to fly at supersonic speeds without producing a sonic boom. Although some theoretical work has been done on "shaping" the sonic boom, an aerodynamic or other solution to the present Federal ban on over land supersonic commercial flights appears to lie many years away. The question of "solutions" to the sonic boom is critical in looking at where technology is headed because restricting any proposed AST to supersonic flight over water also restricts the market—and possibly the overall viability of a supersonic aircraft program.

The Concorde represents proven technology dating back to 1960. This aircraft has shown that a supersonic airliner can be operated safely from existing airports. Its major deficiencies are small size (about 100 seats), high fuel consumption, and engines designed before noise regulations were imposed.

Since 1971, NASA's SCR program has generated knowledge that could realize sizable gains over the Concorde. Among other advances, the work has yielded a new wing configuration that wind tunnel tests indicate would result in much improved aerodynamics and a lift-to-drag ratio in the range of 9 to 10, approximately 20 percent more efficient than the Concorde in supersonic cruise. Advanced computational and finite-element modeling techniques have been developed, reducing the structural design time for *major* aircraft components from 3 months to 1 week and offering promise of lower development costs.

NASA's studies indicate that major weight reductions (10 to 30 percent) and cost savings (up to 50 percent) in aircraft structures may be achieved through superplastic forming and concurrent diffusion bonding of titanium. Various forms of high-temperature polyimide composite structures with further weight-cutting possibilities also have been investigated.

Variable= Cycle Engine

In the propulsion area, a concept has been proposed for a variable-cycle engine which may

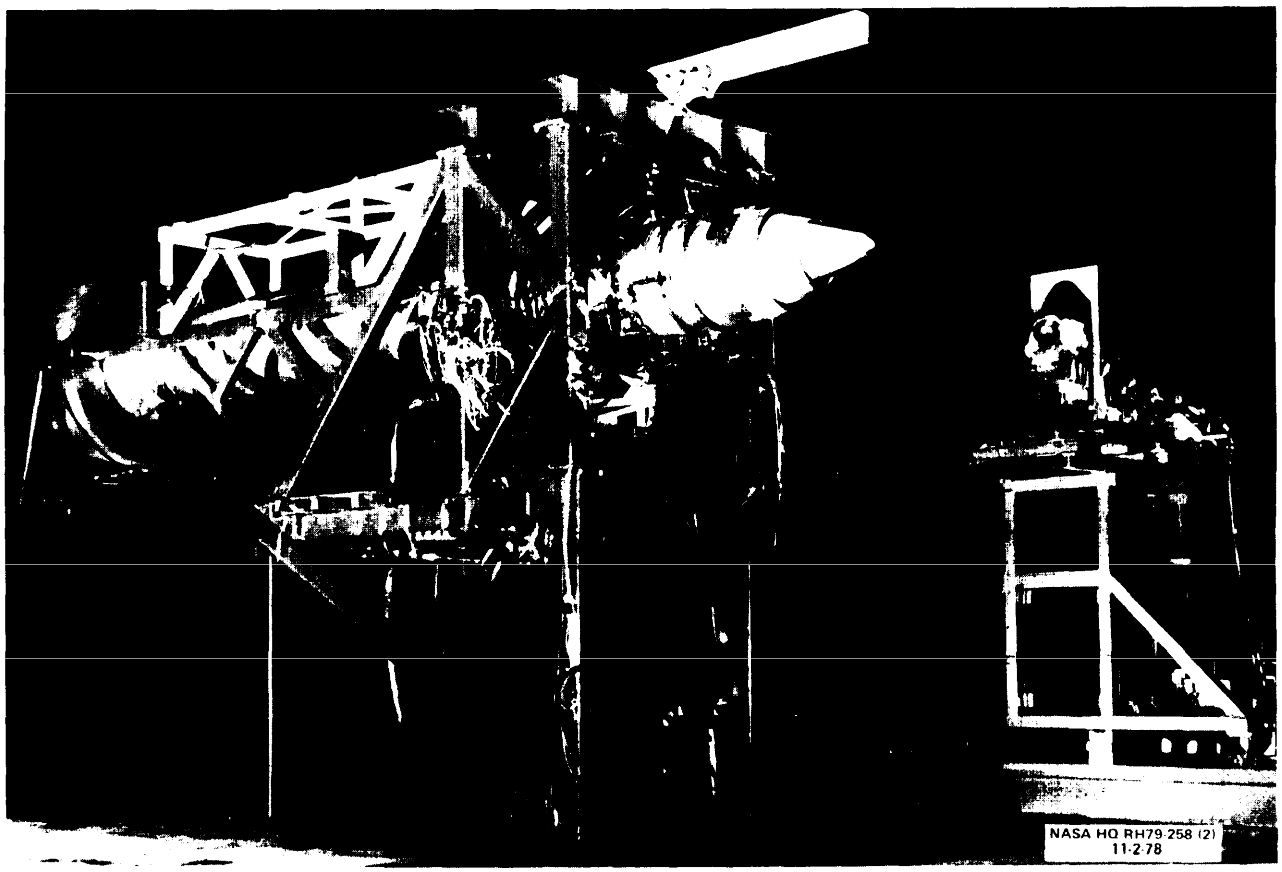


Photo credit. National Aeronautics and Space Administration

Variable-cycle experimental engine testing be able to operate at nearly optimal fuel efficiency while cruising at either supersonic (turbojet) or subsonic (turbofan) speeds. Moreover, the internal configuration of the engine would permit changes in the exit nozzle velocity profile that may lower the sideline noise at takeoff and landing.

A body of opinion within the aviation industry holds that, should the variable-cycle engine prove itself in a development and test program, it would be a significant factor in designing a viable AST. The engine's promise is this: if able to operate optimally at both subsonic and supersonic speeds, the engine would enhance the possibility that an AST could be integrated into regular airline route structures. For example, it would be possible to originate AST service to London or Tokyo from Chicago, Denver, or Dallas. The over land legs would be flown subsonically and the over water legs supersonically.

Technology Validation Program

In August 1979, in response to a request from the House Science and Technology Committee, NASA outlined possible plans which were identified as focused initiatives in a number of aeronautical fields. In supersonic cruise research, NASA concentrated on propulsion, airframe, and aircraft systems technology. In the propulsion area, the program would be broadened to include research on a variable-flow propulsion system and an advanced core engine system that would be integrated with the variable-cycle experimental engine. The aim would be to produce design options for an array of supersonic aircraft applications, plus potential military applications. The airframe technology program would concentrate on nacelle/airframe integration and acoustic suppression design methods and high-temperature structures problems, including the selection, fabrication, and testing of titanium and composite materials. The aircraft systems technology effort would identify those portions of the engine and airframe programs requiring inflight investigation and validation. NASA estimates it would take up to 8 years to accomplish these objectives. If successful, the program would lead to a state of "technology readiness," which would be a decision point for the aerospace industry on whether further development of an AST appears feasible.

The proposed NASA program would cost $662 million (1981 dollars) over an 8-year period, as opposed to an alternate program offered by NASA in **1978,** which was priced at $561 million (1979 dollars) over a similar 8-year period. In addition to these two plans, again in response to a request from the House Science and Technology Committee, NASA prepared a plan leading directly to "technology readiness" in industry. This plan would sustain full competition in the U.S. industry and would require as much as $1.9 billion (1977 dollars). The three widely different plans have raised a question for Congress as to what is the appropriate level of Federal support for supersonic research, because a decision to embark on any one plan would mean a substantial increase over the approximately $10 million a year that has been invested in SCR since 1971.

Fuel Considerations

In the event an AST is eventually developed, the aircraft would be designed for a service life of about **20** to **25** years. This means that when the time for decision on development arrives, in the late 1980's by NASA's timetable, future fuel supplies for the aircraft and confidence in fuel price stability must be assured from the onset,

The impending petroleum shortage has prompted the Federal Government to support a large-scale program to develop alternate energy sources. These efforts may begin to bear fruit in the late 1980's, putting the Nation on a different energy track. If that track is synthetic petroleum, resulting in Jet A fuel with characteristics similar to Jet A from petroleum, only minor modifications would have to be made in aircraft systems to use it. But if liquid hydrogen, methane, or a fuel dissimilar to Jet A should become the track, radical changes might be required in future aircraft design concepts including fuel systems and engines. Thus, uncertainty hangs over what fuel a future aircraft should be designed to use. While that design decision does not have to be made now, it is a reason for adopting a cautious approach in both the funding and the content of the technology program and in continued examination of possible alternative fuels.

FINANCING CONSIDERATIONS

Even if the energy picture becomes clarified, manufacturers still may be hesitant to embark on a full-scale development program because of the cost of design and development, estimated to be around $2 billion in 1979 dollars. An additional estimated $5 billion to $7 billion would be needed to tool up and start production. Such sums are far beyond the present financial resources of any one U.S. aerospace company. This situation could change over the next several years. But it remains questionable whether the industry and private capital markets would be able on their own at the point of "technology readiness" to initiate activities leading to full-scale production.

However, alternative financing arrangements beyond the generic R&D phase, may be possible without direct U.S. Federal Government support. These options include formation of domestic or international consortia involving two or more manufacturers and creation of a COMSAT-type public corporation to assume responsibility for producing the aircraft. These management and financing options are examined and reported in a soon to be published volume on the "Financing and Program Alternatives for Advanced High-Speed Aircraft ."

FOREIGN COMPETITION

The more advanced a supersonic aircraft is economically and environmentally at the time of introduction, the better its chances in the marketplace. The level of technology available at the time of design makes the difference. While this may be a truism, it needs to be kept in mind in deciding the pace of a research program designed to keep our options open in the supersonic transport field. The main reason for maintaining options is the size of the potential AST market and the threat of losing some or all of it to foreign competition.

Our assessment indicates potential aircraft sales of about 400 for an AST that could fly supersonically only over water. This would amount to expected sales totaling $50 billion in 1979 dollars in the 1990-2010 period—or approximately one-third of the value of all sales of long-range transports anticipated *over* the next 30 years. This amount would be a significant sum for the U.S. aircraft industry to lose to foreign manufacturers.

How great is the threat of foreign competition? Though we were unable to collect information on the Russian TU-144, manufacturers in France and England are now engaged in generic AST research and have the same doubts as the U.S. industry. They also believe rising fuel prices and the expense of hurdling the technical barriers of an AST—restrictions on aircraft noise and increasing total operating costs—make the development and production of an AST too risky at the present time. Thus, it appears that the threat of foreign competition is not close at hand or at a point where it might dictate the pace of technology development by the United States.

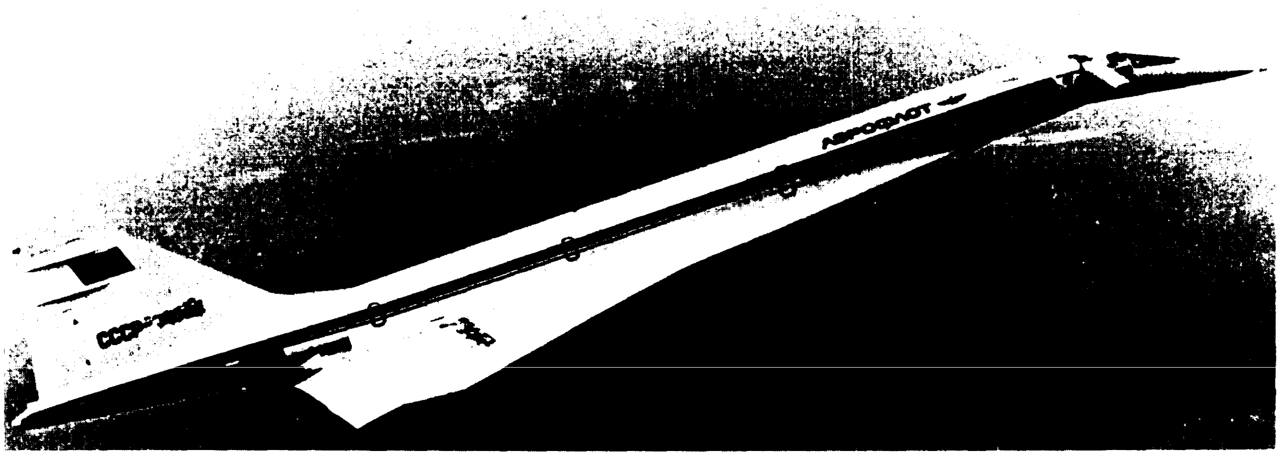


Photo credit: National Aeronautics and Space Administration

Russian supersonic transport (TU-144)

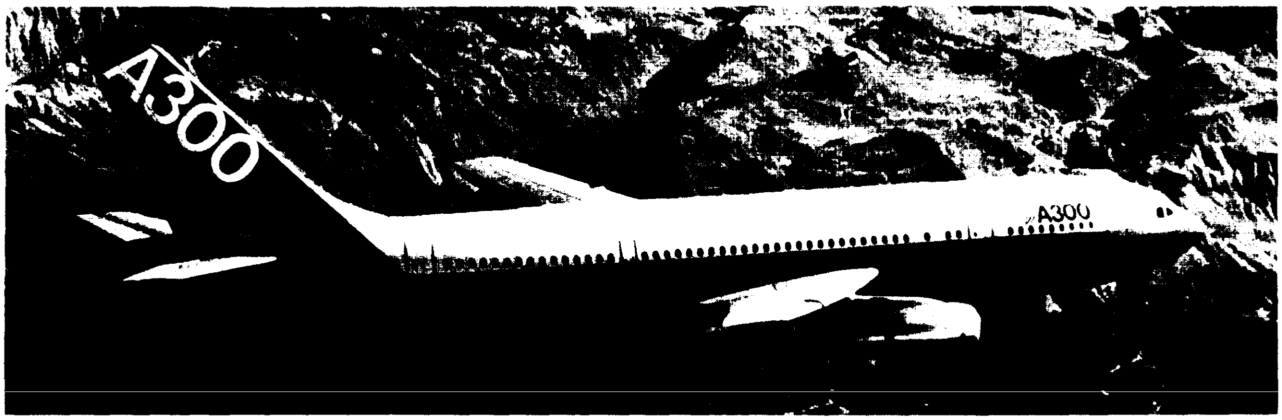


Photo credit: Airbus Industrie

Airbus Industrie's A 300

Photo credit: National Aeronautics and Space Administration

British Airways and Air France Concordes, Dulles Airport, May 24, 1976

ENERGY ISSUES: AVAILABILITY AND PRICE OF FUEL

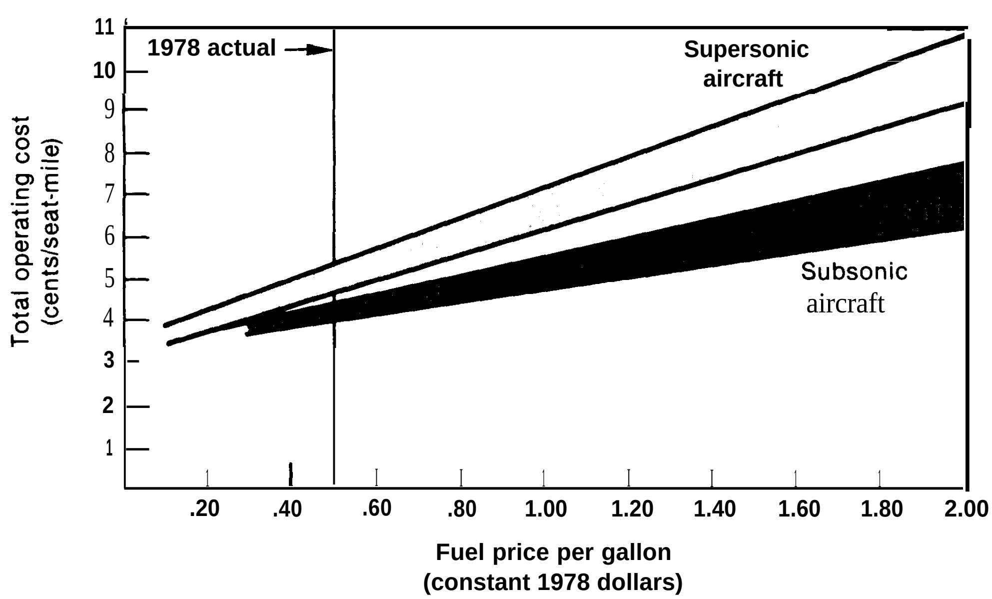
Projections of steadily rising airline traffic over the next 30 years may be optimistic. An expanded market for both advanced subsonic and supersonic aircraft may not materialize. If the market does not materialize, the questions dealing with the impact of advanced aircraft are moot. The controlling factors could be the rising cost and limited availability of fuel. Today, the world's commercial aircraft fleet, excluding the Soviet Union and the People's Republic of China, uses approximately 1.5 million barrels per day (MMbbl/d) of fuel.

Estimates indicate that by the year 2010 the world commercial air fleet fuel usage could represent about 3.5 MMbbl/d. The majority of airline consumption will continue to be for short- to medium-range service with the long-range aircraft using about 15 percent of the total. However, a fleet of **400** ASTs could increase the worldwide petroleum consumption of commercial aircraft by about 10 percent. Furthermore, if serious shortages occur, air traffic may be drastically reduced. This would favor more energy-efficient subsonic aircraft, because, by current estimates, they would consume approximately half the amount of fuel per seat-mile as future supersonic aircraft. The higher fuel consumption of an AST, associated with rising fuel price, would make the increased energy costs of supersonic aircraft greater than those of subsonic aircraft.

Over time, the cost penalty for improved productivity has been decreasing and, as previously shown in figure 2, the difference in the total operating cost of supersonic aircraft compared to subsonic aircraft has been shrinking. Further, if an economically and environmentally acceptable AST could be developed, it is reasonable to expect that this convergence would continue. However, rising fuel costs could offset the gains to be expected from improved AST technology and might actually cause the curves to diverge.

Figure 3 compares the estimated total operating costs (TOC) for an advanced subsonic transport (ASUBT) with those of an AST as a result of increasing fuel price, relative to all other costs. As can be seen, because of higher fuel

Figure 3.—Effect of Fuel Price on Aircraft Operating Cost



SOURCE: Office of Technology Assessment based on industry data usage, the supersonic aircraft is more sensitive to fuel price increases than a subsonic aircraft.

There is much disagreement over the future price and availability of fuel. If all other effects are held constant, figure 3 shows that the ratio of supersonic aircraft TOC to subsonic aircraft TOC would rise from about 1.2 at $0.50 per gallon to approximately 1.4 at **$1.30** per gallon and 1.5 at **$2.00** per gallon. Fuel price could be a significant factor in determining the economic viability of a future commercial AST.

On the other hand, labor cost could also have a major effect on TOC. Rising labor costs would probably be more detrimental to subsonic aircraft economics than to supersonics due to the higher productivity of flight crews in supersonic aircraft operations,

ENVIRONMENTAL ISSUES: NOISE, SONIC BOOM, AND ATMOSPHERIC POLLUTION

The most critical environmental issue facing future supersonic aircraft is the ability to meet increasing community sensitivity to airport noise. In the case of the Concorde, the principal controversy surrounding permission to operate at Washington's Dunes Airport and New York's John F. Kennedy Airport was the anticipated additional noise in neighboring communities. The Concorde was placed at a disadvantage because it had already evolved before noise rules were established for any class of aircraft. Since the start of operations, carefully controlled takeoff and landing procedures have minimized noise complaints. But, it should be recalled that the noise issue played a major part in the cancellation of the prior U.S. SST program in 1971 and most probably will be a major factor in the consideration of any future U.S. SST program.

The noise issue has to be looked at in the context of total aircraft operations expected in the future, If air traffic expands substantially and there is a major increase in the number of jet transports, communities will be exposed to more noise—even if future subsonic transports are made quieter. The number of operations by supersonic aircraft would be relatively small compared to the total. But nonetheless they would add to the total noise—and therefore be controversial. Furthermore, the public seems to be becoming less tolerant toward noise and more active in opposing environmental degradation.

Currently, it seems likely that communities will press for more stringent airport noise regulations. It may be some time before final standards are promulgated. Until the uncertainty over changes in the regulations is resolved, aircraft manufacturers may be reluctant to commit themselves to **a** new supersonic aircraft program. Their investment would be too large to risk failure of not meeting noise standards.

The sonic boom is another environmental concern that remains from the first SST program and the Concorde. Present Federal regulations prohibit civil aircraft from generating sonic booms that reach the ground. This effectively bars present and future SSTs from operating supersonically over land, forcing them to fly at subsonic speeds and at less efficient fuel consumption rates. Research indicates there may be ways to lower sonic boom pressures, but practical aerodynamic solutions appear to be many years off.

Research to ameliorate sonic booms should be emphasized because of its long-term importance to an economically and environmentally acceptable, AST. The capability of cruising supersonically over land would increase the market potential of an AST and might eventually permit it to replace most long-range subsonic transports.

In 1971 there was considerable concern that engine emissions from a fleet of supersonic airliners would deplete the ozone in the upper atmosphere. A reduction in this protective shield against the Sun's rays, it was feared, would increase the incidence of skin cancer. However, studies since then, including an FAA program now in progress to monitor the upper atmosphere, indicate that previous predictions of

Photo credit Environmental Pro tection Agency

Noise pollution

ozone loss through subsonic and supersonic aircraft pollution appear to have been substantially overstated. The science of atmospheric chemistry and physics is still growing and, as new data and models become available, it will be clearer whether the current outlook is justified.

WORLD REQUIREMENTS FOR NEW AIRCRAFT

If a solution can be found for the world's oil problem and national economies are stable and growing, the demand for air travel and for more aircraft—both additional and replacement—is likely to expand substantially in the next 30 years. Technical advances in subsonic jets could make them quieter and possibly more energy efficient. Greater energy efficiency could affect the cost of air travel favorably by permitting the real prices for air transport services to decrease.

Approximately **4,700** jet aircraft are in operation around the world today, excluding the fleets of the Soviet Union and People's Republic of China. Within the next **30 years,** the **total** requirements for new aircraft in the jet fleet could total 7,000 to 12,000 aircraft, as already presented in table 1, if projected demand for air travel materializes. The market for long-range aircraft, which could be on the order of $150 billion in 1979 dollars over this period, is expected to be dominated by continued production of existing widebody jets and by the introduction of new models, such as the Boeing 767 and 757 now under development.

In addition to increasing fuel efficiency, it may be possible to stretch further the body of subsonic jets, thereby increasing the payload, and thus improving productivity. Seating for up to 800 passengers is considered technically feasible. However, the demand for such large aircraft would be limited because of the small number of routes with travel densities sufficiently high to warrant putting them into service. The only other avenue to significantly higher productivity is increased speed. The relationship of

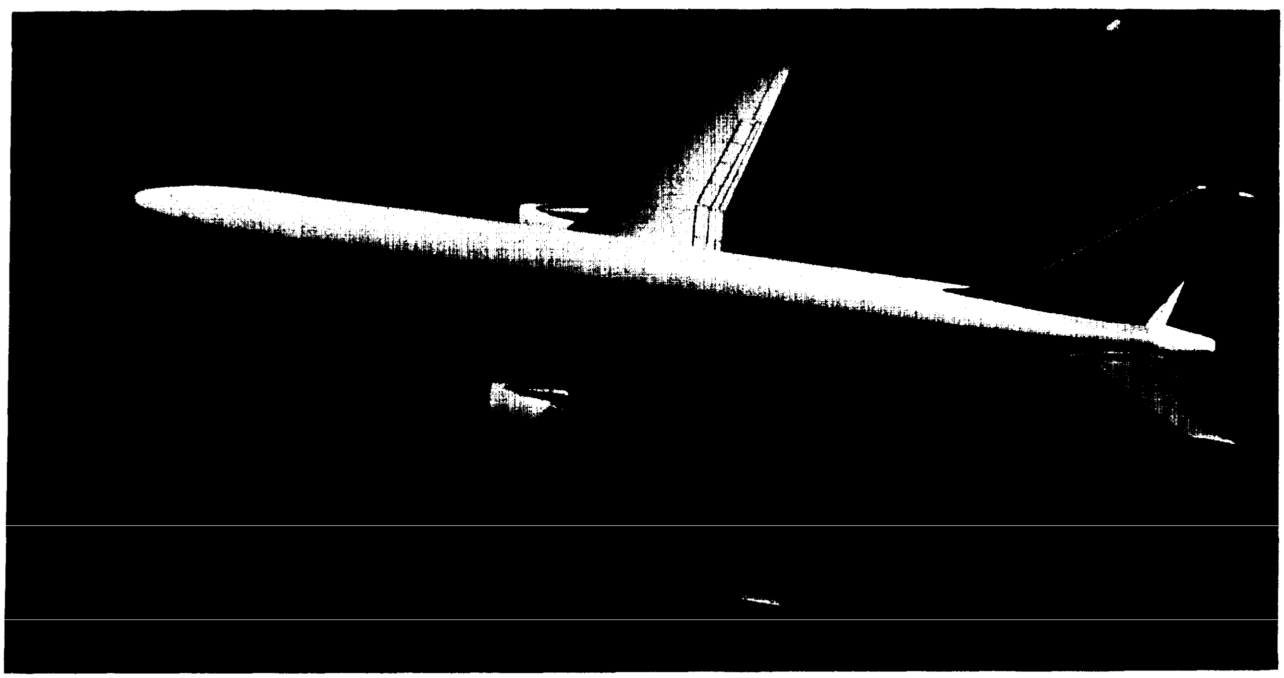


Photo credit' Boeing Aircraft Co

Model of the Boeing 757 now under development improved productivity resulting from increased size and higher speed was illustrated in figure 1.

Thus, in an expanding commercial air system, supersonic transports might satisfy a portion of the long-range market and complement subsonic service. The logic for an AST is that at twice the speed of sound it could carry about twice as many passengers per day as subsonic aircraft of equivalent size. As noted previously, the major drawback is the cost of developing an AST that is both economically viable and environmentally acceptable.

If the technological problems and uncertainties concerning fuel availability, fuel price, and noise are resolved, there could be a market for about 400 ASTs through the year 2010, with expected sales of about $50 billion in 1979 dollars. In arriving at this estimate, it was noted that the Concorde, despite its size limitation, has demonstrated both customer appeal and safe supersonic commercial operations. On its North Atlantic runs, the aircraft has operated at an average of 70-percent capacity, even though the fares are up to three times higher than the average coach fares on subsonic aircraft.

If the problem of sonic boom can be solved to eliminate the annoyance on the ground and further technical advances are made to lower total operating costs, there is a greater potential market for a third-generation AST that could fly supersonically over land. Thus, it is possible to regard continuing generic R&D on an AST as a promising direction in the continuing evolution of aircraft technology.

SOCIETAL CONCERNS

For most Americans, the question of pursuing research on a supersonic aircraft was rendered moot by the cancellation of the previous SST program in 1971. The inability of the Concorde to become a paying proposition in terms of aircraft sales can be expected to reinforce public attitudes that further Government support for research in this area is not warranted.

Furthermore, the Government may be subject to criticism for involvement in a program that may lead to eventual development of an aircraft perceived by some as being affordable only by privileged classes. In this connection, there also may be negative reactions to an aircraft that is a high user of energy in an era of rising fuel costs and dwindling energy supplies.

Another unknown that could affect the future of air travel is the continuing revolution in telecommunications. Over the next 30 years, improved electronic devices may make it easier to transmit more data, voice, and picture information and could substitute for many types of travel. At the same time, better electronic communication could also stimulate travel by making more people aware of new opportunities in other places, both for business and recreation. It is too early to say with certainty what the effect of telecommunications will be on future air travel.

The perceived impacts on society of an AST will be extremely important in determining its acceptability. Prospective concerns about ozone depletion, noise, and sonic boom were critical factors in the cancellation of the previous U.S. SST program. Undoubtedly they will continue to be major considerations in decisions on any future U.S. supersonic aircraft program—along with how much a program would cost and the level of Federal involvement in such a program.

STUDY FINDINGS IN BRIEF

In sum, the study of advanced high-speed aircraft has found:

- The long-term prospects for advanced supersonic transports are significant and **real.**
- **The uncertainties are also significant and real. Specifically:**
  —fuel price and availability,
  —noise, and
  —market size.
- **The potential threat from foreign competitors appears tempered by the same uncertainties.**
- Support of a generic R&D program appears appropriate. This would:
  —maintain the option for future development of an AST, and
  —clarify and reduce the technical uncer**tainties, however, it would not shed light on those external factors governing the viability of an AST: the increasing sensitivity of the public to aircraft noise, the price and availability of adequate fuel supplies, and the availability of financing for such a major capital commitment.**
- **If Congress wishes to maintain the U.S. supersonic option, then the existing level of Federal support is not considered adequate to accomplish this.**

ADVANCED HIGH-SPEED AIRCRAFT: THE NEXT 30 YEARS

Air transport technology is entering a new evolutionary phase. Both American and European manufacturers are midway in the development of the next generation of subsonic jetliners, a first step along a path to create more energy-efficient equipment for the air carriers.

The pattern is being established by the Boeing Company's 757 short-range transport and medium-range 767 and in Europe by the Airbus Industrie's A-310, another new medium-range aircraft, all scheduled for introduction into service during 1981 to 1983. **New** long-range aircraft, including derivatives of present models, are expected to be introduced later in the decade by a number of manufacturers.

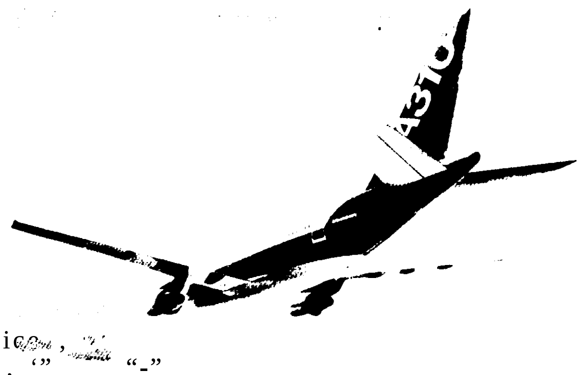


Photo credit. Airbus Industrie

Airbus Industrie's A-310

These new models are incorporating what the industry calls "phased improvements" in technology covering materials, manufacturing techniques, aerodynamics, cockpit automation, and propulsion. The goal is a 15- to 20-percent improvement in fuel efficiency over the decade to offset rising energy costs. Further substantial technological advances are expected in the 1990's and beyond the year 2000.

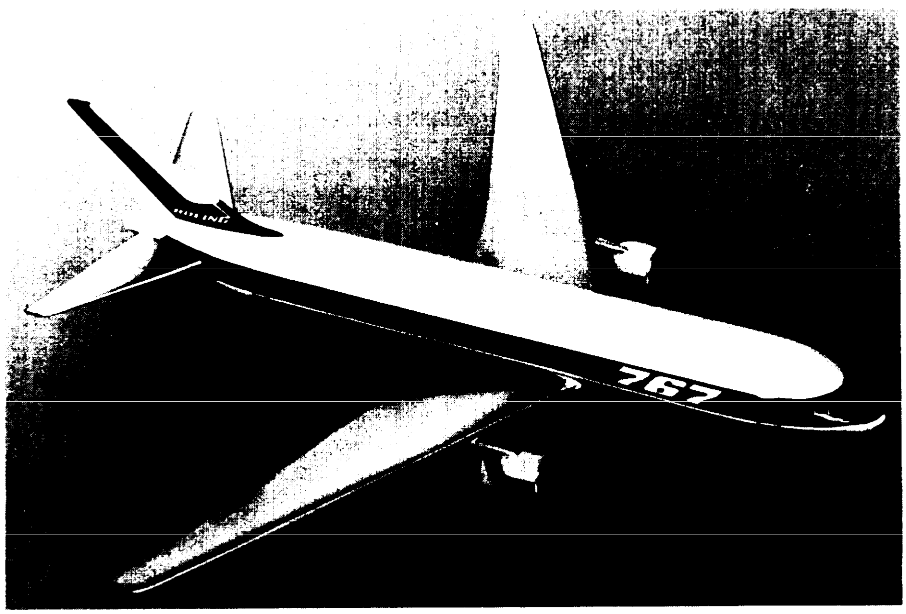


Photo credit: Boeing Aircraft Co

Boeing's 767 medium-range transport

OUTLOOK FOR NEW AIRCRAFT TYPES

Intercontinental versions of these aircraft, designated as advanced subsonic transports (ASUBTs), probably will carry between 200 and 400 passengers, being sized to replace 707s and DC-85, which will be 30 years old by 1990, and to fill market gaps between these early jets and the present generation of widebody aircraft. The range of the ASUBTs will be about the same as the present long-range jets or slightly greater—up to 6,500 nautical miles at cruising speeds of up to 600 mph (Mach 0.85).[1]

[1] J. M. Swihart, *The Boeing New Airplane Family,* paper presented to the American Institute of Aeronautics and Astronautics, 15th annual meeting, Washington, D. C., Feb. 6, 1979.

Under the evolutionary approach, there will be no quantum jump in size or performance, such as occurred with the widebody jets introduced in the early 1970's, to greatly increase productivity (the number of seat-miles generated by an aircraft per unit of time). Instead, the ASUBTs will contain improvements leading toward reduced operating costs. The industry considers it possible over the long run to obtain fuel consumption rates in the ASUBTs that are 20 to 30 percent better per seat-mile than the 2,450 Btu per seat-mile typical of today's widebody jets.

Total operating costs (in constant dollars) could be perhaps 10 to 20 percent below those of

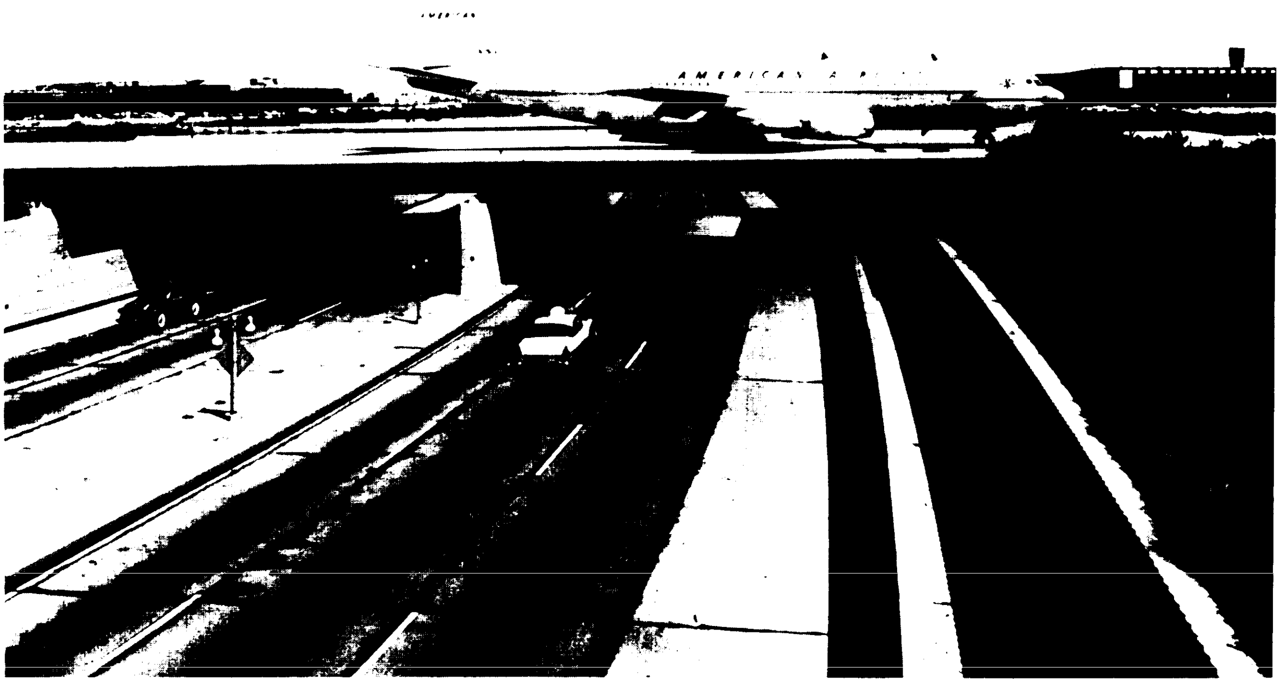


Photo credit: American Airlines

Boeing 707 transport

M D D D

the most efficient aircraft now in service, even with increased fuel prices. High-bypass-ratio engines and noise suppression materials used in inlets and ducts will allow quieter operation over a wide range of power settings to increase environmental acceptance.[23]

Beyond 1990, further development of subsonic aircraft is possible and, therefore, so is the continuation of the trend toward more fuel-efficient, economic, and environmentally acceptable aircraft. These aircraft might be derivations of the ASUBTs introduced in the 1980's or might be of an entirely new design. There is also a possibility that very large advanced aircraft (400 to 800 passengers) will be developed to provide service on high-density transcontinental and transoceanic routes.

The demand for very large aircraft, however, is likely to be restricted because they could be productive only on routes with extremely high passenger travel densities. At present, no estimates are available as to when there will be a sufficient number of high-density routes to warrant undertaking the development of such an aircraft.

A further option would be the development of an advanced supersonic transport (AST), a second-generation aircraft with performance capabilities substantially better than those of the British-French Concorde and the Soviet TU-144. An AST operating at more than twice the speed of sound (Mach 2 +) offers the only remaining path to significantly greater aircraft productivity. It could haul twice the number of passengers as a subsonic airliner of equivalent size in the same time period. There are major questions, however, whether it is possible to create an AST that is both economically viable and *environ*mentally acceptable. These questions are analyzed at length later in this study.

'Ibid., pp. 1, **4-5.**
'OTA Working Paper, Lockheed-California Co., Feb. 5, 1979.

S

Looking beyond an AST to the prospects of hypersonic cruise aircraft coming into commercial service, the consensus of those involved in this study was that it will not happen before 2010. This judgment is based on the present status of knowledge of the hypersonic regime, the time it would take to obtain a state of technology readiness to design such a craft, plus the time needed to go through a development cycle to produce one. Although research has been conducted on problems associated with hypersonic aircraft, the knowledge base is small compared to the status of knowledge in the supersonic area. The technical problems and requirements of a hypersonic transport, although more extensive and severe, do contain all the requirements of a supersonic aircraft. Therefore, it seems reasonable to assume that supersonic technology readiness must be achieved before hypersonic technology readiness and that any decision to leapfrog the supersonic system for a hypersonic aircraft should come after supersonic technology readiness is achieved.

A similar situation exists for suborbital flight. Although technology advances appropriate to this type of flight could come from the National Aeronautics and Space Administration (NASA) space shuttle program, it is doubtful that this technical base could be translated into a suborbital commercial passenger airplane within the **1980-2010** time frame for this study.

As indicated, the consensus decision to delete the hypersonic and suborbital commercial transports from the current study was made on practical considerations. This decision by no means implies that research should not continue in these areas in order to determine the potential of such aircraft.

Illustration' Courtesy of Lockheed Aircraft Corp.

Artist's concept of Lockheed's hypersonic cruise aircraft

WORLD REQUIREMENTS FOR NEW AIRCRAFT

Perhaps one of the more surprising developments during 1979, in view of economic uncertainties, continuing inflation, and an energy supply picture clouded by unrest in Iran and rising oil prices, was the placement of multibillion dollar orders for the 757, **767,** and A-310 by the air carriers. Boeing's sales for the year increased to an unprecedented $12 billion, according to company estimates. Moreover, these orders were booked in the face of an expected U.S. economic recession in 1980 and at a time when the long-range effects of passenger fare deregulation on airline revenues are far from clear.

Underlying the airlines' decision to order hundreds of new planes are projections for continued strong growth in air travel demand. Annual traffic growth has averaged 11 percent since **1977** and hit **15.6** percent in the first half of 1979. While industry analysts expect a recession to hold growth to only 2 percent in 1980, they are forecasting an average annual traffic expansion of 7 percent through 1990.

If air traffic increases by only 6 percent annually on average, passenger-miles over the next 30 years would quadruple. A potential also exists for **a** doubling of present airline route-miles in this period as more areas of the world, such as the Orient, are opened to commercial traffic.

These projections assume that there will be no major disruptions in the growth of the world economy and that the airlines, along with other transportation sectors, will be able to meet their needs for fuel that is becoming increasingly more expensive. If traffic growth holds up, so wiIl the market for new aircraft. Both the aircraft manufacturers and the airlines agree an increase in passenger-carrying capacity already is indicated for mature travel markets over the next decade, particularly for short- to medium-range routes.

Thus, based on current trends and projections, there is a potential market over the 1980-2010 period for 6,500 to 8,500 short- and medium-range aircraft, both additional and replacement. This part of the market could mean sales totaling $235 billion in **1979** dollars. Over the same 30-year period, the potential market for long-range aircraft (more than **2,700** nautical miles) is estimated at 2,200 to 3,300 units with a sales volume of $150 billion. Should a successful AST be developed, it is believed it could capture about one-third of the dollar volume of this market with sales of about 400 aircraft between 1990 and 2010. But many technical problems and other uncertainties need to be overcome in the near term before it is possible to contemplate whether an AST is indeed feasible in all respects.

To gain an appreciation of the magnitude of the difficulties—and the scope of the issues—it is instructive to review briefly the short history of supersonic flight programs in the United States and abroad and to look at where supersonic technology stands today.

BEGINNINGS OF SUPERSONIC TRANSPORT–THE CONCORDE

In the late 1950's, commercial aircraft designers began turning their attention to passenger transports that could add the element of speed to aircraft productivity. In Great Britain and France, studies were initiated independently about 1956 into the feasibility of supersonic passenger aircraft. In the United States, technical feasibility studies were begun slightly later. However, by 1959, NASA was giving serious consideration to a supersonic transport that would be a civilian derivative of the XB-70 bomber which was later canceled.

For the Europeans, the impetus to develop a supersonic transport came from several sources. In Great Britain, it was seen as a way of recouping the loss in prestige and market advantage suffered by the failure of the Comet jet transport. By the time the Comet's problems had been corrected and the aircraft was ready to re-

B

enter service, the U.S. Boeing 707 and DC-8 had built up an unassailable lead. In the words of Sir Cyril Musgrave, permanent secretary of the United Kingdom Aviation Ministry in 1956, "All the major airlines were buying the 707 or the DC-8 and there was no point in developing another subsonic plane. We felt we had to go above the speed of sound, or leave [the market]."[4]

The British aircraft industry had serious doubts about the economic soundness of the supersonic transport proposed at that time. The development costs were estimated to be high, * the market for such an aircraft was uncertain, and the operating cost for a New York-London nonstop flight at Mach 1.2 to 1.8 was projected to be five times greater than the cost of subsonic jets then in service. Designers later increased the speed and capacity of the proposed aircraft, but the industry members of the British Supersonic Transport Aircraft Committee remained skeptical.

While study and debate were going on in Britain, the French Government and aircraft industry were also conducting preliminary studies of a supersonic transport. The French design concept, like the British, was a Mach **2.0, all-aluminum aircraft,** but it had a shorter range and a higher payload intended to serve a European, near Eastern, and African travel market, In France, the impetus for developing such an aircraft came largely from outside the sphere of technology and economics. The French Government was determined to enhance the role of high-technology industries in both the national and the European economy. A supersonic transport was perceived both as a response to "the American Challenge" and as a means to generate the expertise and skills needed to build and sustain a European industry that could compete in high-technology aerospace engineering.

Doubts about development and production costs and about the eventual world market for the aircraft continued to nag the British and the

---

4P. Gillman, "Supersonic Bust: The Story of the Concorde, " *Atlantic, vol.* **239,** January 1977, p. 73.

● Depending on range, speed, and payload, the estimates at that time varied from $165 million to $265 million. These estimates proved to be wildly optimistic—the British Government's final figures on Concorde development costs were **$3.25** billion, shared by Britain and France.

French. In 1960, both began to cast about for ways to lessen cost and to reduce the technological and capital risks. Negotiations between the two governments began in the summer of 1960 and culminated 2 years later in November 1962 with an agreement for a joint effort to build an aircraft appropriately called Concorde. The design team consisted of the British Aircraft Corp. and Sud-Aviation (later reorganized as Aerospatiale), with Bristol-Siddeley and SNECMA providing the engine.

The aircraft that emerged from the joint design effort had a thin, fixed ogee wing and was powered by a "civilianized" version of the Olympus 22R—a then lo-year-old military engine that had been developed by Bristol-Siddeley for the TSR-2 multimission combat plane (which was canceled in 1965 after $532 million had been spent). The Concorde originally was intended to have a payload of 112 to 126 passengers (later reduced to 90 to 100) and a range of 3,500 to 4,000 nautical miles. The speed of the Concorde was limited to Mach 2.2 because of a decision to employ aluminum instead of titanium, which was more difficult and risky to use but would have allowed speeds up to Mach 3.

The cost of the Concorde development program was estimated in 1965 at $400 million and later revised to $770 million, then to $1.26 billion, $1.75 billion, and ultimately $2.63 billion by 1975. The final cost figures quoted by the British Government in 1977 were $3.25 billion for development and $0.85 billion more for production costs and losses sustained in operating the Concorde, making a total program cost of over $4 billion. Sales estimates made at various times during the course of the program varied widely—from 100 to 500—and the projected purchase price fluctuated accordingly, from $30 million to $56 million.[5,6] But only 16 Concordes were built, 2 for testing and 14 for sale; 9 have been sold at a price of $80 million each to the State-owned airlines of the two countries, British Airways and Air France. The Concorde production line was closed in September 1979 and the remaining seven planes were given to the two airlines.

Construction of the first prototype Concorde began in 1965. The first test flight was in March 1969, and the first supersonic flight took place 7 months later in October 1969. Commercial passenger service began in January 1976 with flights from Paris to Rio de Janeiro (via Dakar) by Air France and from London to Bahrain by British Airways. Service from Paris and London to

[5]D. Rodd, "The Concorde Compromise: The Politics of Decision-Making," *Bulletin of the Atomic Scientists*, vol. 34, No. 3, March 1978, p. 47.
[6]Gillman, op. cit., p. 78.

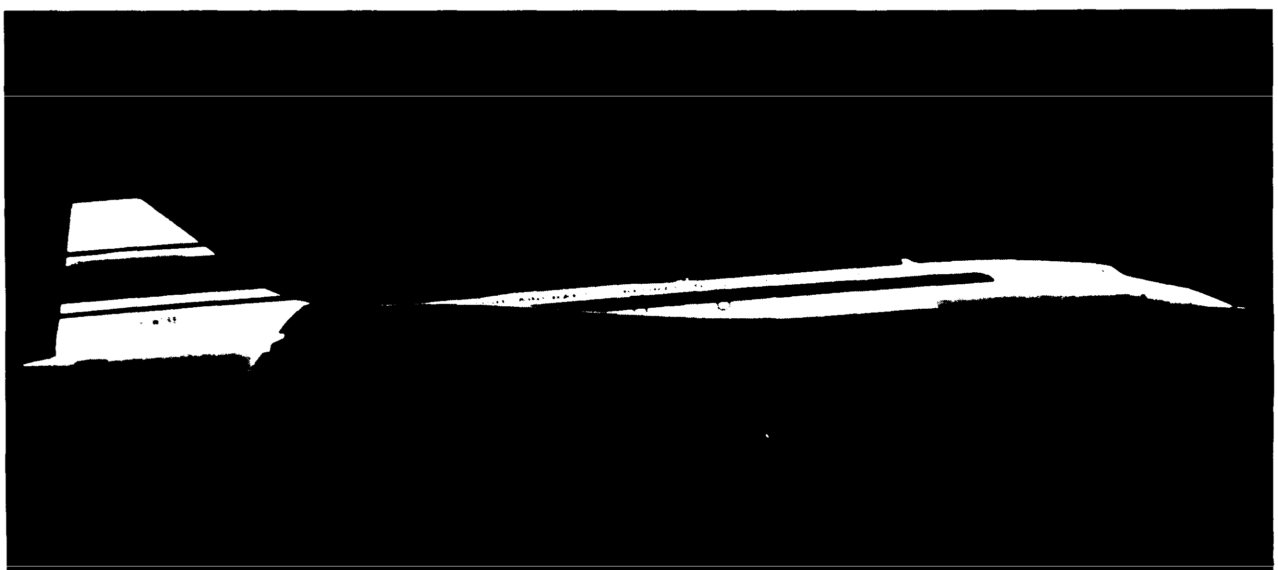


Photo credit: British Aircraft Corp

The Concorde

Washington started on May **24, 1977.**[7] The Concorde now operates on routes from Paris and London to New York, Washington, Caracas (via the Azores), Rio (via Dakar), and Bahrain. The level of service for the two airlines combined was about 110 flights per month for the first year of operation and has risen to about **140** per month since inauguration of flights to New York in December 1977. Load factors for all routes have averaged slightly under **50** percent, but have reached as high as **85** to **90** percent for the North Atlantic routes. g The aircraft presently operates at an average of 70-percent capacity on these routes.

While many feel that the Concorde program proved economically disastrous, several benefits were obtained from it. First, the Concorde showed that an aircraft could be developed and produced which is capable of safe, sustained revenue operations at supersonic speeds. Much has been learned about commercial supersonic aircraft operations which would be extremely beneficial to any future generation of supersonic transports. Secondly, the British and French gained much experience in working together, especially in learning how to manage an advanced technology program with many coordination problems. The Concorde has aided the French in a military regard, specifically in the technology applied to the Mirage series of fighters (Mirage **2000)** which is capable of speeds of Mach 2.5. Last, the project helped preserve and focus the French and British commercial aerospace industry, which has gone on to become a major contender in the world commercial air transport market.

[7]F. Melville, "The Concorde's Disastrous Economics, " *Fortune,* Jan. 30, 1978, p. 67.

[8]P. Sweetman, "Concorde First Passenger Year, " *Flight International,* Feb. 12, 1977, p. 358.

THE AMERICAN SUPERSONIC TRANSPORT (SST) PROGRAM

The official entry of the United States in the supersonic transport competition dates from June 1963 when President John F. Kennedy announced at the commencement exercises of the U.S. Air Force Academy:

> It is my judgment that this Government should immediately commence a new program in partnership with private industry to develop at the earliest practical date the prototype of a commercially successful supersonic transport superior to that being built in **any** other country in the world . . .[9]

Actually, the U.S. interest in an SST began much earlier. The Director of the NASA Office of Advanced Research Programs had testified before the House Committee on Science and Astronautics about the prospects of an SST as early as 1960. [10]

From the outset, the U.S. concept of an SST was shaped by two primary considerations—technological preeminence and economic viability. It was recognized in President Kennedy's speech and specifically stated by NASA and the Federal Aviation Administration (FAA) later that the SST had to be a "better airplane" than the Concorde or the Soviet TU-144 and that "better" meant more advanced technologically and more productive economically. Thus, the initial design concept of the SST called for a 400,0()()-lb titanium airplane capable of flying at Mach 2.7 or faster with a range of at least 4,000 nautical miles and a payload of 125 to 160 passengers. The importance of sonic boom was also recognized, and the FAA request for proposals in August 1963 specified that overpressure could not exceed 2 lb/ft^2 during acceleration and 1.5 lb/ft^2 during supersonic cruise. Further, the SST had to be at least as quiet during approach and takeoff as subsonic jets. [11]

In January 1964, three U.S. aircraft manufacturers submitted design proposals to FAA. The

[9]John F. Kennedy, commencement address, U.S. Air Force Academy, June 5, 1963, in *Public Papers* of *the President,* speech No. 22., cited in M. E. Ames, *Outcome Uncertain:* Science and *the Political Process* (Washington, D. C.: Communications Press, 1978), p. 50.

[10]U.S. Congress, Committee on Science and Astronautics, Special Investigating Subcommittee, *Supersonic Air Transport, Hearings,* May 17, 18, 19, 20, and 24, 1960, 86th Cong., 2d sess. (Washington, D. C.: Government Printing Office, 1960), p. 9.

[11]M.E. Ames, *Outcome Uncertain: Science and the Political Process* (Washington, D. C.: Communications Press, 1978).

Lockheed design theoretically was the fastest, flying at Mach 3.0 with 218 passengers. However, the range of the aircraft was limited. The Lockheed "double delta" wing was designed to provide safe and efficient operation at low speeds while offering good aerodynamic characteristics in the supersonic cruise regime. Boeing proposed a Mach **2.7** aircraft with a small payload of 150 passengers. The unique feature of the aircraft was a variable-sweep wing—developed by Boeing in its unsuccessful bid for the TFX military fighter-bomber—which added mechanical complexity to the design and was perceived as a serious technological risk. North American Aviation, Inc., (now Rockwell International) proposed a commercialized version of the B-70 bomber design, which had a fixed delta wing and a forward stabilizing wing called a canard. The design speed was Mach 2.65 and it carried 187 passengers. Three engine manufacturers—Pratt & Whitney, Curtiss-Wright, and General Electric—proposed various turbojet and turbofan designs, none of which were clearly superior to the others in noise characteristics or efficiency. [12]

The competing aircraft designs were evaluated by the Government and a panel of 10 airlines. None met both the range and payload requirements specified by FAA and none promised to fulfill the general objective that the aircraft be profitable in commercial operation. In May 1964, FAA awarded contracts to Boeing and Lockheed for further airframe design studies and to General Electric and Pratt & Whitney for additional work on the engine. Improvements in three fundamental areas were desired: aerodynamic design (a fixed wing or a variable-sweep wing), engine performance (thrust, fuel efficiency, and noise), and operating economics (payload, range, and commercial profitability). Of these, the economic problem was the most intractable.

In December 1966, after 2½ years of additional design studies and reviews by 3 presidential committees, the National Academy of Sciences, 7 congressional committees, 13 Federal Government agencies and departments, and untold analyses by profit and nonprofit consulting organizations, FAA announced that it was awarding contracts to Boeing to build the airframe and to General Electric to produce the engine. This decision was taken despite the findings of two FAA-sponsored studies—one by the RAND Corp. in 1962 and the other by the Stanford Research Institute—which concluded that there was "no direct economic justification for an SST program."[13] The cost of the program by then had reached **$311 million,** PIUS another $200 million soon to be requested to help finance the construction of two preproduction aircraft. Furthermore, there were major technological problems of range, payload, weight, and engine noise still to be solved.

Why then did the Government (specifically FAA) proceed with the SST program? In part, it was because aircraft designers and Government technical experts presented strong arguments that, given enough money, time, and hard work, the technological problems could be solved. There was some wishful economic thinking, supported by a series of studies commissioned by FAA which raised the market forecast from the original estimates of **25** to **125** aircraft to 500 and eventually to over 800.14 Not to be overlooked was the personal commitment of those in key positions at FAA from 1960 to 1970 —Lt. Gen. Elwood L. Quesada, Najeeb Halaby, Maj. Gen. William F. McKee, Gen. Jewell C. Maxwell, and William M. Magruder. All were publicly avowed proponents of an American SST, and all had had previous involvement with high-technology aerospace programs in military or industrial settings. They never voiced any doubt that the SST could, and should, be built or that it would be technologically and commercially superior to the Concorde and the TU-144.

However, these factors may not have sustained the SST program, if it had not been that the SST had also become a political symbol of the preeminence of U.S. technology. The SST was seen, at that time, as a counterpart to the

[12] 1 bid., p. 59-60.

[13] *Final Report: An Economic Analysis of the Supersonic Transport* (Stanford Research Institute, SRI project No. ISU-4266, August 1963), p. 1.

[14] L. D. Clark, "controversy About Supersonic Transport in the United States, " Miner-m, vol. 12, No. **4, 1974, p. 427.**

Apollo man-on-the-moon program. By failing to keep up with foreign competition the U.S. aircraft industry might lose its leadership in the world market. This argument was advanced in 1962 by FAA Administrator Halaby who listed the consequences of failure to develop an SST as loss of world civil transport leadership, an unfavorable balance-of-payments situation, loss of exports, declining employment in the U.S. aircraft industry, and dependence on foreign sources.[15] Halaby warned that a successful Concorde, with no U.S. equivalent, could "conceivably persuade the President of the United States to fly in a foreign aircraft."[16]

By 1968, after a total of $650 million had been appropriated for the program, the SST was still beset with technological difficulties and political controversy. Boeing announced that the swing-wing design would have to be scrapped on account of its mechanical complexity and the **25** tons it. added to the aircraft weight which affected the range requirements. The redesign to fixed-wing configuration would set back the schedule and raise the development costs of the aircraft. The estimated cost of the overall program, through testing and two preproduction aircraft, had grown to approximately $4.5 billion of which the Government share was about $1.7 billion. The $4.5 billion broke down into: total costs through the prototype of $1.6 billion (of which the Government would supply $1.3 billion); certification cost of $0.8 billion (of which the Government would supply $0.4 billion); and production startup cost of $2.0 billion to $2.5 billion (which the industries would undertake without Government support). The forecasts of sales, return on investment, and operating costs were still not very encouraging.

At about the same time, two new issues emerged that were to prove decisive for the SST program. The first of these was mounting concern about potential environmental and health consequences of a fleet of SSTs. Public reaction to sonic boom tests conducted by FAA convinced Boeing that it would be necessary to restrict supersonic flights by the future SST to over water routes, thus eliminating about one-third of the trips on which the original SST market estimates had been based.

The anticipated noise that the SST would generate over populated areas during takeoff and landing touched off intense public protest. The most heated controversy about environmental impacts, however, centered around the possible changes in the upper atmosphere that might be caused by hundreds of SSTs operating worldwide. Evidence was adduced to show that the water vapor and gaseous emissions released by the SST in the stratosphere could deplete the ozone layer and might lead to irreversible climatic change or an increase in the incidence of skin cancer. There was also concern about possible health hazards to passengers and crew from exposure to cosmic radiation in prolonged and repeated high-altitude flights. These concerns, however, were based on preliminary scientific evidence. They have since been shown to be overblown, but at the time they generated widespread fear of potentially catastrophic environmental damage from the SST.

A second issue which became the subject of public debate centered on the social implications of high technology as represented by the SST. The SST was portrayed by some as an elitist aircraft, financed by taxpayer money for the benefit of a privileged few. It became another object of a growing resistance to technology for its own sake, especially when the costs of that technology were high and its potential consequences for the health and well-being of present and future generations might be harmful. This view was summarized in a New *York Times* editorial:

> The attitude . . . was that technology exists to serve mankind and that proposals to move it ahead at great expense must be judged on the basis of cost-benefit analysis of the widest and most comprehensive sort .. .17

The widening of the debate over the SST to include issues of social goals and priorities was to spell the cancellation of the program. Public discussion about the appropriateness of the SST

[15] M. Horwitch, "The American SST Experience—The Transformation of Multifaceted Technological Enterprises, " working papers for AAAS Symposium, February 1972, p. 5.

[16] N. Halaby, memorandum to President John F. Kennedy, 11/15/62 (JFK Library, President's Office Files), cited in M. Horwitch, loc. cit.

[17] Ames, op. cit. p. 73.

as a technological undertaking for the Nation, coupled with the growing societal concerns and cost, brought the matter to a head in House and Senate votes on fiscal year 1972 appropriations. The cost of the program including preproduction development was $1.6 billion. Design problems for the airframe and engine were still to be solved. The commercial success of the airplane was severely questioned. Fears about environmental effects added fuel to the debate. In March 1971, the House, by a vote of 217 to 203, deleted all SST funds from the Department of Transportation appropriation for fiscal year 1972. An amendment to restore SST funds was defeated in the Senate, 51 to 46. On May 1, 1971, the Senate approved $156 million in termination costs. Thus, after 8 years of R&D and an expenditure of approximately $1 billion, the United States withdrew from the supersonic transport competition.

The total cost of the original SST program through prototype and certification would have been shared by the Government and industry on a 73- and 27-percent basis, respectively. As indicated previously, the production startup cost would have been totally supported by industry. At the same time the program was canceled, 9 U.S. trunk carriers, 2 supplemental, 1 leasing company, and 14 non-U. S. flag carriers had invested $59 million of risk money and $22 million for delivery reservations for 122 U.S. SSTs. The manufacturers had invested approximately $322 million. The program was constructed so that the U.S. Government investment would have been returned on delivery of the 300th production aircraft.

The U.S. SST program did generate a number of technical developments that have contributed to advancing aircraft technology. For example, in the area of aerodynamics, relaxed static stability and variable camber flaps on the wing leading edge were developed and evaluated in the U.S. SST program and have since been applied to the F-16/fighter plane. With regard to human factors technology, various elements in the 747 cockpit are direct descendants of development work on the SST. Other examples include digital displays and advanced navigation systems developed for the SST that are now being incorporated in the 767 aircraft design.

In the structures and materials area, the airframe design problems associated with the SST —more complex than those associated with conventional subsonic designs—prompted the development of more sophisticated and accurate computerized structural design and analysis methods. Methods based on these SST developments are currently employed in the design of advanced subsonic aircraft and are being applied to automotive and other vehicle designs. Also, the work on titanium sandwich structures, formerly conducted concurrently in the SST and 747 programs, contributed to the 747 aircraft and is being applied to military aircraft and missiles. In the propulsion area, the original SST program added substantially to the technology of high-temperature turbines and advanced materials which in turn led directly to improvements in the high-bypass-ratio engines used on most current subsonic transports.

In retrospect, the SST program was probably neither as well-founded an undertaking as its supporters claimed nor as ill-considered as its opponents argued. The goal of the program, in building two preproduction aircraft, was to determine whether a technologically advanced and commercially viable supersonic passenger aircraft could be achieved. The program demonstrated that the technology available at that time would have resulted at best in an economically and environmentally marginal airplane. But it is also true that the technology base was greatly enhanced by the effort and that valuable lessons were learned. However, whatever was achieved was lost from sight in the conflict that led up to cancellation. One of the most important lessons learned is that a genuine and important national interest will have to be clearly identified before any future high-technology large-scale commercial undertaking can expect to receive significant Government support in the future.

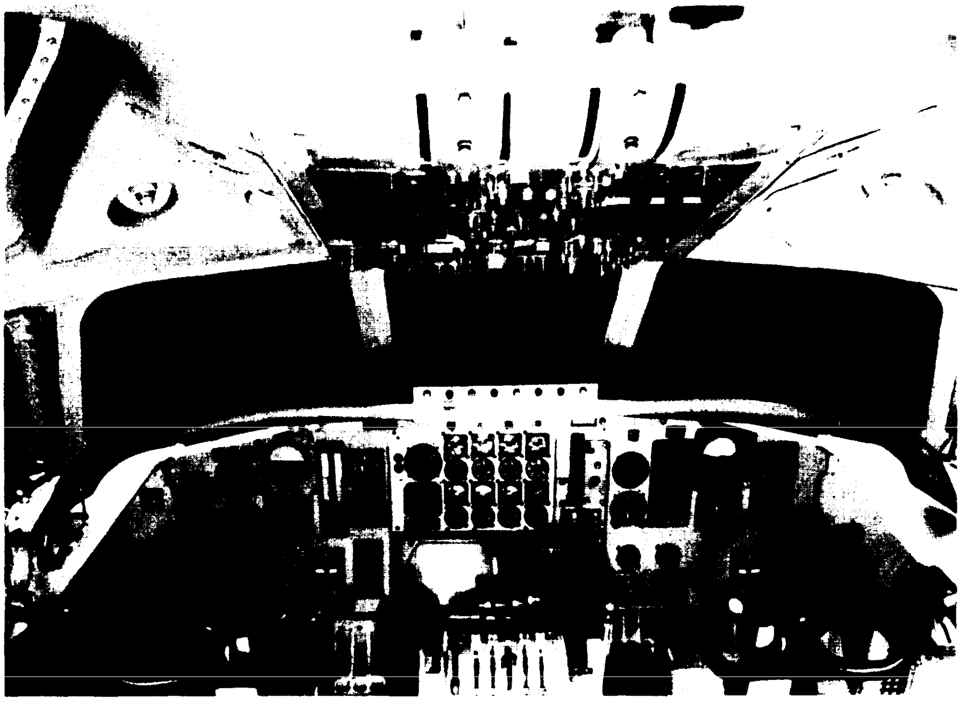


Photo credit National Aeronaut/es and Space Administration

Cockpit of Boeing's 747 aircraft

Photo credit Boeing Aircraft Corp.

Cockpit of Boeing's 767 aircraft now under development

CURRENT STATUS OF SUPERSONIC TECHNOLOGY

Generic research on supersonic cruise aircraft has been continuing at a low funding level since cancellation of the SST program in 1971. Initially, between 1971 and 1973, FAA had responsibility for this research and allotted it a total budget of $15 million, The program was transferred to NASA in 1972 and named the supersonic cruise aircraft research program. In 1979, the name was shortened to the Supersonic Cruise Research (SCR) program. The total appropriation for the NASA program in the fiscal years 1973 through 1979 was $72.9 million, or an average of about **$10** million a year (table 2).

Table 2.—NASA Supersonic Cruise Research Program R&D Expenditures (in millions of dollars; FY 1973.79)

Propulsion	$29.5
Structures and materials	16.7
System integration studies	15.8
Aerodynamics	5.1
Control systems	4.2
Emissions	1.6
Total	$72.9

SOURCE. F. E McLean, Working Paper for OTA, Mar 15, 1979.

Research has concentrated on propulsion, structures, materials, and aircraft and airframe systems technology that might be applied to any AST. At this point in time there are no specific aircraft designs. The results so far indicate that rather impressive improvements over the 20-year-old technology of the Concorde now appear possible. For example, new wing configurations have been tested in wind tunnel tests and have indicated lift-to-drag ratios above 9, which would allow approximately 20-percent more efficient operation than the ratio of the Concorde's wing in supersonic cruise. In the structural area, NASA officials say the most exciting development has been the application of finite-element modeling and advanced computational methods to the design of large aircraft components, allowing for a reduction in design time from 3 months to 1 week. This not only permits rapid analysis of various models but offers promise of lower development costs.

NASA's studies performed with the assistance of aircraft manufacturers show that superplastic forming and concurrent diffusion bonding of titanium may be able to reduce the weight of aircraft structures by 10 to 30 percent and, at the same time, achieve cost savings of more than 50 percent. Various forms of high-temperature polyimide composite structures have been investigated and they show even greater weight-cutting potential.

Variable= Cycle Engine

As seen in table 2, a major portion of the SCR program has been devoted to propulsion technology. These investigations have produced concepts for a variable-cycle engine able to vary the airflow at different power settings. The engine may be able to operate at near optimum fuel efficiency while cruising at either supersonic (turbojet) or subsonic (turbofan) speeds. Because the engine's internal configuration allows the exit nozzle to move and alter the exhaust velocity, it also has potential for reducing sideline noise at takeoff and landing. In addition, an indicated greater combustor efficiency may be able to reduce nitrogen oxide emissions by more than 50 percent, thereby cutting the amount of atmospheric pollution.

Presently within the aerospace industry there is considerable optimism about the engine. Many experts feel that, should the engine prove out in a development and test program, it would bring a second-generation supersonic transport much closer than is generally realized.[18] The engine's promise is twofold:

1. There is a possibility the engine may be able to meet the Federal Aviation Regulation part 36, stage 2 noise rule which was established in 1969.
2. If able to operate optimally at both subsonic and supersonic speeds, the engine would enhance the prospects for integrating an AST into regular airline route

[18] C. Driver, "Advanced Supersonic Technology and Its Implications for the Future, " paper presented to the Atlantic Aeronautical Conference, Williamsburg, Va., Mar. 26-28, 1979.

structures, as opposed to the limited routes flown by the Concorde. For example, it would become possible to originate AST service to London or Tokyo in Chicago, Denver, or Dallas. The over land legs would be flown subsonically and then the AST would switch to supersonic cruise **overseas.** In theory, this extra utility would greatly improve the sales potential for the aircraft. But it still would have higher total operating costs than an advanced subsonic aircraft.

Technology Validation Program

In August 1979, in response to the House Science and Technology Committee, NASA outlined possible plans for technology validation, which were identified as focused initiatives, in a number of aeronautical fields. [19] The completion of generic research in technology validation would be a necessary step in the future development and production of an AST. In supersonic cruise research the plan concentrated on propulsion, airframe, and aircraft systems technology. The propulsion part of the program would be broadened to include research on a variable-flow system and an advanced core engine system that would be integrated with the variable-cycle experimental engine. The aim would be to produce design options for an array of supersonic aircraft applications, plus potential military applications. The airframe technology program would concentrate on nacelle/airframe integration and suppression design methods, and design and high-temperature structures problems, including the selection, fabrication, and testing of titanium and composite materials. The aircraft systems technology effort would identify those portions of the engine and airframe programs requiring inflight investigation and validation. Accomplishment of these objectives would be expected to take up to 8 years and would bring the SCR program through technology validation leading toward "technology readiness, " regarded as a decision point on whether the aerospace industry would consider further development of an AST feasible. There is presently some question whether the aerospace industry on its own would be willing at these decision points to initiate activities leading to full-scale production.

The proposed program would cost **$662** million (1981 dollars) over an 8-year period, as opposed to an alternate program offered by NASA in 1978,[20] which was priced at $561 million (1979 dollars) over a similar 8-year period. In addition, NASA also prepared a $1.9 billion plan (1977 dollars) in 1977 which would have sustained full competition in the U.S. industry and would lead directly to "technology readiness."[21] These three plans have raised a question for Congress as to what is the proper level of Federal support for supersonic research, because any one would mean a substantial increase over the approximately $10 million a year that has been invested in SCR since 1971.

[19] "Potential Future Initiative Directions in NASA Aeronautics Programs, " Office of Aeronautics and Space Technology, National Aeronautics and Space Administration, August 1979.

[20] "A Technology Validation Program Leading to Potential Technology Readiness Options for an Advanced Supersonic Transport, " Office of Aeronautics and Space Technology, National Aeronautics and Space Administration, September **1978.**

[21] "Program Options for Achieving Advanced Supersonic Transport Technology Readiness, " Office of Aeronautics and Space Technology, National Aeronautics and **Space** Administration, September 1977.

PROSPECTIVE ISSUES

The issues surrounding the development of an AST, including the technical difficulties, have been given a considerable amount of study by the aircraft industry both here and abroad. The collective judgment on both sides of the Atlantic appears to be that more intensive generic research is needed to determine whether an AST is technically feasible in view of the environmental objections and economically viable from an energy standpoint.

One question concerns the degree of technical sophistication an AST should achieve. Essentially there are two choices, which are the subject of the analysis in chapters IV and V: 1) a 200-passenger, Mach-2 aluminum aircraft with a design superior to that of the Concorde which could be introduced around 1990 and 2) an advanced titanium aircraft capable of carrying 200 to 400 passengers at speeds of Mach-2.4 or higher at ranges of up to 5,500 nautical miles.

In the United States, the aviation community appears to be persuaded that the more advanced version has the best chance of meeting the demands of the marketplace. There is guarded optimism that, in terms of development costs, operating expense, and market potential, such an AST could be made a commercial success. The technological problems of aerodynamic and engine design, structural materials, and aircraft range and payload are regarded as not insurmountable. It is believed that such effects as noise, emissions, and fuel use can be held within acceptable limits through adequate R&D efforts.

Beyond these concerns there are issues of public policy involving value judgments and allocations of costs and benefits among individuals and segments of society. Energy consumption, environmental effects, costs of the program to the public, and societal benefits have to be addressed in the debate over whether or not the United States should continue to support supersonic research and at what level of funding.

The issues are not new. They were raised in connection with the Concorde and the SST. Back then, proponents emphasized such advantages as contributions to national defense, balance of trade, and the health of the aerospace industry. The arguments against the Concorde and the SST centered on the high cost to taxpayers, noise in the vicinity of airports, sonic boom, air pollution, potential harm to people, and climatic effects because of changes in the upper atmosphere. It can be expected that these issues will arise again in connection with the AST, although perhaps not in the same form or with the same emphasis.

There is also a more comprehensive set of issues to be addressed—issues that concern possible choices between supersonic and subsonic aircraft. Regardless of whether an AST is developed, the world market for advanced subsonic aircraft over the next 30 years is expected to be large, perhaps up to 12,000 aircraft to replace older subsonic aircraft in the fleet and to accommodate the growth in travel demand.[22] Historically, the United States has been the principal supplier of passenger aircraft for the world market (as of 1978, over 80 percent of the passenger aircraft in the free world were of U.S. manufacture), but there is concern about the ability of the U.S. industry to sustain this market supremacy in the face of growing competition from foreign government-industry consortia, such as that producing the A-300 and A-310. This raises a question as to the long-term importance of supersonic technology to a competitive and viable domestic aircraft industry and a favorable balance of trade. An allied issue is the magnitude of U.S. Government support to the aircraft industry in the interest of optimizing the prospects for long-term growth and to maintaining a major U.S. share of the world aircraft market.

[22] OTA Working paper, Working Group A—Advanced High-Speed Aircraft, Boeing Commercial Airplane Co., January 1979.

Photo credits: U.S. Department of Transportation, Federal Aviation Administration

These U.S. manufactured aircraft are serving worldwide fleets

Chapter III

VARIABLES AFFECTING A SUPERSONIC TRANSPORT MARKET

Any supersonic transport that is developed will have to be feasible in economic terms and acceptable from an environmental standpoint. Environmental constraints will definitely enter into the total economic picture, but so will fuel costs, ridership, stage lengths, and other factors. This chapter lays out some of the variables that are involved in projecting the future market for new high-speed aircraft, specifically an advanced supersonic transport (AST). It considers especially how the variables affect the economic viability of the AST relative to a future possible advanced subsonic transport (ASUBT).

The criterion of economic feasibility will be the return on the commercial investment required to bring the aircraft and supporting systems into being. As the early history of the automobile and the airplane witnesses, the first embodiment of a new technology frequently fails to pay for itself. A new technological path cannot be followed for long unless there is promise that along the way the economics will become attractive. It is assumed here that a bright promise for an economically sound and environmentally acceptable system is a prerequisite for pursuing either new subsonic or new supersonic aircraft.

As the historical discussion in chapter 11 brought out, considerations other than long-term economic ones often enter into the decision concerning a long-range technological development program. Some of these, such as national pride, are not economic at all, at least in a strict sense. Others, such as the lobbying of a particular industry, are economic, but not essentially long-sighted. Nonetheless, this study assumes that such considerations will not prevail for long if the program at issue does not make long-run economic sense.

THE PATH TO IMPROVED PRODUCTIVITY

An aircraft's product is seat-miles. Aircraft productivity is usually measured in terms of the seat-miles an aircraft can generate per hour of operation. Two primary ways that productivity can be improved are increased size—moving more seats—and increased speed—moving seats at a faster rate. Other variables affecting productivity are discussed later.

Most major transportation improvements have occurred in a sequence of steps. The first trains, the first cars, the first airplanes all represented a jump—or sometimes only the potential for a jump—in productivity and in service that at first cost too much to attract a broader market. As technology improved in a succession of smaller and diverse steps, vehicle and operating costs came down enough that the gain in productivity eventually yielded an actual decrease in costs.

In the early days of aviation, productivity gains that were derived from changes in aircraft design came from successive improvements in size, range, and speed. However, for over 20 years—since the jet replaced the piston engine—nearly all the gains in aircraft productivity have come from size-related improvements (see figure 1, ch. I). Such improvements have been accompanied by some reductions in vehicle cost and technology-related improvements in operating efficiency. Table 3 shows the historical progression of productivity improvements through increases in size and speed. Size multiplied by cruise speed, labeled "cruise speed seat-miles, " is only a rough index of true productivity because it does not account for time lost at airports.

Table 3.—Progress in Aircraft Productivity

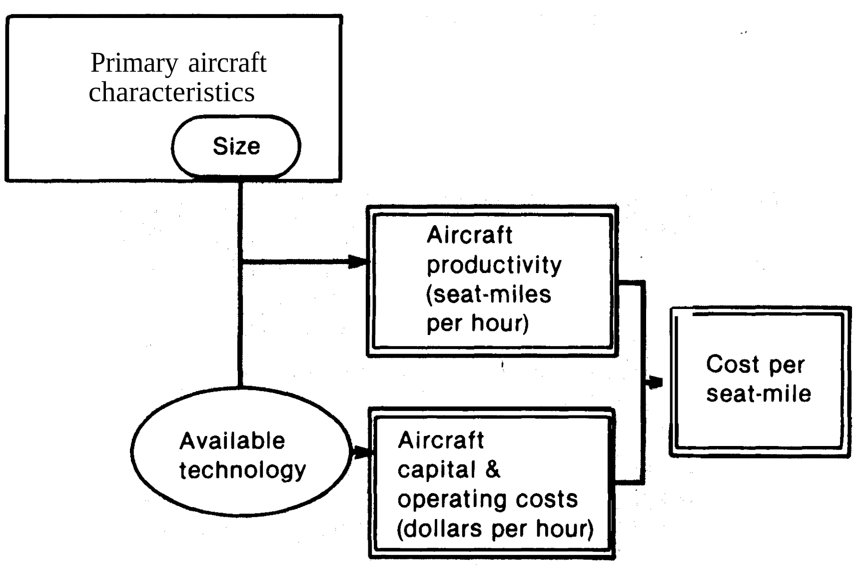
Typical aircraft	Date of introduction	Number of seats	Cruise speed (miles per hour)	Productivity (seat-miles per hour)
Ford Tri-Motor[a]	1926	12	115	1,380
Handley Page[a]	1931	38	127	4,826
Lockheed Orion[a]	1931	6	224	1,344
Douglas DC-2a	1934	14	160	2,240
Douglas DC-3a	1936	21	180	3,780
Convair 240[b]	1948	40	270	10,800
Douglas DC-6...	1948	58	300	17,400
Boeing 707[b]	1958	122	525	64,050
DC-8-61[b]	1967	251	600	150,600
Boeing 747[b]	1970	405	575	232,875
Concorde	1976	90	1,300	117,000
Illustrative AST	?	300	1,600	480,000
Illustrative ASUBT	?	600	575	345,000

SOURCES: [a]Miller & Sawyers, *The Technical Development of* Modern *Aviation*, Praeger, 1970.
[b]Hazard, *Transportation* Management.Econom/cs-Poticy (Cambridge, Mass: Cornell Maritime press, 1977)

The desirability of an improvement in productility depends both on what it costs and on how it is perceived to improve service. Starting with the cost aspect: if doubling the productivity of an aircraft, say, by doubling its size is accompanied by a doubling of what it costs to buy and operate, no net gain in costs per seat-mile has been made. If, however, the cost of increasing size is proportionately less than the productivity gain, then a net reduction in seat-mile costs has been achieved. Such savings have been the motive behind the development of the B-747, the DC-10, the L-1011, and more recently the A-300 aircraft: the cost of size has been proportionately less than the gain in productivity, so costs per seat-mile have come down. These relationships are arrayed in figure 4.

Size-related productivity improvements are still possible, but have less potential than in the past as a means of savings. The 747 is roughly four times the size of the last piston aircraft.

Figure 4.—The Relationship of Aircraft Productivity and Costs



SOURCE: Office of Technology Assessment.

However, comparable gains do not seem likely in the foreseeable future, even if larger aircraft of 600 to 800 seats do come into being, The market for such very large aircraft appears limited because an enormous number of travelers over a given route would be required to keep such aircraft reasonably full and still necessitate frequent enough departures. Furthermore, their size would make them incompatible with current airport facilities. Therefore, the current objective in designing new ASUBTs is not increased size but improved energy efficiency, reduced environmental impact, and better maintenance and reliability. These areas, along with moderate size increases, provide the opportunity for lower cost aircraft.

Other factors affect seat-mile productivity. One is aircraft utilization, the number of hours per day an aircraft is used. A second is stage length, the distance flown between stops. Because short flights involve a larger proportion of total aircraft time spent on the ground, not generating seat-miles, the productivity of short flights is lower than that of longer flights. Extending aircraft range increases productivity because it decreases the number of intermediate stops and thus the time spent on the ground. Today, long-range aircraft are capable of joining all the major cities of the world and, thus, this avenue of productivity improvement is almost entirely exploited.

The rationale underlying a supersonic aircraft is to take advantage of the last remaining path of major productivity improvement—increased speed. Productivity is proportional not simply to cruise speed, but to average speed, because the time lost in airports and on climbout and letdown as well as the demands of route circuity have to be taken into account. As speeds increase from about the Mach 0.8 of subsonic jets to the Mach 2.0 to 2.4 of supersonics, average speed and therefore productivity roughly doubles.[1] Thus, a 300-seat supersonic aircraft could carry as many passengers per day as two 300-seat subsonic aircraft or one 600-seat subsonic aircraft.

[1] E. Q. Bond, E. A. Carroll, and R. A. Flume, *Study of the Impact of Cruise Speed on Scheduling and Productivity of Commercial Transport Aircraft,* NASA report CR-145189, April 1977.

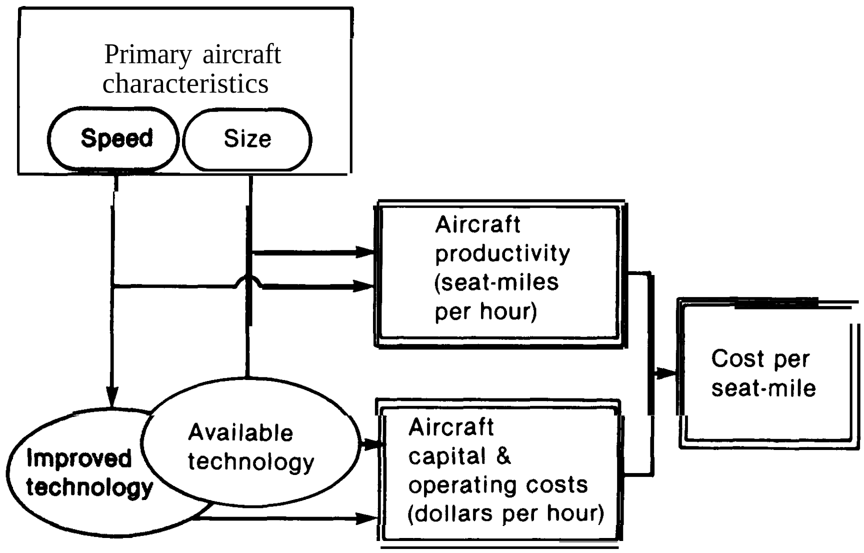
COST OF PRODUCTIVITY FOR SUPERSONIC AIRCRAFT

The uncertainty and controversy over the economics of a supersonic aircraft have never revolved around the issue of its productivity. It is recognized that higher speed will improve productivity, and the degree of improvement is fairly predictable even though it is qualified by other factors such as flight distances and airport turnaround times. The real concern has been the cost associated with obtaining this increased speed. Unlike size increases, which up to a point can usually be achieved with only minor improvements in basic technologies, appreciably higher speeds demand new technological capabilities. Because these capabilities are new, they are expensive and they involve uncertainties.

Figure 5 adds the variable of speed to the relationship arrayed in figure 4. How much the speed costs depends on the state of technology. As the various technologies associated with supersonic cruising flight advance, the cost of building and operating a supersonic transport will come down. As shown in figure 6, the historical experience of subsonic aircraft provides a precedent in this regard.

The first hopes that it might be possible to build a practical supersonic aircraft began to glimmer in the mid-1950's. At the time supersonic flight in military aircraft had been achieved only in dash capability, but anticipated advancements in technology held out the promise of sustained supersonic cruise. The military B-58 achieved limited supersonic cruise capability in the late 1950's. Following an extensive — and, by then current standards, expensive—technical development program, two very high-speed and long-range military supersonic cruise aircraft emerged in the early 1960's: the XB-70 and the SR-71. It is probably safe to conjecture that at this time it would have been technically possible to build a supersonic cruis-

Figure 5.— Influence of Speed on Aircraft Productivity and Costs



SOURCE. Office of Technology Assessment.

ing passenger transport, but at a hopelessly high cost, possibly 5 to 10 times more than the subsonic jets of the day.

During the rest of the decade, technical advancement continued. By 1970, based on the designs produced in the U.S. SST program, the estimated cost of building supersonic aircraft had come down to roughly **3.6** to **4.0** times that of an equivalent subsonic aircraft.[2] Given that the supersonic transport would be roughly twice as productive as the subsonic transport and that indirect operating costs somewhat favored the supersonic, this estimation translated into total operating costs of roughly 1.35 to 1.45 times those of equivalent subsonic aircraft of that period. These higher costs would have implied the need for supersonic fares 1.35 to 1.45 times higher than subsonic fares. Whether these cost estimates were accurate or whether such an aircraft would have been successful in the marketplace is uncertain: there are still strong opinions on both sides of these questions.

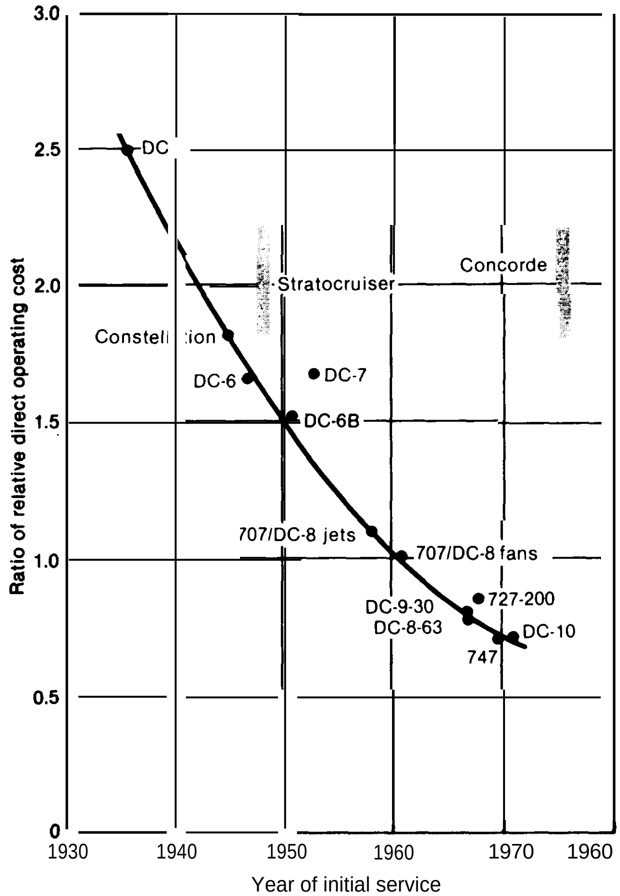
Aerospace industry officials estimate that with reasonably vigorous technology improvement an AST could be built in the late 1980's or early 1990's with the production cost gap narrowed from the 3.6 to 4.0 of the late 1960's to about 2.5 and total operating cost differences from the 1.35 to 1.45 range to perhaps 1.20 to **1.30.**

However, one very important factor stands in the way of further convergence of the costs of the supersonic and subsonic transport. That is the matter of fuel costs. Speed improves the productivity of the capital embodied in the vehicle, the productivity of crew labor, and even the productivity of some of the indirect cost elements such as maintenance labor. But it does not increase the productivity of fuel. It is inevitable that supersonic aircraft will use more fuel per seat-mile than subsonic aircraft. Estimates of the difference vary widely, but a factor of 1.5 to 2 times more fuel per seat-mile for an AST than a present subsonic aircraft seems reasonable. A continuing rise in fuel prices would have a larger impact on supersonic operating costs than on those for a subsonic aircraft (see figure 3, ch. I).

The future availability and price of fuel is an important uncertainty in the future prospects

[2] R. S. Shevell, "Selection of the Fittest: The Evaluation and Future of Transport Aircraft," *Israel Journal of Technology, vol.* **12, 1974,** pp. **1-22.**

Figure 6.- History of DIrect Operating Costs, 1930-75



SOURCE: R. S. Shevell, "Technological Development of Transport Aircraft— Past and Future," *Journal of Aircraft*, American Institute of Aeronautics and Astronautics, vol. 17, February 1980.

for commercial supersonic aircraft. One can probably expect further convergence in the relative costs of building supersonic and equivalent subsonic aircraft because the less well-advanced state of supersonic technology holds more opportunities for improvement than is likely in subsonic technology. For the same reason, one can expect some further improvement in supersonic fuel efficiency. However, it is likely that supersonic fuel efficiency will continue to be substantially lower than subsonic fuel efficiency. As long as this is true, rising fuel costs will cause this element of total operating costs of the two kinds of aircraft to diverge.

THE IMPACT OF QUANTITY

The costs of technological advancement may be quite high and the price of fuel may prove inflexible. The major variable, bearing on both supersonic and subsonic aircraft, that can mitigate these effects will be the number of aircraft built and sold.

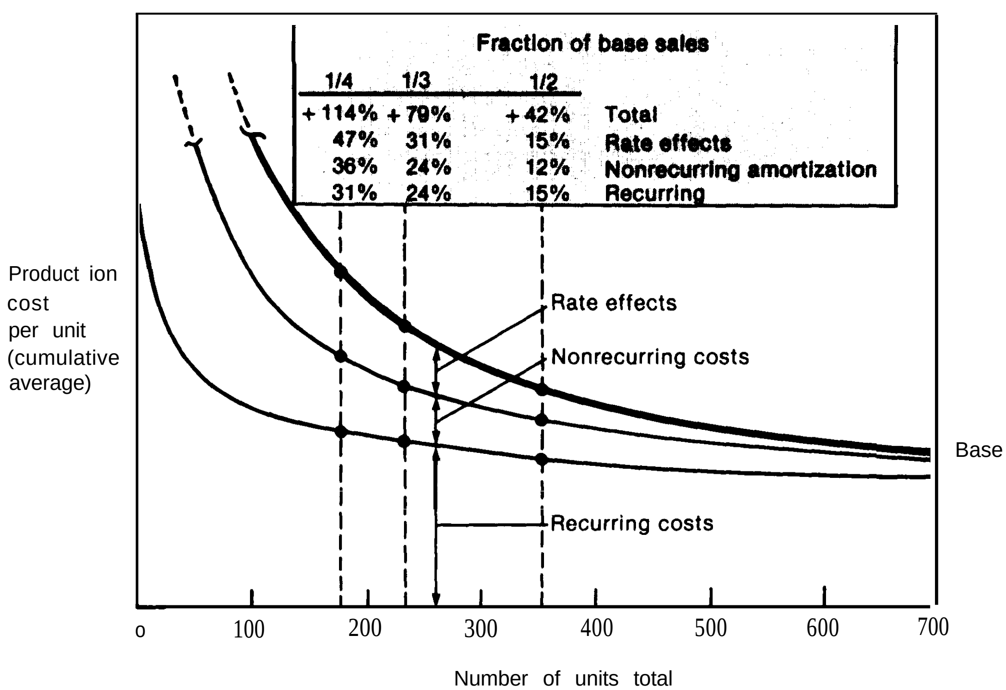
Figure 7 indicates the typical relationship between the cost of an aircraft and the number built. It shows graphically what can happen to costs if an aircraft fails to sell as well as hoped and fewer are built. Such an outcome is a large part of the economic story of the Concorde, production of which halted at 16 aircraft.

Costs decrease with increasing numbers produced for three basic reasons. First, the initial, nonrecurring costs of development, tooling, and facilities are largely independent of the number of aircraft built. These costs are typically absorbed by all the aircraft produced, so the amount allocated to each depends on the number built. Second, there is a learning curve in production, so that recurring production costs come down as more aircraft are built. Third, costs will come down if an optimal production pace is maintained. If aircraft are being built slowly because only a small number are needed and production is extended over a long period of time, the physical facilities and the specialized labor associated with production are not utilized as intensively as they could be and costs rise.

The ultimate cost of an aircraft will depend on the number built, which will depend on the number sold. However, the number sold will depend on their price, which is partially dependent on what they cost. This circular set of relationships is illustrated in figure 8.

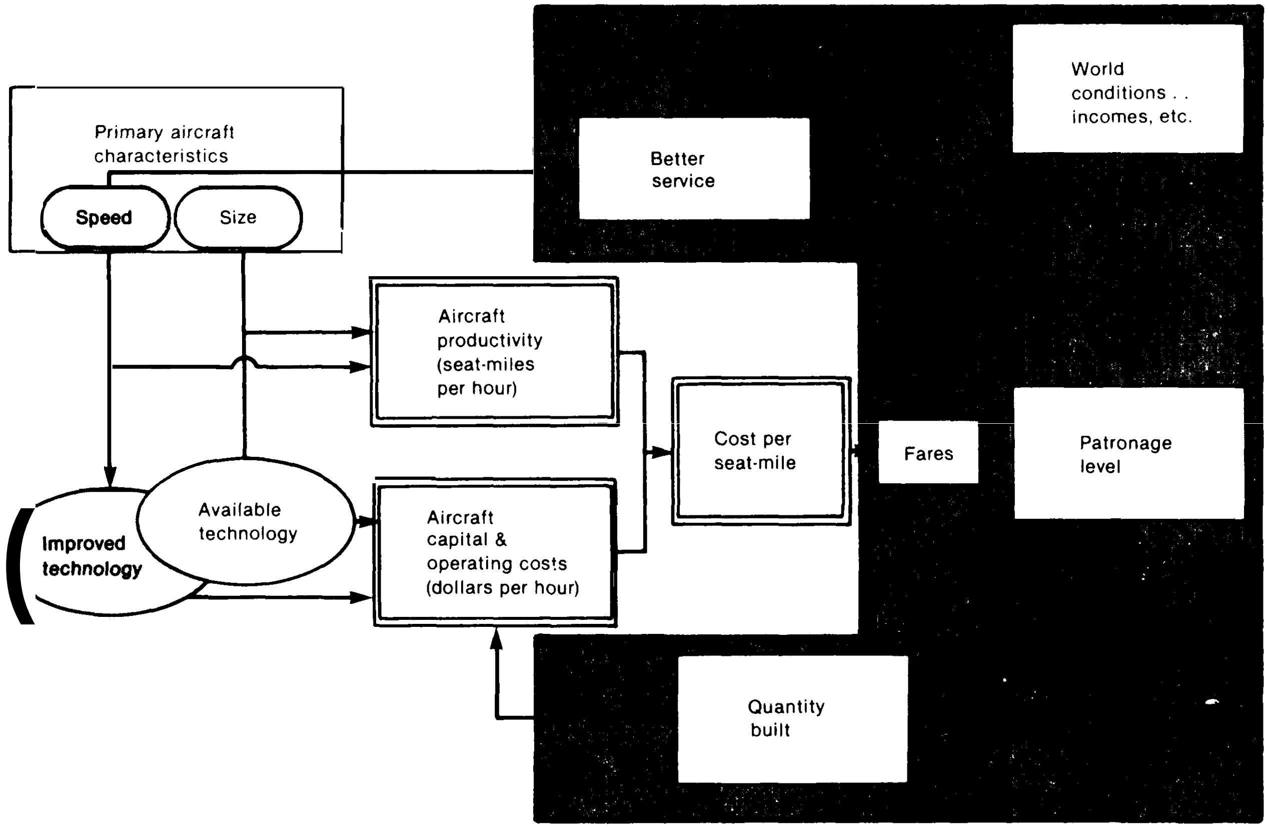
Figure 7.— Influence of Market on Unit Cost

Average unit cost penalties for reduced sales



SOURCE: McDonnell Douglas Corp., Douglas Aircraft Co., Off Ice of Planning,

Figure 8.—Relationship of Aircraft Productivity, Technology, and Costs



SOURCE. Office of Technology Assessment.

THE POTENTIAL MARKET

The number of aircraft built raises the entire issue of the nature and size of the market. Supersonic transportation will thrive only if sufficient patronage can be attracted in competition with alternative subsonic aircraft. The level of patronage is primarily dependent on the fares charged, the incomes of the travelers making the choice, and their perception of the importance of the better service provided by a shorter flight time. Figure 8 illustrates many of these relationships.

Quantifying these relationships so that an estimate can be made of how subsonic and supersonic aircraft will split the market requires hypotheses and assumptions about human behavior. It is assumed here that the choice between subsonic and supersonic service is basically a choice between time and money: supersonic flight will **save** time, but will cost more money. Thus, patronage will depend on how people evaluate the fare difference and the time difference between subsonic and supersonic aircraft. Although there is always a strong motivation to save money, some people will choose the timesaving either because they wish to avoid the discomforts of longer confinement in flight or greater jetlag or because they wish their flight to fit better into the schedule of the business day.

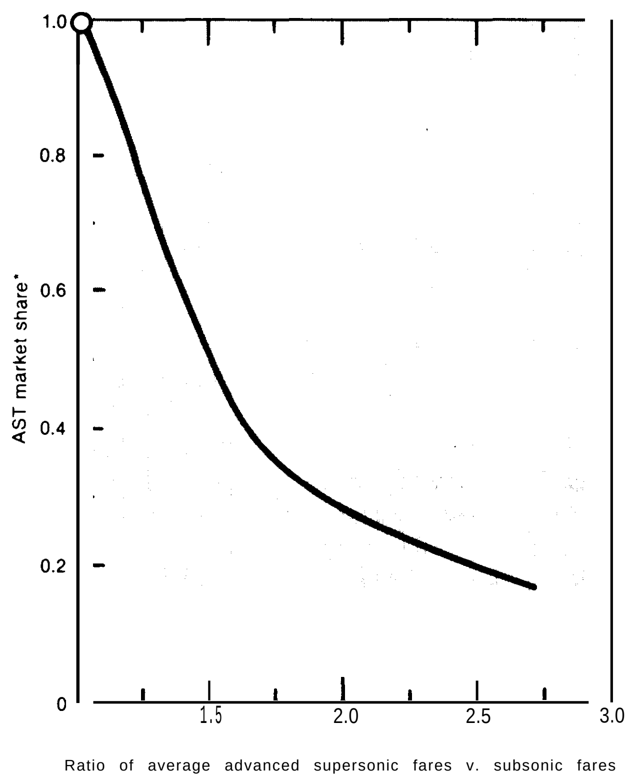
Making quantitative estimates of how many people will choose supersonic service at a given price can be approached in a number of ways. Such estimates may be based on separating potential travelers into different groups based on factors such as income level, purpose of trip, or their typical choice of booking (first-class, full-fare economy, or discount fare). For instance, one approach is to estimate what proportion of first-class, full-fare economy, and discount-fare passengers will choose supersonic service. This approach projects that average revenue per passenger on the AST will be higher than on a subsonic competitor not because different fares are assumed, but because each aircraft carries a different weighted average of the various classes of service.[3]

In order to estimate how future travelers will behave when offered the choice between supersonic or subsonic service, the analyst tries to find past situations where travelers faced dollar-time tradeoffs and deduce from what actually happened how people seem to assign relative value to their time and their money. A common assumption is that an individual's value for time saved varies with income level. This suggests quantifying a traveler's willingness to save time in relation to the traveler's hourly income. A recent analysis[4] used data obtained around 1960 when subsonic jets were still competing with propeller aircraft and from the 1970's on routes where the Concorde competed with subsonic jets to derive the multiple of hourly income that people would pay to save an hour of flight time. This analysis found that, on the average, business travelers would be willing to pay about 2.6 times their hourly income to save one hour of flight time, while nonbusiness travelers would only pay 1.3 times their hourly income.

Such analyses must be interpreted very carefully and recognized as imprecise. Though it may be unsatisfying to use such apparently tenuous reasoning to gauge future markets, such estimates do provide some guides. Their cogency depends on our willingness to assume that the basic logic is correct, that past behavior is a guide to future behavior, that future incomes have been correctly forecast, and that all major variables have been accounted for.

Figure 9 shows the results of an analysis of how a supersonic aircraft could split the market with a subsonic transport for varying fares. The curve applies to the New York-Paris route and to income levels projected for 1995. If we assume real incomes continue to rise, then this curve would shift to the right for points further in the future, i.e., if incomes rise, then for the same relative supersonic-to-subsonic cost ratio, more people would be willing to pay for supersonic. Conversely, such curves for the lower income levels of today would show fewer people selecting supersonic service.

Figure 9.—AST Market Shares, New York-Paris Route in 1995



*Assumes a speed greater than Mach 2.0.

SOURCE: A. Dubin, *Supersonic Transportation Market Penetration Model,* AIAA Conference Paper, Los Angeles, Cal If., August 1978.

[3] R. D. Fitzsimmons, "Testing the Market," *Aeronautics and Astronautics,* July/August 1974.

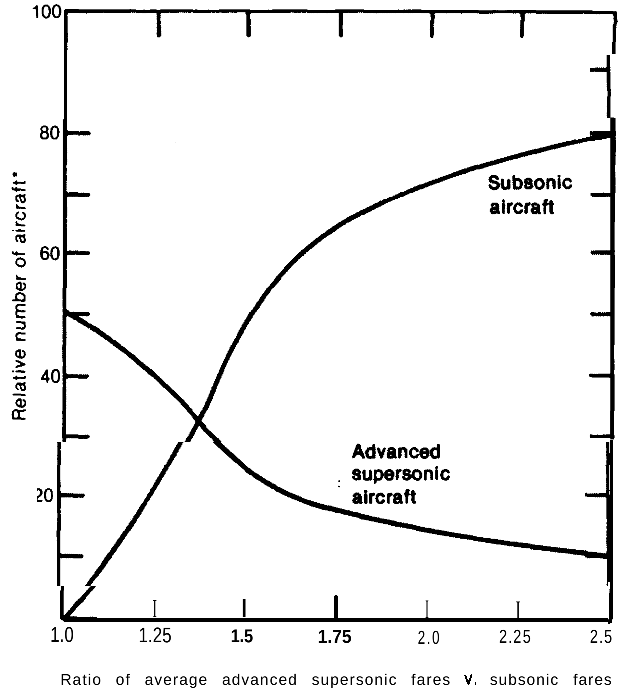
[4] A. Dubin, *Supersonic Transport Market Penetration Model,* presented at the AIAA Conference on Air Transportation: Technical Perspectives and Forecasts, Los Angeles, Calif., August 1978.

While not used in later analyses, this curve, which is drawn simplistically, illustrates how the cost convergence between supersonic and subsonic aircraft will affect patronage. According to figure 9, if the average AST fare were, for example, 75 percent higher than that of a subsonic jet (that is, 1.75 on the curve), then roughly 35 percent of the people would fly the supersonic aircraft and **65** percent would fly the subsonic. This would suggest that, out of 100 total aircraft, 35 would be supersonic and 65 would be subsonic aircraft. However, because an AST would be twice as productive as a subsonic aircraft only half of the 35 ASTs would be required (assuming all the aircraft were the same size). Therefore, only 17 ASTs and 65 subsonic aircraft would be needed to satisfy the given demand. The total of supersonic and subsonic aircraft would be reduced to 82, of which 21 percent would be supersonic. If AST costs could be lowered so that fares were only 25 percent above subsonic (1.25 on the curve), then roughly 80 percent of the travelers would choose the AST: now 66 percent of the aircraft could be supersonic.

By filling in other values, the curves of figure 10 are obtained. These show how the markets for both supersonic and subsonic aircraft change as the net costs (as indicated by fares) of the one aircraft change relative to those of the other. The aircraft are assumed to be otherwise equivalent: the same size and utilization and operating at the same passenger load factor. As AST costs (and therefore fares) approach ASUBT costs, approaching 1.0 on the figure, the shift in the relative AST-ASUBT market accelerates. Because the AST is twice as productive as the ASUBT, one added AST displaces two ASUBT aircraft, so the ASUBT market drops twice as fast as the AST market grows. The number for aircraft in the total fleet also drops correspondingly.

As a final point, the impact of any reduction in the net costs of an AST that might be achievable through improving technology is leveraged by the combined and interacting effects of the expanding market (figures 9 and 10) and the lowering of aircraft purchase costs with increased quantity built (figure 7). For example, if

Figure 10.—Impact of Relative Fares on Fleet Mix, New York-Paris Route in 1995



*Assumes same aircraft size and load factor.

SOURCE: Office of Technology Assessment.

one starts with a 100 AST market at 1.5 times subsonic fares, a reduction of roughly 10 percent of the potential fare brought about by technological advancement can expand the market to roughly 175 aircraft and lower the fares by 17 percent, i.e., to 1.25 times subsonic fare. * This is because of the additional cost reductions derived from the increased quantity built as the market expands. The total cost reduction from R&D (10 percent) and the quantity effect (7 percent) is the 17 percent needed to move from 1.75 to 1.25.

Improving technological capabilities should lower the cost of supersonic flight by a greater percentage than it will lower the cost of sub-

* This calculation is illustrative only and assumes the 30-percent reduction in airplane purchase costs from figure 7 results in a 7-percent reduction in the net costs on which fares are based. This varies with other conditions and costs, but it is a reasonable figure for illustration.

sonic flight. Progressive cost convergency should increasingly expand the supersonic market and shrink the subsonic market. Likewise, a continuation in the rise of incomes would be likely to expand the potential market for supersonic transport. Because prices depend in part on market size, the impact of both technological improvements and rising incomes would tend to allow lower prices and thus a further expansion in the market.

ENERGY UNCERTAINTIES

The major uncertainty and adverse factor for the supersonic market is the cost of fuel, as noted above. Fuel consumption per seat-mile for an AST is estimated to be about twice that of an ASUBT based on current projections and fuel costs are therefore a much larger proportion of total costs for supersonic than for subsonic aircraft. Thus, the general uncertainty about fuel costs in the future is more serious for supersonic aircraft. For example, in one design study comparison, doubling fuel costs over 1976 levels raised the supersonic total operating costs by 33 percent as compared to a 19-percent increase in subsonic costs.

But costs are only part of the question. An aircraft introduced in 1990 would likely be in production in 2005 or 2010, and these aircraft would still be flying in the years between 2025 and 2040. By then, parts of our economy may be based largely on entirely new fuels, say, hydrogen or methane. While the technology—the state of metallurgy, fabrication, aerodynamic knowledge, electronics—to build a supersonic aircraft using hydrogen is not really different from that for a kerosene-fueled aircraft, the specific design is very different. Thus, one of the uncertainties is deciding what fuel should a new supersonic be designed to use. This decision does not have to be made now, but it would have to be before starting a new aircraft program.

STAGE LENGTHS AND ENVIRONMENTAL CONDITIONS

Besides fuel considerations, two other factors are important in evaluating the ultimate potential of the AST and ASUBT markets.

First, stage length—the distance between stops—must be large for the AST to have an advantage over the ASUBT. The productivity of an AST is twice that of an equivalent subsonic aircraft (100-percent advantage) only at ranges beyond about 2,000 nautical miles. As the distance decreases to 1,500 nautical miles, the advantage drops to about 80 percent and, at 1,000 nautical miles, it drops to slightly over 60 percent. The reason subsonic and supersonic productivities converge with decreasing stage length is that the productivity of the higher speed aircraft is penalized more by the time lost in airports and in climbout and letdown. This loss in relative productivity of the AST causes its costs to rise relative to the ASUBT. As the AST's relative advantage in regard to speed decreases, so also does its advantage in regard to service. Thus, it is hard to visualize ASTs competing successfully with less expensive subsonic aircraft on short- or even medium-distance routes (although supersonic planes may sometimes fly these routes as segments of longer trips). As far as can be judged, this portion of the market is secure for subsonic aircraft.

A second constraint on the potential AST market is the sonic boom associated with supersonic flight. It must be assumed that the next supersonic aircraft, like the Concorde today, will be prevented from operating supersonically over inhabited land because of regulations against sonic booms propagated by commercial aircraft over land. This assumption eliminates the AST from contention in the large U.S. coast-to-coast domestic market and equivalent over land markets in other countries and confines its market to international flights over water.

Work has been done indicating the possibility of designing a low-sonic-boom supersonic aircraft at some penalty in operating costs.[5] If an acceptable over land supersonic aircraft could be designed with only a moderate cost penalty, a very much larger market could be realized. For example, the capability of cruising supersonically over land would increase the market potential of an AST and might eventually permit it to replace most long-range subsonic transports. This is another technological "if" that should be researched further and considered in evaluating the long-term potential for supersonic aircraft. Given the potentially large size of this market and the sensitivity of aircraft unit cost to quantity, solving this problem might be of great consequence.

An over land AST would not have the same configuration as the basic over water craft, but it might have many subsystems in common with it. The important point is that the physical phenomena that would permit alleviation of the noise impact of sonic booms have in general been identified and understood, and design principles to exploit them are known and have been partially explored. Further research is needed, although based on what is known today it is not likely such over land derivatives are possible for a next generation of AST.

[5] L. J. Runyon, A. Sigalla, and E. J. Kane, "The Overland Supersonic Transport With Low Sonic Boom—A Feasibility Study," *Acta* Astronautic, vol. 4, 1977, pp. 163-179.

THE COST OF ENVIRONMENTAL ACCEPTABILITY

Noise is now considered to be the principal environmental constraint for either an ASUBT or an AST. Significant upper atmospheric pollution that could decrease the ozone protection against radiation, which was a widely publicized concern a few years ago, is not presently believed to be a problem. Nevertheless, our knowledge is still imperfect, and that issue should remain open.

These and other environmental issues are discussed in chapter VII. However, in this context, it is important to remember that there is a relationship between environmental constraints and economics and therefore the size of the AST market. It now appears that it is possible to build an AST that meets the Federal Aviation Administration's (FAR part 36, stage 2) noise standards for subsonic aircraft at a relatively small penalty in direct operating costs. If noise standards are made much more stringent, however, the costs of meeting them begin to rise much more rapidly unless some better technological approaches to noise suppression are found. The impact of costs on market size has already been illustrated. The direct relationship between the size of the market and the stringency of environmental standards should thus be clear.

PROSPECTS FOR FUTURE LONG-RANGE AIRCRAFT: FIVE SCENARIOS

Historically, the United States has been the leading producer of commercial aircraft in the free world. The U.S. civil aviation industry (manufacturers and airlines) has dominated the free-world aircraft market for the past 40 years. The industry presently provides more than 80 percent of the free-world's transport aircraft. Although the United States has a competitive advantage in the development and production of commercial jet aircraft, this advantage is now being challenged by Western Europe, where consortia, with strong financial backing from governments, are developing advanced aircraft.

Foreign competition is an extremely important issue for national economics and international trade. For example, the dollar value of all commercial jet aircraft and engines produced and sold in the world to date (excluding the U.S.S.R. and the People's Republic of China) has been about **$50** billion. Of this, the U.S. aircraft manufacturers' share has been about $45 billion, or **90** percent. Approximately one-third of this share has consisted of exports, contributing positively to the U.S. balance of trade. In 1977, exports of aircraft and aircraft parts accounted for a net of $7 billion in the U.S. balance of trade.[1] Figure 11, which compares aircraft with other export commodities in 1977, shows this graphically. Over the next 20 to 30 years, the potential sales of long-range aircraft and parts could amount to $150 billion, depending on the market, of which about half could be exports if U.S. firms continue to capture a predominant market share.[2] Exports amounting to as much as $50 billion to $75 billion would contribute substantially to a favorable balance of payments and would partially counteract the negative impact of petroleum imports. The choice to develop or not to develop an advanced transport with a potential payoff as indicated above involves stakes that are quite high.

Assuming that there will be this potentially very remunerative market, the question comes down to what country or countries, if any, will attempt to exploit it and how any country would do so, developing what kind of aircraft on what kind of a time schedule. This study looked at various answers to these questions and attempted to evaluate the risks and advantages associated with several plausible routes by which advanced high-speed aircraft might enter the worldwide commercial aviation market. As already indicated, the key variables in projecting these possibilities for the aircraft future are who will take the lead in developing a supersonic transport; whether development will proceed under noncompetitive, competitive, or cooperative conditions; how sophisticated an aircraft will be developed; and how the development program and introduction into commercial service will be timed.

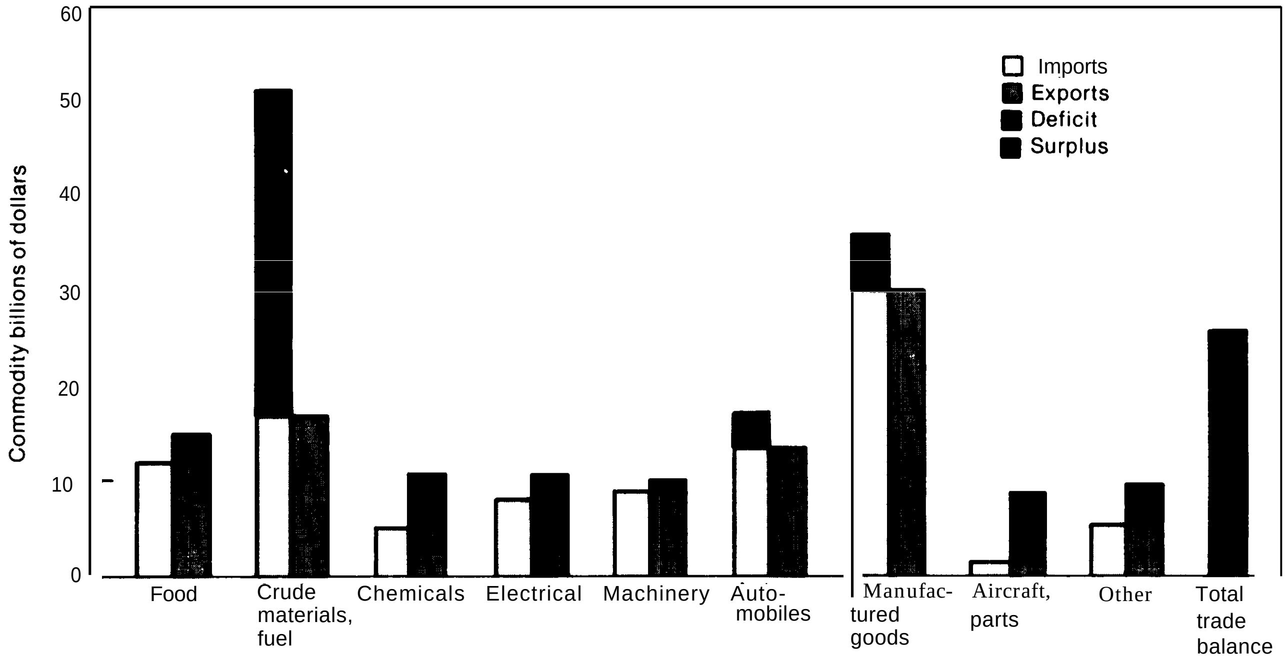
Five plausible futures or scenarios are described in greater detail below. In brief, they are: a base case in which no advanced supersonic transport (AST) is developed by either a U.S. or foreign manufacturer and the world commercial fleet continues to consist virtually entirely of subsonic craft; scenario 1 in which an AST is developed by the United States without foreign competition; scenario 2 in which an AST is developed by foreign manufacturers without U.S. competition; scenario 3 in which both U.S. and foreign manufacturers develop ASTs in competition with each other; and scenario 4 in which a consortium of U.S. and foreign manufacturers undertake joint development of an AST.

---

[1] American Institute of Aeronautics and Astronautics, *Astronautics and Aeronautics,* vol. 15, No. 9, September 1978.

[2] OTA Working Paper, Working Group A, "Advanced Hi@-Speed Aircraft, " Douglas Aircraft Co., Task 5, January 1979.

Figure 11.–Commodity Input to U.S. Balance of Trade–1977



SOURCE: F. E. McLean, OTA Working Paper, "Advanced High Speed Aircraft."

PROJECTED FLEET SIZE

To assess the impact of the AST for each scenario, it was necessary to estimate the size of the subsonic and supersonic aircraft fleet in the period from 1980 to 2010.

In 1978, the world passenger jet fleet included about 4,700 aircraft, ranging from small two-engine standard-body aircraft (e.g., B-737, DC-9) to large three- or four-engine, widebody aircraft (e.g., B-747, DC-10, L-1011). With regard to future aircraft requirements, there have been several recent forecasts of fleet size for various years in the period covered in this study.[3-12] The forecasts range from 7,000 to 12,000 aircraft, depending on the assumed growth rate for air travel and the assumed mix of aircraft types and sizes. The estimated world fleet size used in this study to examine the impact of an AST is based on a review of these studies and on working papers prepared by industry participants in Working Group A.[13-15]

[3] "Studies of the Impact of Advanced Technologies Applied to Supersonic Transport Aircraft," NASA contract No. 11938, Boeing Commercial Airplane Co., April 1973.

[4] "Aviation Futures to the Year 2000," Federal Aviation Administration, February 1977.

[5] R. D. Fitzsimmons, "Market Trends," McDonnell Douglas Corp., November 1976.

[6] E. Q. Bond, E. A. Carroll, and R. A. Flume, "Study of the Impact of Cruise Speed on Scheduling and Productivity of Commercial Transport Aircraft," NASA report No. CR-145189, April 1977.

[7] E. Q. Bond, B. R. Wright, E. A. Carroll, and R. A. Flume, "Impact of Cruise Speed on Productivity of SST's," Jan. 15, 1979.

[8] R. D. Fitzsimmons, "Testing the Market," McDonnell Douglas Corp., August 1974.

[9] A. Dubin, "Supersonic Transport Market Demonstration Model," presented at the AIAA Conference on Air Transportation: Technical Perspectives and Forecasts, Los Angeles, Calif., August 1978.

[10] "Dimensions of Airline Growth," Boeing Commercial Airplane Co., March 1978.

[11] G. G. Kayten, "A View of the Future—Constraints and Opportunities," National Aeronautics and Space Administration, August 1977.

[12] "Potential for Advanced Air Transport —Preliminary Economic and Market Analysis," Working Paper for Impact of Advanced Air Transport Technology Assessment, deButts Associates, Nov. 15, 1978.

[13] OTA working paper, Working Group A, "Advanced High-Speed Aircraft," Boeing Commercial Airplane Co., January 1979.

[14] OTA Working Paper, Working Group A, "Advanced High-Speed Aircraft," Lockheed California Co., January 1979.

[15] OTA Working Paper, Working Group A, "Advanced High-Speed Aircraft," Douglas Aircraft Co., January 1979.

Using the estimate that approximately 8,000 to 9,000 subsonic commercial jet aircraft would be needed to satisfy demand in the period 1980 to 2010, approximately one-fourth of these aircraft (2,000 to 2,200) would then be required to satisfy the long-range travel demand; the remainder would serve the medium- and short-haul markets.

If an AST were introduced, U.S. restrictions on sonic booms would allow it to compete with subsonic aircraft only on long-distance over water routes. On the basis of stage lengths and city pairs appropriate to the AST and assuming that no additional travel would be induced by its introduction, * a market for as many as 300 to 500 ASTs in the world commercial fleet by the year 2010 has been predicted. In examining the impact of the AST below, a round value of 400 ASTs was used.

The AST, because of its speed, would be approximately twice as productive as a subsonic aircraft of equivalent size. Thus, the introduction of 400 ASTs would eliminate the need for 800 to 850 subsonics and advanced subsonics of comparable capacity on long-distance over water routes. Table 4 shows one possible detailed estimate of fleet size and composition by the year 2010, with and without ASTs: ASTs could replace 850 subsonic aircraft, reducing the total subsonic aircraft fleet to about 7,250.

In the scenarios which follow and in the analyses in later chapters, fleet estimates are limited to the portion of the market for which ASTs might compete with subsonics. Thus, the overshadowing effects of short- and medium-haul subsonic aircraft are removed from the analysis and attention is focused sharply on the central question: the impact of the U.S. or foreign manufacturers introducing ASTs into the world fleet during the next 30 years.

*In fact, some travel may be created by the higher speed service of an AST. However, to simplify the analysis, all such induced travel was excluded. The estimated impacts of the AST are, therefore, limited to those that would result from the single substitution of supersonic for subsonic aircraft.

Table 4.—Free-World Commercial Jet Fleet With and Without ASTs—Year 2010

Aircraft type[a]	Passenger seats	World fleet: Without AST	World fleet: With AST	Number of subsonic aircraft replaced by AST
Short and medium haul				
2S	100	150	150	—
3S	130	700	700	—
2S	160	1,200	1,200	—
2W	200	2,000	2,000	—
3W	250	1,550	1,550	—
3W	290	400	400	—
Long haul				
3W	200 LR[b]	150	100	50
3W	250 LR	400	200	200
4W	420 LR	750	350	400
4W	530 LR	500	400	100
4W	600 LR	300	200	100
4AST	330	—	400	—
Totals		8,100	7,250 subsonic 400 supersonic	850

[a]Aircraft are classified by the number of engines (2, 3, or 4) and by body (S= standard, W = wide); AST = advanced supersonic transport.
bLR = seating configuration for long-range flights

SOURCE: OTA Working Paper, Boeing Commercial Airplane Co., Jan 22, 1979.

TYPES OF AIRCRAFT

Constructing the scenarios required a projection of types of aircraft that might be in service from 1980 to 2010. Four possible types were used in the scenarios—one advanced subsonic transport (ASUBT) and three ASTs. Table 5 lists the characteristics of the possible types. The supersonic aircraft are designated AST-I, AST-11, and AST-III in order of their sophistication in technology and performance. However, the designations are not to be regarded as successive generations of supersonic transports. It is assumed that U.S. or foreign manufacturers will each develop at least one model of supersonic aircraft during the period considered in this study, if either develops a supersonic at all. It should also be realized that, as indicated in chapter II, the real choice comes down to a **200-** passenger, Mach-2 aluminum aircraft with a better design than the Concorde (along the lines of the AST-I in the scenarios) or a **200-** to **450-** passenger advanced titanium aircraft to fly at Mach **2.4** or faster (like the AST-III of the scenarios).

In fuel economy and noise characteristics, the ASUBT aircraft are expected to be more advanced than the generation of subsonic aircraft (such as the B-757 and **B-767)** scheduled for introduction by the mid-1980's. The model ASUBTs, used for analysis in the scenarios, would have a range of **3,600** to 5,500 nautical miles and a payload of from 400 to 800 passengers. The ASUBT family could make its first appearance by the late 1980's or early 1990's and, if so, reach full deployment in the world fleet by about 2005.

The three model versions of supersonic aircraft considered in the scenarios vary in speed, range, payload, structural material, and type of engine. They represent a spectrum of technological possibilities, from an advanced Concorde to an advanced Mach 2.4, 300-passenger, titanium aircraft with a range of up to 5,500 nautical miles that might enter service in the mid-1990's. Figure 12 indicates a schedule postulated for the introduction and deployment of the aircraft in the several scenarios. The rationale for the aircraft used in each scenario is provided below.

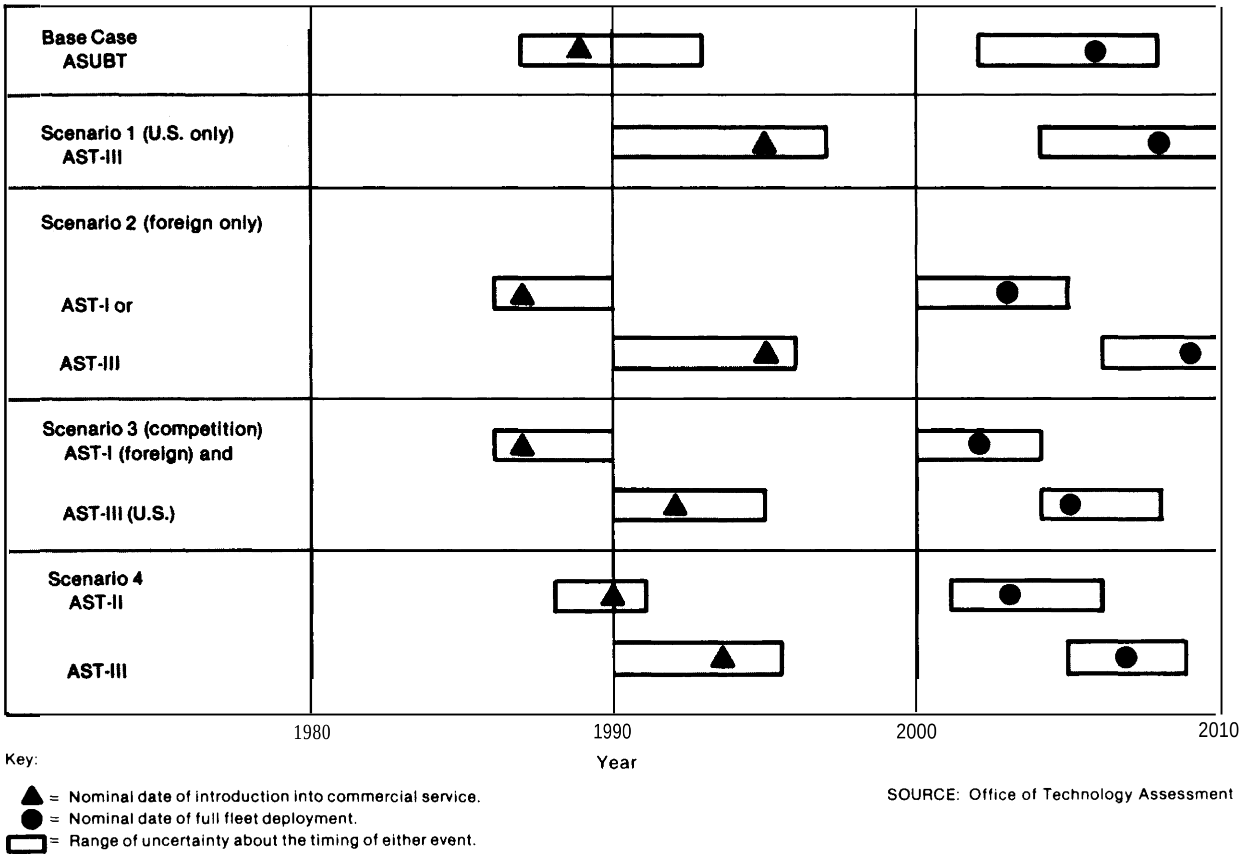
Table 5.—Characteristics of Four Projected Aircraft Types

	Subsonic	Supersonic		
	Advanced subsonic transport (ASUBT)	Advanced Concorde (AST-I)	Advanced supersonic transport-II (AST-II)	Advanced supersonic transport-III (AST-III)
Passengers	400 (600) 800	200	225	200 (300) 450
Design range (nautical miles)	**3,600** to 5,500	4,200	4,800	5,500
Speed (Mach)	0.85	2.0	2.2	2.2 2.4 2.7
Material (primary structure)	Aluminum	Aluminum	Titanium	Titanium
Engine type	Advanced turbofan	Low bypass w/ mechanical suppressor	Low bypass w/ mechanical suppressor	Variable-cycle engine
Noise	Satisfy legal requirements at time of introduction	Stage 2[a]	Stage 2[a]	No more than other comparable aircraft introduced at that time
Sonic boom	NA	← No over land boom →		

[a]At Introduction
( )Nominal value

SOURCE Office of Technology Assessment

Figure 12.—Scenario Timetables



SOURCE: Office of Technology Assessment

SCENARIOS

The base case assumes that there will be no further development of supersonic transport aircraft by either U.S. or foreign manufacturers prior to **2010.** The base case thus serves as a reference for comparing the impacts of other scenarios involving some form of supersonic transport aircraft.

The market in the base case consists of only those **850** subsonic aircraft which, as shown in table 4, would have been competing with or replaced by supersonic transport in the case of the other scenarios. It is assumed that, without any additional supersonic transports (besides the existing Concords), ASUBTs will be developed and introduced into commercial service by the late 1980's or early 1990's with full fleet deployment around 2005.

Scenario 1 projects that the United States is the sole developer of an AST and that the aircraft is an AST-III, the most technologically advanced of the transports considered. It is assumed that, given an orderly development program in the absence of foreign competition, the United States will not elect to undertake to produce an aircraft of lower capability and dimmer economic promise. Thus, this scenario allows the examination of the impact of the United States alone developing the most technologically advanced, economically viable, and environmentally acceptable supersonic transport achievable within the period considered in this study.

The market in scenario 1 consists of 400 AST-111 aircraft that replace 850 of the subsonic aircraft in the base case. Introduction into commercial service is assumed to take place in the mid-1990's, with full deployment around **2005.**

Scenario 2 projects that the United States does not participate in the development of an AST and that foreign manufacturers do develop and introduce it. It is assumed that, depending on how foreign manufacturers exploit the technical advantage of Concorde experience, they will develop either an AST-I or AST-III. This scenario allows the examination of the consequences of a U.S. decision not to become involved in a supersonic transport program.

If the foreign countries elect to develop an AST-III, it is expected that the market will be satisfied by the same number of supersonic aircraft **(400) as** in scenario 1. Because it is anticipated that U.S. airlines will buy some of these AST-IIIs instead of American-built subsonic aircraft, this scenario will involve a significant impact on the U.S. economy. If foreign countries adopt a different strategy—early development of an AST-I based on existing technology in order to solidify their competitive position—the market for aircraft sales will be different. Although it is estimated that there could be a market for perhaps 400 AST-Is, the number of subsonic aircraft replaced by the AST-I will be less than in scenario 1, because the size of the AST-I will be smaller than that of an AST-III.

Scenario 3 examines the possibility of supersonic transports being developed and introduced by U.S. and foreign manufacturers in competition with each other. Given the existing technology bases here and abroad and the differing degrees of readiness to produce a significantly advanced supersonic aircraft, it is assumed that the competition takes the form of a less advanced, foreign-built supersonic aircraft (AST-1) developed rather early (by the late 1980's) pitted against a U.S.-built AST-III introduced about 5 years later. The foreign strategy would be to take advantage of Concorde experience to capture sales that would otherwise go to a more advanced aircraft that will not be available until later. The U.S. strategy would be to attempt to win a large market by the promise of a technologically advanced aircraft with significantly higher productivity and lower operating costs than the foreign-built AST-I available earlier.

This scenario depicts the effects of competition on the market. It is projected that a total of **250** AST-Is and **250** AST-IIIs are sold. Thus, both the U.S. and the foreign participants realize a smaller share of the market than if there is no competition. However, the total supersonic market is larger because there are two versions of supersonic transports available. Nonetheless, the total number of subsonic aircraft replaced by the two versions of supersonic transport is about the same as in the other scenarios—850—because the AST-I is not as productive as the AST-III. Hence, the market share—in terms of passenger trips diverted to supersonic aircraft—does not change significantly even though more supersonic aircraft are in use.

The consortium scenario (scenario 4) assumes that a supersonic transport is developed and introduced into commercial service around **1990** through a joint venture by a consortium of U.S. and foreign manufacturers. The joint effort reduces the economic risk for each party, but at the cost of diminished returns for each because the revenues from sales must be shared. Furthermore, a joint program may cost more than a program run by a single manufacturer as a result of the extra expense of coordinating more than one supplier and utilizing duplicate facilities and production lines.

Two possible consortium scenarios have been projected, one leading to an AST-II and the other leading to an AST-III.

The consortium scenario leading to an AST-II assumes that the United States has pursued only a modest technological advancement program and lacks technology for an AST-III and that the consortium results from foreign initiative. It is projected that the aircraft produced is an AST-11, of a design reflecting the differences in the technological bases of the participants. In range and payload the AST-II falls about midway between the AST-I and the AST-III. It is assumed titanium is used for many structural components and the aircraft has a cruise speed of Mach 2.2.

The market for such an aircraft is estimated at **450,** slightly larger than the market for the AST-111, partly because of the lower productivity of the aircraft and partly because of the stimulation of sales to airlines by the cooperative aspects of the venture. For the purpose of examining one possible joint undertaking, it is assumed that the contribution of each party is determined by its experience and technological capability and, more particularly, that the U.S. share of the program is about **30** percent and the foreign share, the remaining **70** percent. It is assumed these percentages are reflected in sales to world airlines (30 percent to U.S. carriers and 70 percent to foreign ones) and in apportionment of the revenues from sales.[16]

The consortium scenario leading to an AST-111 assumes that the United States has pursued the technology for an AST-III and initiates a consortium effort to help solidify a world market as well as to reduce the financial risk. The ratio of U.S. and foreign contributions is assumed to be **50/50,** although a larger U.S. proportion is possible. Likewise, sales to world airlines and apportionment of sales revenues are assumed to be 50/50.

The AST-III assumed for this scenario is the same aircraft envisioned in scenarios 1, **2,** and 3. However, its introduction is projected as earlier than an AST-III's introduction under a single manufacturing effort (scenarios 1 and 2) and later than an AST-III's introduction under a competitive venture (scenario 3). The rationale behind this projection is that a joint venture would produce the aircraft faster than would one manufacturer but would most likely not be able to produce it as fast as would occur in the competitive situation. However, as shown in figure 12, the projected ranges for introduction and deployment are quite broad.

The market for such an aircraft is estimated to be **400,** the same number used for the AST-III in the other scenarios.

[16] Boeing Commercial Airplane Co., "Prototype Make or Buy," SST Industrial Engineering Planning Group, 1977.

ECONOMIC ISSUES: AN ANALYSIS

Given the several ways in which the world may meet its future needs for advanced, intercontinental air transport, an analysis can now be presented of the economic implications for each scenario described in chapter IV. The aerospace industry has contributed significantly to improving the U.S. balance of trade and, in addiction, the level of employment in the industry is closely associated with the overall economic posture of the United States. Therefore, these two variables are the focus of this economic analysis.

ASSUMPTIONS

Two types of aircraft sales are examined in this analysis—total worldwide program sales by all manufacturers and total sales of U.S. programs alone. The difference between these two has significance for the U.S. economy. If worldwide sales are much larger than U.S. sales, the proportion of U.S. aircraft in the world fleet will be lower and so will be the U.S. aerospace industry's contribution to the balance of trade. In the analysis, the total aircraft sales are determined by multiplying the world market, defined in chapter IV, by the aircraft's selling price; U.S. aircraft sales are determined by multiplying the number of U, S.-manufactured aircraft in the world market by the aircraft's selling price.

As in chapter IV, the world market analyzed for each alternative included only those aircraft, subsonic or supersonic, that would be in competition with, or replaced by, other aircraft for long-range over water routes. Inevitably, other subsonic aircraft in each of the scenarios will be a part of the world market during the period from **1990** to **2010,** but these are not included in this analysis.

A key concern in this analysis was to identify the number of subsonic and/or supersonic aircraft in the world market that would be exported from the United States. The exports would be in addition to the number of U.S. aircraft purchased by U.S. airlines. The amount of U.S. aircraft exports will differ under each scenario.

The base case can be construed in two lights: viewed optimistically, it would involve the United States maintaining the major percentage of the world's market of advanced subsonic transports (ASUBTs); viewed less optimistically, it would assume that, on account of competition from comparable foreign subsonic aircraft, the hold of U.S. manufacturers on the world market of ASUBTs would diminish to about half.

In scenario 1, the assumption, based on the total number of long-range B-7475 and DC-10s exported to date, is that 70 percent of the 400 U.S.-built AST-IIIs in the world market would be exported and the remaining **30** percent would be sold to U.S. airlines.

Because scenario 2 only involves foreign manufacturers, there would be no U.S. exports to consider; on the contrary, to stay in competition, U.S. airlines would need to buy a certain number of foreign supersonic aircraft, the number depending on the type of aircraft produced.

The competitive scenario (scenario 3) assumes that U.S. airlines would initially have to purchase a small number of AST-Is just to remain in the market, but it is assumed that the United States would export 55 percent of the AST-IIIs introduced later.

Scenario 4, the consortium scenario, would allow for two cases. A consortium in which foreign efforts dominate would reduce the amount of both risk and profit, and would also allow only a small number of AST-IIs to be exported by the United States. The U.S.-initiated consortium would develop and produce AST-IIIs, half of which would be U.S. exports.

RESULTS

Based on these assumptions, economic impacts were determined for each scenario. As table **6** reveals, the impact of choices regarding the development of a supersonic transport varies significantly among the scenarios. For example, cash inflow to U.S. manufacturers over the **20** years from 1990 to 2010 ranges from a high of $35 billion, * in the case of the United States alone introducing an AST-III, to a low of – $15.0 billion, in the case of the United States refusing involvement in any supersonic program despite the pursuit of such programs by foreign manufacturers.

U.S. aircraft manufacturer employment (column 9) and total U.S. aerospace employment (column 10) are both functions of total U.S. program sales (column **7):** aircraft manufacturer employment is calculated at the rate of **30** man-years per million dollars of U.S. aircraft sales and total aerospace employment is a multiple of aircraft manufacturer employment by a factor of **2.75.**[1] Cash inflow to U.S. manufacturers (column 11) is determined directly from the U.S. program sales (column 7) and the percent U.S. exports (column 8).

The base case would yield a return to the U.S. manufacturers of from $12.9 billion to $23.1 billion depending on which subsonic strategy is assumed and would produce from **0.77** million to 1.38 million man-years of effort in U.S. aircraft manufacturer employment. The U.S.-only scenario for supersonic transport development would yield a cash flow of $35.0 billion, which is from **50** to **170** percent greater than in the base case.

● A1I dollars are in 1978 values.

[1] R. D. Fitzsimmons, "Civil Aviation Joint Venture Analysis: The Effects of Several Proposed Alternatives, " **1971.**

Table 6.—Economic Impacts

1	2	3	4	5	6	7	8	9	10	11
Alternatives	World market	U.S.-manufactured aircraft	Foreign manufactured aircraft	Selling price per aircraft 1978$ (million)	Total program sales 1978 $ (billion)	Us. program sales 1978 $ (billion)	Percent Us. exports	U.S. aircraft manufacturer employment (million man-yrs)	Total U.S. aerospace employment (million man-yrs)	Cash inflow to U.S. manufacturers 1978$ (billion)
Base case	a. 850 ASUBTs	765	85	$60	$51.0	$45.9	50(385)	1.38	3.79	$23.1
	b. 850 ASUBTs	425	425	60	51.0	25.5	50(215)	0.77	2.10	12.9
Scenario1 (U.S. only)	400 AST-IIIs	400	0	125	50.0	50.0	70(280)	1.5	4.1	35.0
Scenario 2 (foreign only)	400 AST-Is	0	400	90	36.0	0	– 5	0	0	– 1.8
	400 AST-IIIs	0	400	125	50.0	0	-30	0	0	-15.0
Scenario 3 (Competition)	250 AST-Is and	0	250	90	22.5	0	– 5	0	0	– 1.1
	250 AST-IIIs	250	0	125	31.3	31.3	55(138)	0.94	2.6	17.3
Scenario 4 (Consortium)	a. 450 AST-IIs	135	315	110	49.5	14.9	50(68)	0.45	1.2	7.4
	b. 400 AST-IIIs	200	200	125	50.0	25.0	50(100)	0.75	2.1	12,5

SOURCE Office of Technology Assessment

If foreign manufacturers pursued the supersonic market without any U.S. competition (scenario 2), U.S. manufacturers would lose from $1.8 billion to $15.0 billion. The difference in the balance of payments between the U.S. introducing the AST-III and the same aircraft being introduced by foreign manufacturers might be as much as $50 billion. The difference between the case of foreign manufacturers alone developing the AST-III and the case of the United States and foreigners continuing to develop only subsonic aircraft would range from $27.9 billion to $38.1 billion.

In a competitive situation (scenario 3), in which 250 foreign AST-Is and 250 U.S. AST-IIIs are introduced, a total cash inflow to U.S. manufacturers of $17.3 billion would result. The difference in the balance of payments projected for scenario 3 and the base case ranges from – $5.8 billion to + $4.4 billion. The difference for scenario 3 and scenario 1 is $17.7 billion—a reduction of 51 percent. Since the employment difference for the same two scenarios is 38 percent, scenario 1 can be seen to provide a larger return (in terms of cash inflow) for the same investment (in terms of employment) than scenario 3.

In the case of a foreign-initiated consortium producing 450 AST-IIs (scenario 4a), total cash inflow to U.S. manufacturers would be $7.4 billion. Between this scenario and the base case, the balance of payments would differ by a negative $5.5 billion to $15.7 billion. Although this effort would result in the lowest cash inflow to U.S. manufacturers of any scenario involving the United States with the introduction of supersonic aircraft, it also involves the lowest cost and the least risk. It may be unrealistic, however, to assume that U.S. manufacturers would join a consortium in which they would have such a small share of the program.

However, if the United States were to join foreign manufacturers to develop and introduce 400 AST-IIIs, splitting the enterprise equally (scenario 4b), a total cash inflow of $12.5 billion would result to U.S. manufacturers. This would be anywhere from $0.4 billion to $10.6 billion less than the total cash inflow in the base case. Here it was assumed that the United States would build so percent, or 200, of the total world market of 400 AST-IIIs and that, on account of competition with foreign manufacturers, the United States would export to third-world countries 50 percent, or 100, of the U. S.-manufactured aircraft.

Scenario 4b points up the sensitivity of both employment and cash inflow values to variations in the level of participation of U.S. and foreign manufacturers in a consortium. For example, if the share of U.S. involvement were to increase from so to 70 percent and U.S. exports were to remain at so percent, the cash inflow to U.S. manufacturers would increase to $17.5 billion, which is 40 percent more than the $12.5 billion inflow in the so/so program split.

Finally, certain observations must be made to place the values in table 6 in perspective. First and most significant, the future market is uncertain. The economic variables are very sensitive to any changes in the assumptions on which projections have been made. Second, the values assigned for both employment and balance of payments are included within the 20 years from 1990 to 2010. In reality, however, the time frame for aircraft sales, exports, and employment differs for each scenario which affects the present worth of cash inflow over the period covered. Third, these figures focus on only a small portion of the total number of aircraft that will be in operation from 1990 to 2010, omitting consideration of long-haul subsonic aircraft that will not fly strictly over water routes and the entire medium- and short-haul markets.

As previously indicated, when the world requirements for all future long-range aircraft are considered, the expected sales could approach $150 billion. ASTs could command a third of these sales dollars. It should be remembered that the AST considered here was assumed to be restricted to only over water flights, mainly due to the sonic boom. If, as discussed in chapter III, a solution is found to this phenomenon, the market for the AST could expand significantly and a “third generation” AST after 2010 could replace most long-range subsonic aircraft. This occurrence would have a further significant impact on the U.S. balance of trade.

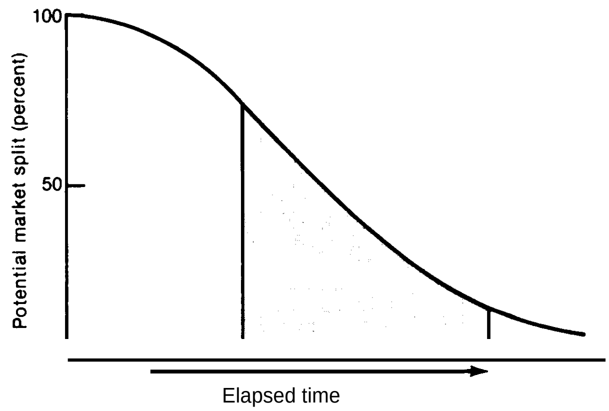
THE EFFECTS OF COMPETITION

In addressing the competitive situation of scenario 3, a significant question is when, if at all, the United States should enter a program of this nature. Two variables are important in this discussion—the aircraft type and the time of introduction. If both manufacturers introduce comparable aircraft into service at the same time, the market will most likely be shared about equally. As the time between introduction of the two aircraft widens, the first aircraft will have a firmer position on the market and an advantage over the competitor.

A second wrinkle enters the competitive situation by adding another variable, a more advanced aircraft, so that competition exists between an AST-III versus an AST-I. If manufacturers of two different aircraft decided to introduce their respective aircraft at the same time, the more advanced aircraft would capture nearly all of the market from the less advanced competitor, provided that the fare structures of the aircraft were similar. (Even if the fare structures were different, some passengers might be willing to pay more to travel in a more advanced aircraft offering them higher speed and greater convenience, including nonstop service.)

However, as the time between introductions widens, an AST-III, introduced after an AST-I, would most likely satisfy a smaller percentage of the market. This is illustrated by the diversion curve in figure 13. In fact, a period would come in which an advanced aircraft (AST-III) introduced by the United States would not be able to attract the market or divert any traffic from that being satisfied by the foreign aircraft (AST-I). Such an immunity of the market to U.S. penetration might occur despite the airlines' knowledge of the imminent introduction of a more advanced supersonic because they might be unwilling to wait the extra time for a more advanced aircraft and so buy a less advanced one. Moreover, having bought a less advanced one, they might not then be in a position to buy the superior aircraft. The key issue here is to be able to determine the time period when it would be inappropriate for the United States to enter the market with an AST-III.

Figure 13.—Time Between Introduction of AST-I and AST-III v. Market Split



SOURCE: Office of Technology Assessment.

One last point is relevant. While program costs influence selling prices, the basic determinant is the market. What are the airlines willing and able to pay? The existence of two competing programs tends to limit the profit potential of both programs because it may force prices below the market potential. On the other hand, lower prices for the aircraft may imply both lower fares for the traveler and increased aircraft sales.

ENERGY: FUEL PRICE AND AVAILABILITY

Of all the uncertainties confronting the future of commercial aviation, the most serious are the future availability and price of fuel. Recent temporary shortages of petroleum have driven up prices and prompted industrial nations to take conservation measures. Total world production of oil is leveling off and is expected to begin declining over the next decade.

If limitations are imposed upon aviation fuel supplies in the future or prices rise too high, the projected growth in air traffic over the next 30 years may not materialize. This, in turn, would restrict any major expansion in the market for new advanced aircraft and significantly affect the prospects for developing an advanced supersonic transport (AST), which would have higher fuel consumption rates than a subsonic jet.

PRESENT FUEL CONSUMPTION

The world now uses about 305 quadrillion Btu (Quads) of energy from all sources each year. The United States consumes about 25 percent of this (or 78 Quads). About half of U.S. energy consumption derives from petroleum. In 1977, the U.S. used 17.5 million barrels per day (MMbbl/d) of petroleum equivalent. Transportation needs accounted for slightly over half this amount, or 9.2 MMbbl/d. Commercial aviation used 0.5 MMbbl/d, 5.4 percent of the transportation figure and 2.9 percent of all petroleum used in the United States. By comparison, private passenger automobiles used about 5.2 MMbbl/d of petroleum in 1977, or 10 times as much as U.S. commercial aviation.[1,2]

The worldwide commercial aviation fleet of about 4,700 jet aircraft (excluding the U.S.S.R. and the People's Republic of China) consumes 1.5 MMbbl/d or 3 percent of the world's daily petroleum use. In the period from 2000 to 2010, utilizing the projections indicated in chapter IV, about 8,100 commercial jet aircraft would be in service. Such a fleet, depending on the fuel efficiency achieved by aircraft at the time, would consume between 3.5 and 4.4 MMbbl/d, or 3.8 to 4.8 percent of daily world petroleum consumption.[3,4] However, according to current predictions, unless the percentage of petroleum fuels available to aviation is increased (perhaps as other energy-consuming sectors convert to alternative sources), world production capabilities will not satisfy these needs. Thus, although these numbers were used to perform an analysis of the impact of supersonic aircraft on energy use, it is unclear where this petroleum will be coming from and whether it actually will be available.

The long-haul portion of the present world market —transcontinental and transoceanic flights with stage lengths of 2,700 to 3,000 nautical miles or more—now consumes approximately 0.2 MMbbl/d or 15 percent of all commercial aviation fuel. Given the projected growth in air travel, long-haul aircraft would use between 0.5 and 0.7 MMbbl/d by 2000-10, again 15 percent of projected total fuel usage by commercial aviation. The portion of the com-

[1]D. B. Shenka, ed., *Transportation Energy Conservation Data Book*, Edition 3, Oak Ridge National Laboratory for the U.S. Department of Energy, ORNL-5493, February 1979.

[2]*Changes in the Future Use and Characteristics of the Automobile Transportation System* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, February 1979), vol. I, OTA-T-83, p. 6.

[3]OTA Working Paper, Boeing Commercial *Airplane Co.*, March 1979.

[4]OTA Working Paper, Pratt and Whitney Engine Co., Jan. 17, 1979.

mercial jet fleet now serving long-haul routes is about 33 percent, a percentage expected to diminish to about 25 percent by the period 2000-10. Table 7 compares present and projected commercial air service and fuel consumption.

Table 7.—Present and Projected Commercial Air Service and Fuel Consumption

Commercial fleet[a]	1976	2000-2010
Short and medium range	3,200 (67%)	6,000 (74%)
Long range	1,500 (33%)	2,100 (26%)
Total	4,700	8,100
Route air miles (billion)[b]	5.05	10.7
Available seat-miles (billion)[b]	798.5	3,170
Revenue passenger miles (billion)[b]	463.1	2,150
Load factor	58%	67%
Weekly departures		
Short and medium range	130,400 (840/o)	220,600 (870/o)
Long range	24,800 (16%)	32,700 (13%)
Total	155,200	253,300
Fuel consumption (MMbbl/d)		
Short and medium range	1.3 (85%)	3.0- 3.7 (85%)
Long range	0.2 (15!40)	0.5- 0.7 (15YO)
Total	1.5	3.5 4.4

MMbbl/d = millions of barrels per day.
a Base case, subsonic aircraft only.
b Scheduled air carriers plus charter.

SOURCE: OTA Working Paper, Boeing Commercial Airplane Co., Working Group A, "Advanced High-Speed Aircraft," January 1979.

FUEL PRICE EFFECTS

The rise in fuel price since 1974 has intensified the importance of fuel economy in commercial aviation. The price of jet fuel has dramatically increased since 1974 to over $1.00 per gallon in early 1980. The continuing rise in jet fuel prices is cited as a major cause for the 6- to 8-percent increase in airfares observed by the end of 1979. Opinion varies about what will happen to the price of petroleum in both the short and long run, making analysis of possible impacts extremely difficult.

Rising fuel prices have particular effects on prospects for supersonic transport. Although it can be shown that, through technological improvements, total operating costs (TOC) for a supersonic aircraft may continue to converge over time with those for a subsonic aircraft (see figure 2, ch. I), such a convergence would be threatened by rising fuel prices. The supersonic aircraft is more sensitive to fuel price increases because it uses more fuel than a subsonic aircraft of the same size.

Thus, a key factor in assessing the feasibility of supersonic aircraft is fuel efficiency. * Fuel

*For purposes of this analysis fuel efficiency is generally expressed in Btu per seat-mile, although in actual airline service a more appropriate measure is Btu per passenger-mile, a function of attained load factor and design efficiency. However, to eliminate having to guess future airline passenger patronage and thus simplify the later analysis, all comparisons are made in terms of Btu per seat-mile, which is a measure of the fuel efficiency designed into an aircraft.

adds weight, so that the more fuel an aircraft of given size and range requires, the smaller the payload. Reduced payload results in reduced productivity, as does inefficient fuel use (say, on account of wasteful operational procedures). The amount and cost of fuel consumed per seat-mile bear directly on operating costs and, hence, on an aircraft's profitability in airline service.

Most commercial aircraft introduced during the past **40** years have been successful, in part, because they offered greater fuel efficiency per seat-mile than older aircraft they replaced. For example, the latest generation of passenger jets (B-747, DC-10, L-1011) are about 30 percent more fuel efficient than the first generation of passenger jets (B-707, DC-8).[5 6] One of the major operational disadvantages of the Concorde is its high fuel consumption in comparison with that of competing subsonic aircraft. Assuming a full load for each aircraft, the Concorde obtains **15.8** passenger-miles per gallon of fuel, compared to 33.3 for the B-707, 44.4 for the DC-8-61, 46.3 for the B-747, and **53.6** for the DC-10.[7]

5A. B. Rose, "Energy Intensity and Related Parameters of Selected Transportation Modes: Passenger Movements, " Oak Ridge National Laboratory for the U.S. Department of Energy, ORNL-5506, January 1979.

[6]J. M. Swihart, *The Boeing New Airplane Family*, paper presented to AIAA 15th annual meeting, Washington, D. C., Feb, 6, 1979, pp. 3-6.

'*Secretary Decision 0) 1 Concorde Supersonic Transport* (Washington, D. C.: U. S. Department of Transportation, Feb. 4, 1979), p. 29.

COMPARATIVE FUEL EFFICIENCY

Estimates of the technological improvements possible for supersonic aircraft vary widely. Projections for fuel usage per seat-mile range from a low of 1.2 to a high of 2.0 times that of present subsonic aircraft. However, supersonics of the future would likely be competing not with present subsonics but the advanced and more fuel-efficient versions of the subsonics, using **20** to **30** percent less fuel per seat-mile than current subsonics.

These estimates are reflected in table **8,** which shows fuel-efficiency values that might be attainable by each of the ASTs considered in this assessment. For the AST-III, the table indicates high, medium, and low fuel-efficiency values based on the possible technological improvements. In the interest of simplifying the analysis of energy impacts, the later comparison of fuel usage in each scenario will be based on single-point estimates. These assumed values must be regarded with caution since they may vary by as much as **25** to **50** percent. Where this variance has a particularly important influence on the outcome of the analysis, the reader will be reminded again of the magnitude of the uncertainty.

Given the projected fuel efficiencies arrayed in table **8,** it is possible to assess the impact of the several scenarios described in chapter IV with regard to fuel use. Four assumptions are made in this analysis. First, for all comparisons, it is assumed that 75 percent of the world fleet will operate on short- and medium-haul routes and, thus, that the AST will be in competition with, and replace some portion of, the **25** percent of the fleet operating at stage lengths of 2,700 nautical miles or *longer*. Second, it is assumed that short- and medium-haul aircraft will consume **85** percent (3.7 MMbbl/d) of the fuel estimated in the base case for an all subsonic fleet. Third, it is assumed that the AST will capture a 40-percent share of the long-haul travel market, i.e., **400** ASTs will replace 850 long-haul subsonic aircraft as discussed in chapter **IV.**

The fourth assumption is that the AST will be competing against and replacing a 300-passenger advanced subsonic transport (ASUBT), that is, an aircraft with a seating capacity equivalent to the AST-III. In reality, the ASTs will be replacing less efficient, older subsonic aircraft of various sizes rather than the more efficient

Table 8.—Estimated Fuel Efficiency of Advanced Subsonic and Supersonic Aircraft

Parameters	Present subsonics[a]	ASUBT	Concorde	AST-I	AST-II	AST-III
Passengers	200-400	400-800	100	200	225	300
Maximum range (rim)	5,000	5,500	3,200	4,200	4,800	5,500
Speed (Mach)	0.85	0.85	2.0	2.0	2.2	2.4
Fuel-efficiency						
Btu/seat-mile	2,450	1,700[b]	6,000	4,900	4,400	2,900 3,900 4,900
Load factor	58%	67%	60%	67%	67%	67%
Btu/passenger mile	4,225	2,550	10,000	7,350	6,600	5,850 4,350 7,350
Relative fuel-efficiency (per seat-mile)						
v. present subsonics[a]	1	0.70[b]	2.45	2.0	1.8	1.2 1.6 2.0
v. ASUBT	1.4	1	3.5	2.9	2.6	1.7 2.3 2.9
v. Concorde	0.4	0.28	1	0.8	0.75	0.5 0.65 0.8

[a]B-747, DC-10, L-1011.
[b]Upper bound of a 20- to 30-percent improvement in ASUBT fuel efficiency

SOURCES: Present aircraft: A. B. Rose, *Energy Intensity and Related Parameters of Selected Transportation Modes,* U.S. Department of Energy, ORNL-5506, January 1979 Projections: OTA, Working Group A.

ASUBTs. However, this assumption allows a comparison of the AST scenarios with the base case in which, assuming no ASTs were built, **850** ASUBTs would be produced. The last assumption represents a major simplification. Some of today's aircraft can carry 400 passengers, and it is projected by some that subsonic transports with a seating capacity of up to 800 may be developed for use on high-density, long-haul routes by **2010.** Eliminating such very large aircraft from the analysis allows direct comparison of subsonic and supersonic aircraft fuel usage, without the confounding but significant effect of productivity differences arising from size as well as speed differences.

ANALYSIS OF ENERGY IMPACTS

Scenario 1 envisions the operation in 2010 of 400 U.S.-built AST-IIIs, which would replace 850 of the long-haul subsonic fleet projected for the base case and so reduce this fleet from 2,100 to 1,250 aircraft. Thus, the split in the long-haul market would be **60** percent for the subsonic and 40 percent for the supersonic. The fuel efficiencies of the ASUBT and the AST-III are estimated to be, respectively, 1,700 Btu and 2,900 to 4,900 Btu per seat-mile. The AST-III would therefore use between 1.7 and 2.9 times more fuel per seat-mile than the ASUBT. Table 9 shows fuel consumption increases over the base case if scenario 1 eventuates. (The fuel efficiency of the ASUBT is based on a 30-percent decrease in fuel usage over the present subsonics. If there is only a 20-percent decrease, the AST-III would use 1.5 to 2.5 times more fuel per seat-mile than the ASUBT.)

In scenario 2, the United States would refrain from an AST program, but foreign manufacturers would develop and introduce a version of a supersonic aircraft by 2010. If they were to develop an aircraft roughly equivalent to an AST-111, the effect of this scenario on the energy situ-

Table 9.—Energy Impacts of AST-III: Scenario 1

Fuel consumption	Base case	Scenario 1: AST-III fuel efficiency High	Medium	Low
Short and medium range (MMbbl/d)	3.74	3.74	3.74	3.74
Long range (MMbbl/d)	0.66	0.84	1.00	1.15
Increase over base case (MMbbl/d)	–	0.18	0.34	0.49
Percent of increase	—	+ 27%	+ 50%	+ 75%
All commercial aviation (MMbbl/d)	4.40	4.58	4.74	4.89
Percent of increase	—	+ 40/0	+ 8%	+ 11%
Percent of increase in world petroleum use	—	+ 0.2%	+ 0.30/0	+ 0.5%

MM bbl/d = millions of barrels per day
Assumptions:
1 Short- and medium-range aircraft make up 75 percent of the fleet and use 85 percent of the fuel in the base case
2 Base case fleet = 6,000 short- and medium.range and 2,100 long-range subsonics.
3 Scenario 1 fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 400 AST-III.
4 Long. range subsonic fuel efficiency = 1,700 Btu/seat.mile
5 AST-III fuel efficiency (Btu/seat-mile). High = 2,900, Medium = 3,900; Low = 4,900
6 Long. range subsonic and AST-III are 300-passenger aircraft

SOURCE Off Ice of Technology Assessment

ation would be identical to that projected for scenario 1. If the foreign manufacturers were to develop an AST-I, the impact on the energy situation would probably be somewhat less because in reality fewer aircraft may be sold. The effect also would be minimal because the AST-I would be less fuel efficient than the AST-III; however, detailed estimates for this case have not been calculated.

Competition in the supersonic market (scenario 3) would result, according to our assumptions, in a foreign-built AST-I introduced in the late 1980’s and a U.S.-built AST-III introduced **5** to 7 years later. It is calculated that by **2010, 1,250** ASUBTs, **250** AST-Is, and **250** AST-IIIs would be in service. The assumed fuel efficiency of the AST-I is 4,900 Btu per seat-mile and that of the AST-III 2,900 to 4,900 Btu per seat-mile (3,900 Btu per seat-mile was estimated for simplicity in this analysis). Assuming an ASUBT fuel efficiency of 1,700 Btu per seat-mile, the ratios of the fuel efficiencies of the supersonics to the fuel-efficiency of the ASUBT would be, for the AST-I, 2.9 and, for the AST-III, 2.3. Table 10 shows the increases in fuel consumption over the base case if scenario 3 were to occur.

Scenario 4 projects a joint program by U.S. and foreign manufacturers resulting in the introduction of either an AST-II in **1990** (scenario 4a) or an AST-III in the mid-1990’s (scenario 4b). Scenario 4a estimates that by 2010, 450 AST-IIs are in operation replacing 850 long-haul

Table 10.—Energy Impacts of AST-I and AST-III: Scenario 3

Fuel consumption	Base case	Scenario 3: fuel efficiency All aircraft	AST-I port ion	AST-III port ion
Short and medium range (MMbbl/d)	3.74	3.74	—	—
Long range (MMbbl/d)	0.66	1.06	0.30	0.36
Increase over base case (MMbbl/d)	–	0.40	0.20	0.20
Percent of increase	—	+ 61 %.	+ 30%	+ 30%
All commercial aviation (MMbbl/d)	4.40	4.80	—	.
Percent of increase	—	+ 9%	+ 4.50/o	+ 4.5%
Percent of increase in world petroleum use	—	+ 0.4%	+ 0.2%	+ 0.2%

MMbbl/d = millions of barrels per day
Assumptions.
1. Short- and medium-range aircraft make up *75* percent of the fleet and use 85 percent of the fuel in the base case,
2 Base case fleet = 6,000 short- and medium-range and 2,100 long-range subsonics.
3. Scenario 3 fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, 250 AST-I, and 250 AST-III.
4. Long-range subsonic fuel efficiency = 1,700 Btu/seat.mile
5 AST-I fuel efficiency = 4,900 Btu/seat-mile, AST-III fuel efficiency = 3,900 Btu/seat.mile
6. Long. range subsonic and AST-III are 300-passenger aircraft, AST-I IS a 200-passenger aircraft.

SOURCE Off Ice of Technology Assessment

subsonics. AST-II fuel consumption is considered to be 4,000 Btu per seat-mile which is 2.6 times an ASUBT fuel efficiency of 1,700 Btu per seat-mile. Scenario 4b differs from scenario 1 only in the matter of timing in that a joint venture could introduce 400 AST-IIIs earlier than a unilateral undertaking by the United States. Table 11 shows the results of fuel consumption analyses for either of the consortium cases.

Table 12 summarizes fuel consumption in the base case and in the four scenarios. Any scenar-

Table 11 .—Energy Impacts of AST-II or AST-III: Scenario 4

Fuel consumption	Base case	Scenario 4a: fuel efficiency AST-II	Scenario 4b AST III: fuel efficiency High	Medium	Low
Short & medium range (MMbbl/d)	3.74	3.74	3.74	3.74	3.74
Long range (MMbbl/d)	0.66	1.19	0.84	1.00	1.15
increase over base case (MMbbl/d)	–	*0.53*	*0.18*	*0.34*	*0.49*
Percent of increase	—	*+ 80%*	*+ 27%*	*+ 50%*	*+ 75%*
All commercial aviation (MMbbl/d)	4.40	*4.93*	*4.58*	*4.74*	*4.89*
Percent of increase	—	*+ 12%*	*+ 4%*	*+ 8%*	+11%
Percent of increase in world petroleum use	—	+ 0.6%	+ 0.2%	+ 0.3%	+ 0.5%

MMbbl/d = millions of barrels per day.
Assumptions:
1. Short- and medium-range aircraft make up 75 percent of the fleet and use 85 percent of the fuel in the base case.
2. Base case fleet = 6,000 short- and medium-range and 2,100 long-range subsonics,
3 Scenario 4a fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 450 AST-II.
Scenario 4b fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 400 AST-III.
4. Long-range subsonic fuel efficiency = 1,700 Btu/seat-mile
5. AST-II fuel efficiency = 4,400 Btu/seat-mile; AST-III fuel efficiency (Btu/seat-mile): High = 2,900; Medium = 3,900; Low = 4,500.
6 Long-range subsonic is a 300-passenger aircraft; AST-II is a 225-passenger aircraft; and AST-III is a 300-passenger aircraft.

SOURCE: Off Ice of Technology Assessment.

Table 12.—Summary of Energy Impacts

Impacts	Base case	Scenarios 1 U.S. only	2 Foreign only	3 Competition	4 Consortium a	b
Fleet characteristics						
Number & type of long-haul aircraft	2,100 ASUBTs	1,250 ASUBTs 400 AST-IIIs	1,250 ASUBTs 400 AST-Is or 400 AST-IIIs	1,250 ASUBTs 250 AST-Is 250 AST-IIIs	1,250 ASUBTs 450 AST-IIs	1,250 ASUBTs 400 AST-IIIs
Fuel efficiency (Btu/seat-mile)	1,700	AST-III; 3,900a	AST-I; 4,900 AST-III; 3,900	AST-I; 4,900 AST-III; 3,900	AST-II; 4,400	AST-III; 3,900a
Fuel-efficiency ratio (AST/ASUBT)		2.3	AST-I; 2.9 AST-III; 2.3	AST-I; 2.9 AST-III; 2.3	2.6	2.3
Fuel consumption						
Long-haul fuel (MMbbl/d)	*0.66*	1.00	NE[b]	*1.06*	1.19	1.00
Increase over base case (MMbbl/d)	—	0.34	NE[b]	0.40	**0.53**	**0.34**
Percent of increase	—	+ 500/0	NE[b]	+ 600/0	**+ 800/0**	**+ 500/0**
Total commercial fleet (MMbbl/d)	*4.40*	4.74	NE[b]	**4.80**	**4.93**	4.74
Percent of increase	—	+ 8%	NE[b]	**+ 9%**	**+ 12%**	+ 8%
Percent of increase in world petroleum use	—	**+ 0.3%**	NE[b]	**+ 0.40/o**	+ 0.60/0	+ 0.3%

MMbbl/d = millions of barrels per day.
[a]Middle value of estimated range of 2,900 to 4,900.
[b]Not estimated

SOURCE Off Ice of Technology Assessment

io involving the introduction of a supersonic transport will involve greater overall fuel consumption than if no supersonic is developed. The percentage of fuel use increase in the long-haul market (which consumes about 15 percent of the total commercial fleet fuel) ranges from a high of 80 percent in the case of a consortium-built AST-II (scenario 4a) to a low of 50 percent in the case of a U.S.-built AST-III (scenario 1). These values depend heavily on estimates of fuel efficiency for the various aircraft. Because these estimates are uncertain, the fuel consumption figures may vary by 20 to 25 percent.

According to table 12, the impact of supersonic aircraft on the total amount of fuel consumed by the commercial aviation fleet would be approximately 8 to 12 percent—if the market estimates for supersonics are reasonably accurate. Likewise, the impact of supersonic aircraft on worldwide consumption of petroleum fuels would be miniscule —0.3 to 0.6 percent, figures much smaller than the probable error in the estimation process used here.

If supersonic aircraft were introduced and used in numbers comparable to those assumed in these scenarios, overall worldwide fuel consumption by commercial aviation would approach 5 MMbbl/d by 2010. This figure is equivalent to the amount of petroleum-based fuel anticipated to be used by all private automobiles in the United States at that time. If these types and numbers of supersonics were not introduced, worldwide commercial aviation fuel consumption would be 4.4 MMbbl/d, or about 10 percent less.

ALTERNATIVE FUELS

The rising cost of petroleum-based fuels and the uncertainty of the long-term supply of petroleum have prompted all sectors of the economy to intensify the search for alternative energy sources. The need for substitute fuel is keenly felt in the air transportation industry, which is particularly dependent on an assured supply of a low-cost fuel that is equivalent to kerosene in weight and energy content. Because air transportation is a world activity, it is also of critical importance that the substitute fuel—whatever it is—be a uniform and generally available product .

The prospect facing the aircraft and airline industries has been summarized by one observer thus:

> The question is, in view of the grim outlook for the future of petroleum-based fuel, what are the alternatives facing the air transport industry? What other fuels offer more promise and what are the criteria that should serve as a guide in making the choice of a fuel in the future? The design and development cycle for large commercial transport aircraft of advanced design is approximately 10 years. The normal design life expectancy for aircraft of this type is about 20 years. Assuming a production cycle of 10 years, any new commercial transport aircraft whose design is started in 1976, for example, would normally be in service from 1986 through 2015, at a minimum. It is not realistic to assume that current quality fuel will continue to be generally available around the world at economically acceptable prices that far into the future.[8]

The question of alternative fuels is a general one that will affect the development of all types of advanced aircraft, and future decisions concerning supersonic aircraft will be conditioned by broader trends and developments in the aviation industry. Thus, it seems unlikely that supersonic aircraft would evolve toward the use of one fuel and subsonic aircraft toward another. More likely both forms of air transport technology will follow a single course and the fuel eventually selected will be one compatible for all advanced aircraft operating in the period 2000 to 2010. Questions that will have to be addressed in making a transition to an alternative fuel are:[9]

- What is the preferred fuel for commercial aviation from the standpoints of cost, per-

“D. G. Brewer, Hydrogen Fueled *Transport Aircraft, paper presented* at the U.S.-Japan Joint Seminar on “Key Technologies for the Hydrogen Energy System, ” Tokyo, Japan, July 1979, p. 7.

‘Ibid.

formance, emissions, energy, noise, and long-range availability?

- How can the transition to a new fuel be implemented without serious disruption of existing commercial airline service?
- How much will it cost to provide facilities to store and handle the new fuel at airports, and how should this process be financed?
- Recognizing that the problem is international and that the choice of the new fuel requires cooperation among the principal nations, how can this choice best be accomplished?

At present, several candidate fuels are being considered. Generally they fall into two categories: synthetic liquid fuels with properties similar to kerosene, and cryogenic fuels such as liquid hydrogen or methane. These fuels could be derived from a number of sources—oil shale, tar sands, coal, or heavy crude oils. Table 13 summarizes the properties of some of the candidate fuels.

The National Aeronautics and Space Administration (NASA) has conducted and sponsored several studies of coal-derived aviation fuels.[10] Coal has been identified **as** one of the more plentiful remaining U.S. energy resources (at an order of magnitude greater than crude oil). The fuels considered were synthetic aviation kerosene, because it appears more compatible with the present air transportation system than other fuels, and liquid methane and liquid hydrogen, because they offer high energy content per pound. The investigations addressed the areas of fuel production, air terminal requirements for aircraft fueling, and the performance characteristics of aircraft designed to utilize alternate fuels. In the fuel production studies, the energy requirements associated with the production of each of the three selected fuels have been determined, as have estimates of the fuel prices. In the area of air terminal requirements for alternate fuels, only liquid hydrogen has been assessed thus far. Subsonic commercial air transports, designed to utilize liquid hydrogen fuel, have been analyzed and their performance characteristics have been compared to aircraft utilizing conventional aviation kerosene. Environmental and safety aspects were addressed as were key technical and economic issues.

Lockheed-California Co. has produced information on the processes and costs of production of several alternate fuels .11 When conventional crude oil is refined into a variety of fuels, including jet fuel, the energy content of fuels coming out of the refinery can vary from about 88 to 95 percent of the energy input to the refinery depending on the type of crude oil being refined and the mix of products. When fuels are produced from coal, an even smaller percentage of

[10] R. D. Witcofski, "Alternate Aircraft Fuels—Prospects and Operational Implications, " NASA TMX-7403, May 1977.

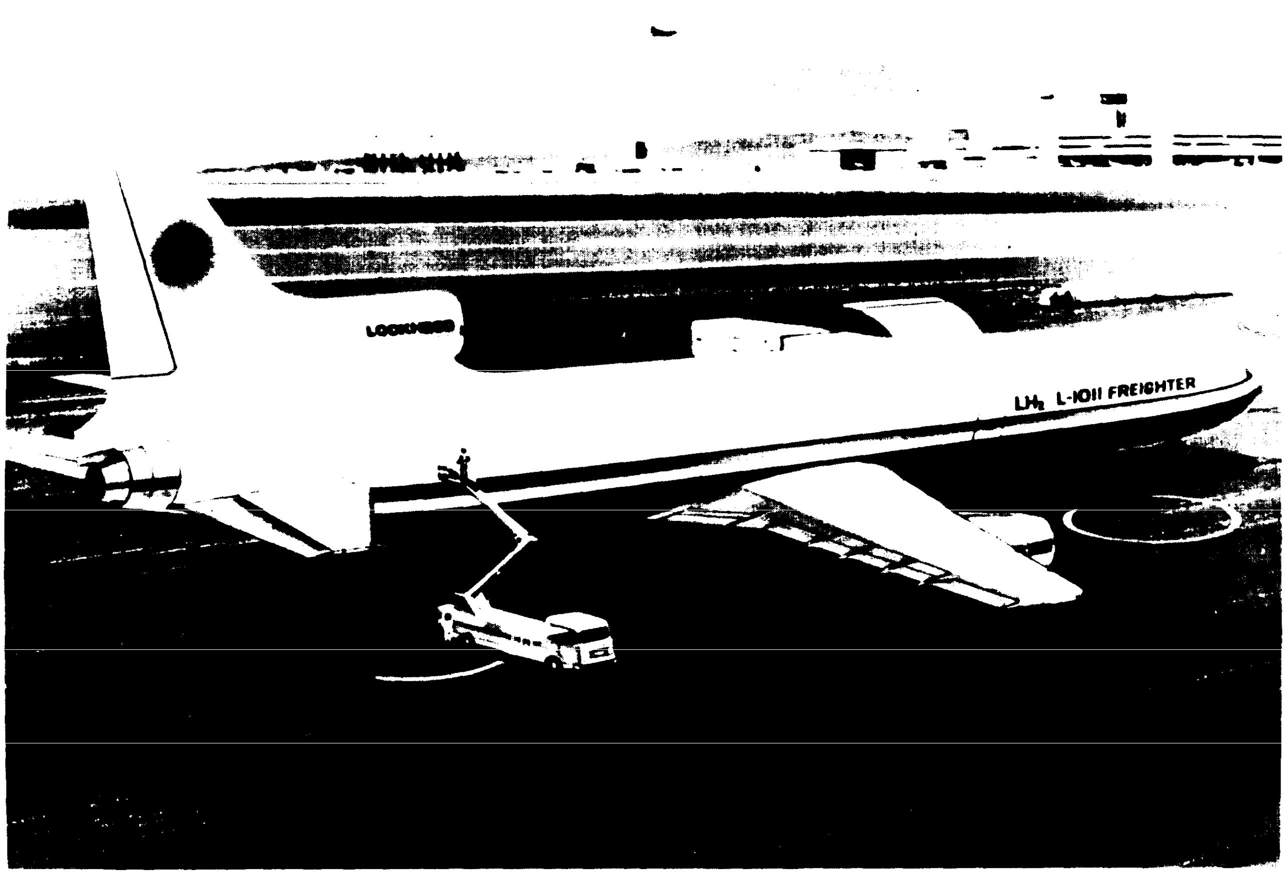
"OTA Working Paper, Lockheed-California Co., Feb. 5, 1979.

Table 13.-Properties of Some Candidate Fuels

	Synthetic jet fuel[a]	Methane	Ethyl alcohol	Methyl alcohol	Ammonia	Hydrogen
Nominal composition	$C\,H_{194}$	CH_4	C_2H_5OH	CH_3OH	NH_3	H_2
Molecular weight, ...	120	16.04	46.06	32.04	17.03	2.016
Heat of combustion (Btu/lb). . .	18,400	21,120	12,800	8,600	8,000	51,600
Liquid density (lb/cubic ft at 50° F)	47	26.5[b]	51	49.7	42.6[b]	4.4[b]
Boiling point (°F at 1 atmosphere)	400 to 550	– 258	174	148	- 2 8	– 423
Freezing point (°F)	– 58 to – 90	– 296	– 175	– 144	– 108	– 484
Specific heat (Btu/lb °F)	0.48	0.822	0.618	0.61	1.047	2.22
Heat of vaporization (Btu/lb). . .	105 to 110	250	367	474	589	193

[a] Derived from coat or shale.
[b] At boiling point.

SOURCE: D. G. Brewer and R. E. Morris, *Tank arrd Fuel Systems Considerations for Hydrogen Fueled Aircraft,* Society of Automotive Engineers, paper No. 751093, November 1975.



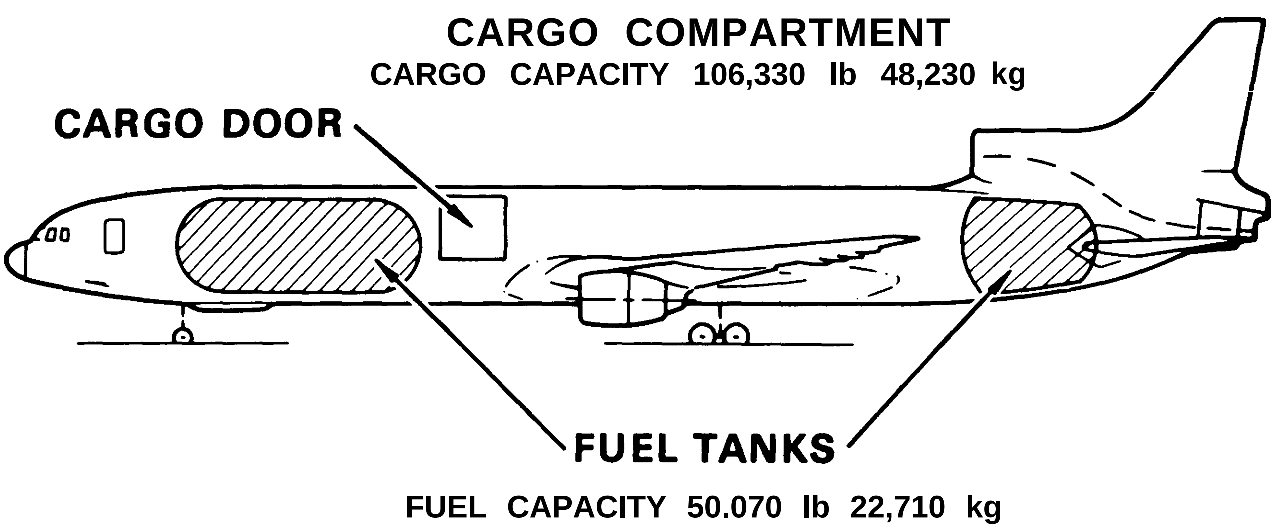


Illustration. Courtesy 01 Lockheed Aircraft Corp.

Artist's concept of hydrogen-fueled cargo aircraft the energy in the coal feedstock actually comes out the plant as useful fuel.

The thermal efficiency of the consol synthetic fuel (CSF) process for producing aviation kerosene from coal is about 70 percent. After hydrogen has been produced from the high-Btu gas product and used to hydrocrack and hydrogenate the heavy oil from the CSF process to produce a synthetic aviation kerosene, the overall thermal efficiency is 54 percent.

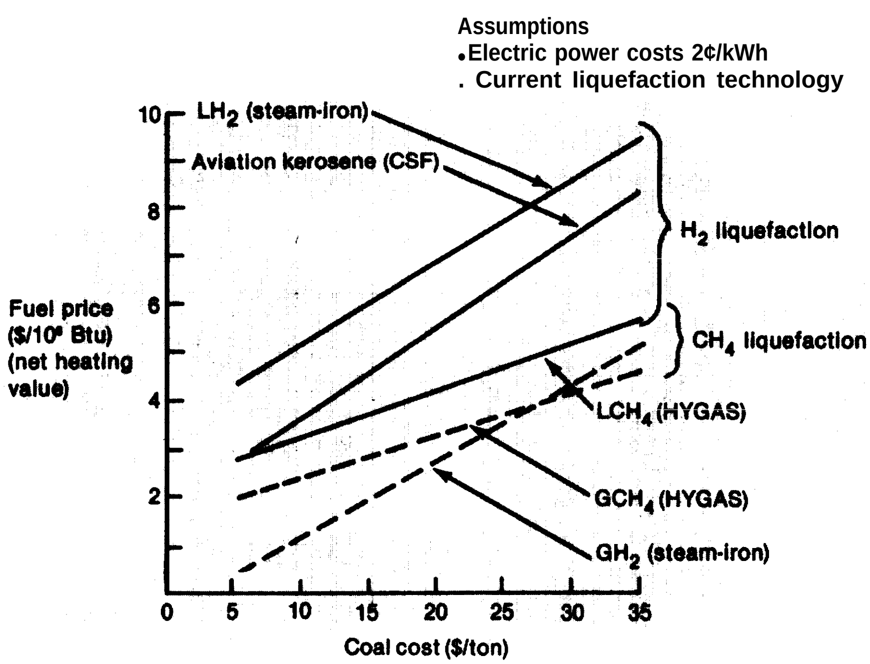
Of all the fuels and fuel processes investigated, liquid methane produced by the HYGAS process is the most thermally efficient coal-derived liquid fuel (64 percent). The relatively low energy requirements for liquefying methane (reported at 12.2 kWh per million Btu of liquid product) account for this efficiency.

Of the hydrogen production processes considered, the most thermally efficient process is the steam-iron process. Depending on whether the byproduct gas (heating value plus sensible heat) or electrical power generated from the gas is credited as the byproduct energy, the thermal efficiency of liquid hydrogen product via the steam-iron process is 49 or 44 percent. The energy requirements for hydrogen liquefaction were determined to be 104.7 kWh per million Btu of liquid product.

At the time of the Lockheed study (1977) domestic airlines were paying about $0.32 per gallon ($2.60 per million Btu) for aviation kerosene. The price in early 1980 was over $1.00 per gallon. The price of synthetic fuels will be determined by a number of factors, including the cost of the energy source from which they are produced (coal in the present discussion), the cost of labor and materials for constructing the plants, the cost of a method of financing the construction of plants, and the price of competitive fuels.

A summary of fuel prices as a function of coal cost is presented in figure 14. Although not based on current prices, the data are still useful in comparing one fuel or fuel production process against another. As a point of reference, Virginia Electric and Power Co. was paying be-

Figure 14.— The Price of Coal-Derived Aviation Fuels as a Function of Coal Cost



SOURCE: OTA Working Paper, Lockheed-California Co., Feb. 5, 1979.

tween **$20** to **$25** per ton for mine-mouth coal in May 1977. The figure shows that, for the processes and fuels considered, liquid methane produced by the HYGAS process is the least expensive, and the price increase on account of increased coal cost would be less than for the other fuels and fuel processes. Liquid hydrogen is the most expensive fuel within the range of coal costs considered. Synthetic aviation kerosene (produced from the CSF process) falls between liquid hydrogen and liquid methane.

Figure 14 also shows that the price of gaseous hydrogen and methane are comparable and, at the lower coal costs, gaseous hydrogen is less expensive than gaseous methane. The reason that the liquid hydrogen prices are so high in comparison to the other two fuels is the cost of liquefying the hydrogen. At $25 per ton, the cost of coal represents more than half of the total cost of liquid hydrogen produced by liquefaction. Studies are currently underway at Linde to assess the possibility of reducing the cost of hydrogen liquefaction. These studies include an analysis of the idea of joining to the liquefaction plant a heavy water plant from which byproduct heavy water would be sold.

In summary, at a coal cost of **$20** per ton, Lockheed estimates that liquid hydrogen would be priced at $7 per million Btu, synthetic kerosene at **$5.50,** and liquid methane at **$4.30.** However, a later study conducted by NASA[12] has indicated that at a coal cost of $18 per ton, liquid hydrogen would be priced at $11 per million Btu, synthetic kerosene at $8.47, and liquid methane at $8.00. The variance surrounding these estimated costs indicates the uncertainty in this area.

Application to Supersonic Transports

Studies of the use of synthetic fuels and liquid hydrogen for supersonic aircraft have been conducted by NASA,[13] Boeing,[14] Lockheed,[15] and EXXON. I' Lockheed has probably been the most active supporter of hydrogen-fueled aircraft, and table **14** summarizes some of their findings. The Lockheed view is that liquid hydrogen is superior to other fuels as a long-term substitute for petroleum, especially as a fuel for supersonic aircraft, Among liquid hydrogen advantages cited by Lockheed are reduced aircraft weight, lower engine thrust requirements, better specific fuel consumption, lower direct operating cost, and reduced sonic boom overpressure.

However, EXXON in a study comparing alternative aviation fuels has reached opposite conclusions concerning the relative advantages of hydrogen. The study pointed out that, on a volume basis, the heat content of liquid hydrogen is 25 percent that of synthetic jet fuel and, thus, more storage volume would be required for a given flight. Other disadvantages of liquid hydrogen are low density and boiling point, as well as being very expensive fuel compared to liquid fuels from coal or shale. Table 15 summarizes advantages and disadvantages of liquid hydrogen enumerated in the EXXON study. It should be remembered that disagreement remains within the industry over findings in both the Lockheed and the EXXON studies.

The following summation, excerpted from the EXXON study, highlights some of the major points of comparison among the various alternative aviation fuels that might be used for supersonic and subsonic aircraft.

- Of the cryogenic and the synthetic jet fuels considered, hydrogen has the highest heat of combustion on a weight basis and the highest specific heat (a measure of its ability to be used as a coolant), but it has the

[12] R. D Witcofski, "Comparison of Alternate Fuels for Aircraft, " NASA Technical Memorandum, September 1979.

[13] R. D. Witcofski, "Hydrogen Fueled Subsonic Aircraft, " NASA Langely Research Center, presented at the International Meeting on Hydrogen and Its Prospects, Liege, Belgium, November 1976.

[14] G. J. Schott, "Alternate Fuels for Aviation, " Boeing Commercial Airplane Co., presented at the 29th annual conference, California Association of Airport Executives, July 1975.

[15] G. D. Brewer and R. E. Morris, *Tank and Fuel Systems Considerations for Hydrogen Fueled Aircraft,* Society of Automotive Engineers, paper No. 751093, November 1975.

[16] EXXON Engineering and Research Company, *Alternate Energy Sources for Non-Highway Transportation,* for U.S. Department of Energy, contract No. **EC-77-C-05-5438,** December 1978.

Table 14.—Comparison of a Supersonic Transport Aircraft Fueled With Liquid Hydrogen or Jet A Fuel
(Mach 2.7,4,200 nm, 234 passengers)

Parameters	Unit	LH_2	Jet A	Ratio Jet A / LH_2
Gross weight	lb	394,910	762,170	1.93
Operating empty weight	lb	245,240	317,420	1.29
Block fuel weight	lb	85,390	330,590	3.88
Thrust per engine	lb	52,820	86,890	1.64
Wing area	ft^2	7,952	11,094	1.39
Span	ft	113	113.5	1.18
Fuselage length	ft	304.2	297	0.87
Field length required	ft	7,800	9,490	1.22
Lift/drag (cruise)	—	7.42	8.65	1.17
Specific fuel consumption (cruise)	lb/hr /lb	0.575	1.501	2.61
Aircraft price	$10'	45.5	61.4	1.35
Direct operating cost	¢/seat nm.	3.40'	3.86[b]	1.14
Energy utilization	Btu/seat nm.	4,483	6,189	1.38
Noise, sideline	EPNdB	104.0	108.0	—
Flyover	EPNdB	102.2	108.0	—
Sonic boom overpressure (start of cruise)	psf	1.32	1.87	1.42

[a]Based on a cost of $3.00 per 10⁶ Btu.
[b]Based on a cost of $2.00 per 10⁶ Btu.

SOURCE: OTA Working Paper, Lockheed-California Co., January 1979

Table 15.—Advantages and Disadvantages of Liquid Hydrogen Compared to Synthetic Jet Fuel

Advantages	Disadvantages
• Lighter weight aircraft than synthetic jet fuel aircraft.	• Airport modification to add hydrogen storage and handling facilities would be a major undertaking.
• Longer range possible.	• Overall economics unfavorable compared to shale oil based fuel for subsonic and supersonic aircraft. *
• Greatest performance advantage is with supersonic flight	• Overall economics unfavorable with coal-based liquids for subsonic, but close for supersonic. *
• Emission of CO, CO_2, HC, and odor eliminated; NO_x emission equal to or less than synthetic jet fuel.	• Requires more energy from mine to engine.
• Reduction in noise and sonic boom due to smaller size aircraft.	• Amount of water vapor emitted in flight is higher.
• Initial cost lower for supersonic aircraft, about same for subsonic.	• Handling liquid hydrogen is more hazardous than synthetic jet fuel.
• Maintenance cost may be lower.	
• Can use shorter runways.[a]	

'Based on a ratio of coal based liquids to shale oil fuel cost per gallon of 1.8 to 1.

SOURCE" EXXON Research and Engineering Co., *Alternate Energy Sources for Non-Highway Transportation,* December 1978.

disadvantage of a low density and so low volumetric heat content and also a low boiling point.

- Liquid methane is 15 percent more energetic on a weight basis and has a specific heat 1.7 times greater than synthetic jet fuel. It is six times more dense than liquid hydrogen.
- The fuel costs, on a per-flight basis for a subsonic aircraft, are lowest for shale-derived jet fuel, followed by an indirect coal-liquid jet fuel. A direct coal-liquid jet fuel

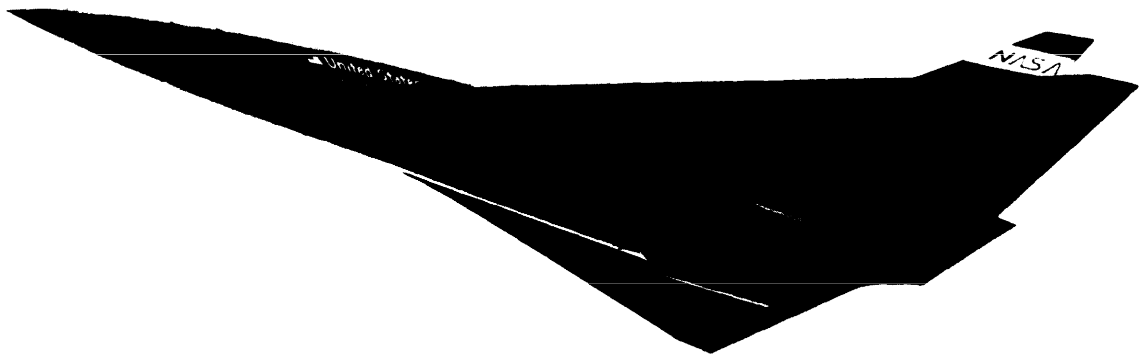


Illustration: Courtesy of Lockheed Aircraft Corp

Artist's concept of hydrogen-fueled hypersonic aircraft

and liquid methane are roughly equal in cost. The hydrogen-fueled aircraft would be the most expensive to operate—over three times the cost of operating an aircraft fueled with a shale-derived liquid. *

- For a supersonic aircraft (Mach 2.7, 4,200 nautical miles, and **234** passengers), the design advantages with hydrogen are greater than for a subsonic aircraft. However, the fuel cost per flight still favors the synthetic liquid fuels—shale oil first, followed by coal-derived jet fuel and then hydrogen. *
- With regard to natural resources and the *re*sources required between the mine and the aircraft, a shale-oil-derived jet fuel is the most efficient. Hydrogen requires about double the amount of natural resources as shale oil.
- Laboratory tests have shown that acceptable jet fuels can be made from either coal or shale. Production of aircraft fuels from shale oil should be more straightforward than from **coal.**
- Coal-based jet fuels will have poorer combustion properties than shale oil fuels because they form naphthenes rather than paraffins when the coal liquids are hydrogenated.
- An economic comparison between upgrading fuels to meet current hydrogen levels and modifying the engine shows that there are incentives to develop an engine that can accept **a** poorer quality fuel. If a fuel of 12 percent hydrogen can be used, the incentive would be about $170,000 per year per engine to operate an engine capable of using a fuel with a lower hydrogen content.

The Federal Government currently is planning to launch a large-scale synthetic fuel production program. But the details of the plan and where this new fuel would be allocated have not been worked out, so they cannot be related to development of a supersonic aircraft at this time. However, due to the uncertainty of the energy picture, it seems quite appropriate to continue the examination of alternative fuels to ensure fuel availability for any new type of advanced air transport—either subsonic or supersonic.

*Based on the following cost ratios per 10^6 Btu: liquid hydrogen from coal (3.8); jet fuel from coal liquefaction (1 **.8);** and jet fuel from shale oil (1 .0).

Chapter VII

ENVIRONMENTAL ISSUES

Over the past two decades, the potentially adverse effects of commercial supersonic flight on the environment have been the subject of considerable controversy and, at times, heated debate. The principal issues are noise, the sonic boom, pollution from engine emissions, and, to a lesser extent, radiation effects on passengers and crew. During the debate, both fact and conjecture have been used to support opposing points of view, clouding the issues in the minds of most Americans.

In an effort to remove these clouds and to determine whether the environmental concerns are real or imagined, the U.S. Government initiated several research efforts following cancellation of the U.S. supersonic transport (SST) program in 1971. These research programs, although still not providing complete and final answers, have generated a greatly improved understanding of potential advanced supersonic transport (AST) environmental impacts. In the following sections, the results of U.S. Government studies are summarized briefly and the environmental impacts that are currently perceived for an AST design are discussed.

NOISE

Engine noise was a critical factor in the cancellation of the prior U.S. SST program and also the focus of controversy about the Concorde operating at Washington and New York airports. The noise issue will figure prominently in the consideration of any future U.S. aircraft program. Consequently, engine noise has been a major subject of the National Aeronautics and Space Administration's (NASA) research programs on both subsonic and supersonic technology.

Since the Concordes have been operating at Dunes and Kennedy and more recently at Dallas-Fort Worth airports, a doubt has surfaced as to whether these supersonic aircraft have actually increased the overall noise exposure of neighboring communities because the number of supersonic aircraft operations compared to the total number of aircraft operations is small. It is expected that supersonic aircraft will comprise only about 5 to 15 percent of future total aircraft operations and, hence, will always contribute relatively little to overall noise. In this regard, it is important to keep in mind that only one generation of supersonic transports is in operation today. This generation's design represents the technology available roughly between 1955 and 1965, a period before noise rules for any class of aircraft were promulgated. Thus, the supersonic transport has had no opportunity for the evolutionary progress in noise control that has benefited the subsonic fleet through several generations of aircraft and propulsion cycles.

Notwithstanding the fact that the noise impact of future ASTs would be relatively small, the NASA supersonic research program has aimed at achieving noise levels comparable to those of advanced long-range subsonic aircraft. The research centers on an advanced variable-cycle engine, which appears to have the capability of lessening noise by inherent design, and on advanced mechanical suppressors, which would substantially reduce noise with relatively small thrust loss. I The NASA program has made significant progress and, while verification through actual hardware is still necessary, it appears that an AST would be able to meet the Federal Aviation Administration (FAA) noise rule (FAR part 36 stage 2), issued in 1969. Thus,

'Cornelius Driver, "Advanced Supersonic Technology and Its Implications for the Future, " presented at the AIAA Atlantic Aeronautical Conference, Williamsburg, Va., May 26-28, 1979.

Photo credit: Environmental Protect/on Agency

Noise pollution

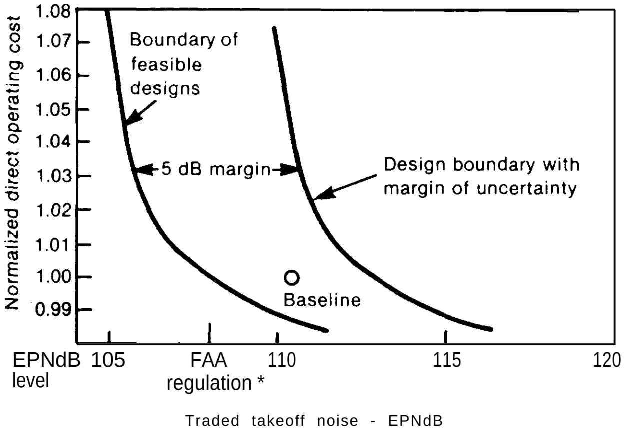
this research promises a considerable improvement over the-noise levels of currently operating Concordes and of models reached by the close of the prior U.S. SST program.

However, the viability of these improvements is thrown into doubt by the outstanding question of what additional noise standards both future subsonic and supersonic aircraft may have to satisfy by the time they are introduced into revenue operations. More stringent standards could affect the feasibility and acceptability of both kinds of aircraft and require further research and technology development.

Because of the greater interdependence of all design facets in the aircraft, an AST will probably be more sensitive to strict noise requirements than comparable subsonic aircraft. Given the current status of supersonic technology, achieving noise levels below FAR part 36, stage 2 will be very costly. Lockheed recently performed a study to provide data for FAA to use in working with the International Civil Aviation Organization (ICAO) Committee on Aircraft Noise, Working Group E. This committee is setting noise standards for possible future supersonic transports. Lockheed addressed the relationship between predicted noise levels at the FAR part 36 measurement points and predicted direct operating costs for a supersonic transport with a specified emission. The results are shown in figure 15.

This figure plots achievable noise versus operating cost penalties. The curve on the left reflects the results of Lockheed's calculations. Optimistically it shows that such an airplane would readily meet FAR part 36, stage 2 (108

Figure 15.—The Cost and Uncertainty of Noise Reduction



"FAR part 36 stage 2.

SOURCE OTA Working Paper, Lockheed California Co , January 1979

EPNdB) without economic penalty and that it may meet stage 3 (about 105 EPNdB) with a 5- to 6-percent direct operating cost penalty. However, when the second curve is added, reflecting the margin of uncertainty, the cost of meeting the various noise regulations greatly increases. Part of the reason for the 5 db margin of uncertainty, is the lack of solid experimental data to support the theoretical predictions. Thus, the results indicate that going much beyond the **1969** FAR part 36, stage 2 standards is likely to involve substantial direct operating cost penalties. Unless much of this uncertainty in noise calculations for supersonic aircraft is removed or reduced significantly, no manufacturer is likely to commit to a new supersonic aircraft program because the investment is too large to risk failure in meeting the standard. Substantial research and engine hardware testing will be needed to develop the data with which to reduce the margin of uncertainty to acceptable proportions.

SONIC BOOM EFFECTS

The general issue of noise dovetails with the specific problem of the sonic boom. Designed without regard to limiting the sonic boom, the typical supersonic transport would produce overpressure levels ranging from 1.5 to 4.0 pounds per square foot (lb/ft^2). These shock waves generated during acceleration and cruise flight remain an environmental concern which U.S. regulations have responded to in prohibiting civil flights at speeds which generate a boom that reaches the ground.

Sonic boom effects on humans are difficult to pinpoint because of the subjectivity of the people's responses and because of the diversity of variables affecting their behavior. Responses depend on previous exposure, age, geographic location, time of day, socioeconomic status, and other variables.

Research and experimentation by FAA, NASA, and ICAO have turned up several findings about sonic boom phenomena related to humans, structures, and animals:[2 3]

- Sonic booms do not affect adversely human hearing and vision or the circulatory system. The human psychological response is more complex, involving attitudes and habituation to sonic booms and their sources. In addition to the general observation that unexpected and unfamiliar noise startled people, the research indicated that intense booms tend to disorient people.
- Damage to structures appears the most serious potential impact of sonic boom, although even here the projected damage caused by supersonic transports may be minimal. Sonic booms with an intensity of 1.0 to 3.0 lb/ft^2, that is the intensity associated with a large supersonic transport, can cause glass to break and plaster to crack. In the range of 2.0 to 3.0 lb/ft^2, overpressure will damage about 1 window pane per 8 million boom pane exposures. Booms with overpressure from **3.0** to **5.0** lb/ft^2 can cause minor damage to plaster on wood lath, old gypsum board and bathroom tile,

[2]Anon., *Concorde Supersonic Transport Aircraft, Draft Environmental Impact Statement (Washington,* D. C.: U, S, Department of Transportation, Federal Aviation Administration, March 1975).

[3]L. J. Runyan and E, J. Kane, *Sonic Boom Literature Survey. Volume I: State of the Art,* Federal Aviation Administration report No. RD-73-129-1, September 1973.

and to new stucco. Sonic boom impact will vary according to the condition of the structure.

- Boom overpressure dissipates with depth of water (e.g., to a tenth of initial value at a depth of about 122 feet) and so appears to pose no threat to aquatic life, including the capacity of fish eggs to hatch.
- Research on chickens, embryo chicken and pheasant eggs, pregnant cows, race horses, sheep, wild birds, and mink indicates that sonic boom effects on fowl, farm, and wild animals are negligible. Like humans, animals are startled by loud noises, but this reaction was found to diminish during testing.

Although research indicates that overpressure of 4.0 lb/ft^2 or less produces little damage and few lasting psychological effects, sonic booms of such intensity would constitute a public nuisance. As ‘present regulations prescribe, current and, at least, any second-generation supersonic transport cannot fly supersonically over populated land masses. Thus, market studies for future ASTs are restricted to flight patterns involving city pairs with over water supersonic legs.

NASA has expended considerable effort on sonic boom minimization studies,[4 5] which point to the possibility of supersonic aircraft designs with a boom of lower intensity. Such low-boom airplanes will require a degree of technological refinement beyond current capabilities and are not a likelihood for the period considered in this report. Additional research could alter the picture, perhaps allowing an AST to be developed for introduction beyond the year 2010 that could operate over land.

[4]F. E. Mclean and H. W. Carlson, “Sonic-Boom Characteristics of Proposed Supersonic and Hypersonic Airplanes, ” NASA TN D-3587, September 1966.

‘E. J. Kane, *A Study to Determine the Feasibility of a Low Sonic Boom Supersonic Transport,* NASA CR-2332, December 1973.

Recently, the term “secondary sonic boom” has been used in connection with some Concorde operations. Secondary sonic boom is caused occasionally by certain meteorological phenomena. For example, the structure of the atmosphere is such that its temperature decreases from sea level up to an altitude of about 5 miles. From this altitude the temperature continually increases and decreases up to a region called the thermosphere.[6] This temperature structure is the primary factor that determines the noise profile in the atmosphere. With the wind profile it determines how sound propagates through the atmosphere and can result, under special circumstances, in sound radiated into the atmosphere being returned back to Earth.

In the case of aircraft-produced sonic boom, the source of the noise could be waves from the airplane that propagate upward and are then returned or could be waves that reflect off the surface of the ocean, travel upwards, and then are returned. Measurements of these shock waves have been taken showing overpressures on the order of 0.02 lb/ ft^2.[7]

Sources of these secondary sonic booms have been identified as Concorde flights, distant gunnery practice, quarry blasting, and similar activities. They have also been associated with the overflight of space vehicles, including the Apollo 12 and 13 moon flights.[8]

A Naval Research Laboratory study has concluded that secondary sonic booms from Concorde are of sufficiently low amplitude and frequency that it is unlikely that they are either responsible for some mysterious sounds observed off the east coast in 1979 or likely to disturb the public.[9]

[6]M. Lessen and A. W. Pryce, “ Now Don’t Get Rattled,” *Journal of Acoustical Society* of America, 64(6), December 1978.

‘Ibid.

[8]D. Cotten and W. L. Dorm, “Sound From Apollo Rockets in Space,” *Science, vol.* 171, February 1971.

‘J. H. Gardner and P. H. Rogers, “Thermospheric Propagation of Sonic Booms From the Concorde Supersonic Transport, ” Naval Research Laboratory, NRL memorandum report 3904, Feb. 14, 1979.

EMISSIONS

In the early 1970's, concern was aroused that the engine emissions from a fleet of supersonic transports would deplete the ozone in the upper atmosphere, reduce the shielding from the Sun's ultraviolet rays, and, thus, cause an increase in the incidence of skin cancer. This concern, originally directed only at anticipated supersonic aircraft, spread to the potential impact of the growing fleet of subsonic aircraft. At the time the issue was raised, there was simply not enough knowledge from which to draw the needed scientific conclusions.[10]

During the congressional debate over the future of the SST program in 1970, the Department of Transportation (DOT) was directed to mount a Federal scientific program to obtain the knowledge needed to judge how serious the conjectured ozone-depletion effects might be and report the results to Congress by the end of calendar year 1974. This directive led to the establishment of DOT's climatic impact assessment program (CIAP), which drew on 9 other Federal departments and agencies, 7 foreign agencies, and the individual talents of 1,000 investigators in numerous universities and other organizations in the United States and abroad. At the same time, a special committee of the National Academy of Sciences (NAS) was organized to review the work of CIAP and to form an independent judgment of the results.

The principal findings of the CIAP study[11] were:

- Operations of present-day supersonic aircraft and those currently scheduled to enter service (about 30 Concordes and TU-144s) cause climatic effects which are much smaller than minimally detectable.
- Future harmful effects to the environment can be avoided if proper measures are taken in a timely manner to develop low-emission engines and fuels.
- If stratospheric vehicles (including subsonic aircraft) beyond the year 1980 increase greatly in number, improvements over 1974 propulsion technology will be necessary to assure that emissions do not significantly disturb the stratospheric environment.
- The cost of developing low-emission engines and fuels would be small compared to the potential economic and social costs of not doing so.
- Many uncertainties remain in our knowledge of the dynamics and chemistry of the upper atmosphere. A continuous atmospheric monitoring and research program can further reduce remaining uncertainties, can ascertain whether the atmospheric quality is being maintained, and can minimize the cost of doing so.

On the recommendations of the CIAP studies, Congress has supported a NASA program to develop the technology for low-emission jet engines. This program has been successful in defining and testing a conceptual design for a burner which might solve potential future high-altitude emission problems as well as reduce low-altitude emissions.[12]

Also, on the CIAP recommendations, FAA initiated a high-altitude pollution program (HAPP) to monitor continuously the upper atmosphere and conduct systematic research to address the uncertainties regarding ozone depletion attributable to future subsonic and supersonic aircraft. The ongoing HAPP studies have already indicated that the earlier CIAP and NAS studies substantially exaggerated the extent to which future aircraft will reduce the ozone layer. Present understanding of the phenomena indicates much smaller impacts and perhaps no net impact at all.[13 14 15] The current predictions are compared with earlier CIAP and NAS predictions in figure 16.

---

[10] A. J. Grobecker, S. C. Coroniti, and R. H. Cannon, Jr., *The Effects of Stratospheric Pollution by Aircraft* (Washington, D. C.: U.S. Department of Transportation, report DOT-TST-75-50, December 1974).

[11] A. J. Grobecker, et a]., op. cit.

[12] Cornelius Driver, op. cit.

[13] A. Broderick, "Stratospheric Effects from Aviation, " presented at the AIAA/SAE 13th Propulsion Conference, AIAA paper 77-799, July 1977.

[14] See p. 90.

[15] See p. 90.

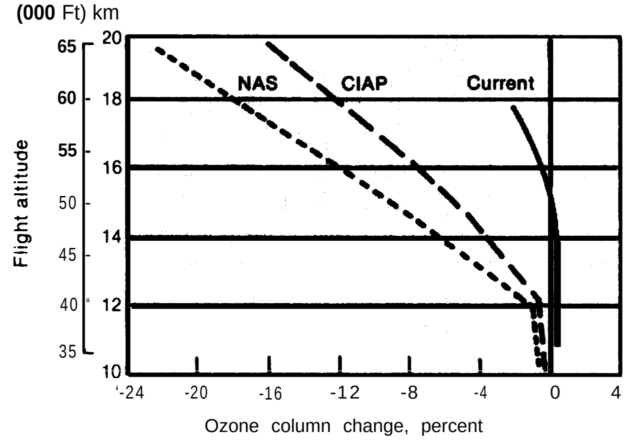
This is a significant finding, but it should be accepted only tentatively. Knowledge about atmospheric chemistry is growing and continued assessments are necessary as new data and improved atmospheric models become available. Current findings, however, are on much firmer ground than prior estimates and give some reason for optimism on the emission problems of advanced aircraft.

(Footnote continued from p. 89.)

14P. J. Crutzen, "A Two-Dimensional Photochemical Model of the Atmosphere Below 55 km: Estimates of Natural and Man Caused Ozone Perturbations Due to NO_x," *Proceedings of the Fourth Conference on the Climatic impact Assessment Program* (Washington, D. C.: U.S. Department of Transportation, report DOT-TSC-OST-75-38, 1976).

15I. G. Poppoff, R. C. Whiteen, R. P. Turco, and L. A. Capone, *An Assessment of the Effect of Supersonic Aircraft Operations on the Stratospheric Ozone Content,* NASA reference publication 1026, August 1978.

Figure 16.—Predicted Effect of Improved Aircraft Technology on the Ozone Layer



SOURCE: "High Altitude Pollution Program," Federal Aviation Administration, December 1977.

COSMIC RAY EXPOSURE

At the higher cruise altitudes expected of supersonic transports, cosmic rays are filtered by the atmosphere less than at subsonic cruise altitudes or on the ground. This factor has given rise to some concern that crew personnel will undergo excessive exposure to cosmic rays. However, the increased intensity of radiation will be somewhat compensated for by the decrease in exposure time resulting from the aircraft's supersonic speed. The best evidence to date is that such radiation exposure will not exceed permitted occupational levels.

SUMMARY

Based on the current state of knowledge and assuming all supersonic legs will be flown over water, noise is the most significant environmental problem of a new generation of supersonic aircraft. Although other concerns do not appear to be as critical at this time, it is likely that all of the environmental issues of a future supersonic transport will both intensify and subside in the future. They will intensify in the sense that regulation is likely to become more comprehensive and stringent, and measurement and evaluation techniques more sophisticated and accurate. At the same time, the regulations are more likely to be shaped by compromise between all relevant considerations and thus viewed as an equitable balance between diverse points of view and conflicting objectives. Debate concerning environmental standards will be a more familiar and established process. The regulations that will be derived from them will be more accepted, so that the equipment that conforms to these regulations will likewise be more accepted. While this process is evolving, it seems clear that the continued technical assessment and research on the environmental issues of future advanced aircraft are highly appropriate.

Chapter VIII

SUPERSONIC TRANSPORTATION AND SOCIETY

It is clear that advancements in transportation technology, such as the development of viable supersonic flight, would have an impact that alters the world we live in. It is possible to have a clear sense of the tangible ways in which technology changes the human environment, But at the same time, it can be very difficult to foresee exactly what a projected technological development will demand in the way of specific accommodations in the status quo.

The more specific the technological development we are considering, the more general or speculative attempts at prediction become. The impact of the advent of advanced high-speed aircraft will be felt in the area of long-range, and especially international, travel. Advanced high-speed aircraft would not appear to offer a dramatic change in the character of patterns of international travel, but it would seem to offer the opportunity for an increase in the scale of travel.

However, this potential for enhanced transportation is proceeding at the same time as revolutionary improvements of all sorts in communications capabilities. It is conceivable that progress in the communications area could allow the replacement of some amount of travel by rapid and sophisticated communications; however, as discussed below, it is often noted that increases in the quality and quantity of communications tend to be accompanied by similar increases in transportation. Assessing and projecting the effects of the mutual interactions of improving transportation and improving communications are very difficult tasks, and perhaps impossible.

IMPACT OF INCREASED LONG-DISTANCE TRAVEL

Underlying the assumption that an advanced supersonic aircraft would be economically feasible is the assumption that there would be a ridership for an aircraft that could fly basically international flights at very high speeds (see ch. III). The analysis here has not considered the amount of new travel induced by the higher speed service, especially offered by an advanced supersonic transport (AST) (see ch. IV). However, past experience suggests that most new transportation systems do in fact create a certain amount of new travel. A continuation in the rise of general real incomes and hence of discretionary incomes would tend to reinforce an increase in air travel.

The late anthropologist, Margaret Mead, suggested that mankind is just now on the verge of a new consciousness of air as the ordinary medium for transportation: "We have only begun to think in air terms instead of land and sea terms. The air sets up a new set of possibilities for human development, but also a new set of challenges." She writes, "It is a framework within which the people of the world who have fought each other for land rights and water rights must now cooperate or perish. " Indeed, at least four major trends can be conjectured that roughly follow from this recognition.

The first is global cultural and linguistic homogenization, Habits and practices are transmitted across borders by both business and tourist travel. Xenophobia is likely, in general, to recede. This trend is likely to be turbulent and not universal. The portent of change can be the precipitator of resistance—witness the recent events in Iran. But in the longer run, the general direction seems more likely to be toward softening rather than hardening of differences.

The second phenomenon is the slow strengthening of supranational cooperative organizations. Increasing travel brings increasing awareness of common interests and mutual impacts. An example was the impact of nuclear testing in

an atmosphere that the whole world shares. As the awareness of need for supranational organizations grows, so will their likelihood. It is relevant that the strata of society most likely to understand these issues, and most likely to be in a position to take an activist role in their establishment, are also most likely to be the people who do the traveling.

The third is a growing economic interdependence. This is really a subset of the trends addressed above, restricted to the sphere of the private sector and economic organization. Strengthening of the trend toward multinational companies should improve the efficiency of global resource usage.

The fourth is a further strengthening of the position of the large cities in the world's social and economic geographical hierarchy. The links in travel will be large cities. Given an AST, Tokyo and San Francisco will be closer in time than Bakersfield, Calif., and Eugene, Ore. As Margaret Mead has said, "The ports of the future will be air cities, not coastal cities or railroad centers. "

COMMUNICATIONS AND TRANSPORTATION

The communications field is undergoing a revolution with the application of advances in electronics to the transmission of information. It will be easier in the future to transmit more data, more voices, and more picture information and, in addition, it will become easier to set up more versatile combinations of these forms of communication (through holography, for instance) and thus extend telecommunications capabilities into new uses. It is anticipated that these innovations will take place at costs that, sooner or later, will make them quite attractive. Many of the anticipated developments in communications will have an immediate bearing on the continuing practicability of local and short-range transportation, but they also can help establish a framework in which the interactions of communications and long-distance travel can be considered.

The way the issue of the interaction of communications developments and transportation is typically framed is in terms of better communications either substituting for certain kinds of travel or stimulating travel. It is possible to conjure long lists of ways in which communications technology can serve both functions, but lists will not really **analyze** the problem. Developments in data communications and "electronic correspondence" may, in conception, allow the elimination of instances in which material or people are physically transported from office to office, from office to bank, or even from home to office. The development most relevant to long-distance travel is in teleconferencing technology. AT&T's picturephone meeting service is a step in this direction, although it currently still operates only out of a small number of large American cities and requires that conferees travel to a special center for the long-distance audiovisual encounter. One report states that although "there could be some impact on air transport, replacing business trips with audiovisual transmission, " such teleconferencing "may as often stimulate as replace or supplement the need for travel. " It is noted that in most organizations that use teleconferencing no diminution of overall travel budget has taken place: travel money has been reallocated for purposes other than for travel to and from meetings. [1]

Other evidence suggests that, although communications innovations may eliminate the need for certain kinds of trips at least in theory, such innovations will not have the overall effect of reducing time and money spent on travel. For one thing, evidence from past communications developments does not suggest that a communications breakthrough reduces travel. The introduction of neither the telephone nor the telegraph appears to have been followed by a discernible reduction in travel. In a more recent instance, we do not tend to think of satellite communications as having reduced contemporary

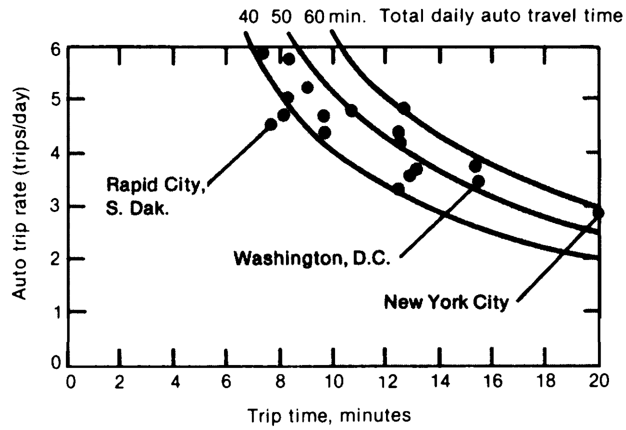
"'National Transportation Policies Through the Year 2000," *National Transportation Policy Study Commission,* Final Report, June 1979.

reasons or opportunities for travel, although no empirical work can be elicited to show this.

In fact, there is a fair amount of evidence that the average time people spend in daily travel has remained essentially constant as far back in history as clues can be obtained. For the past century, more systematic data bears out that average travel time per person per day has remained roughly the same. This is rather remarkable, considering that during this century the telephone was invented and proliferated and the physical character of cities has changed from relatively dense developments where people depended largely on walking to extended areas crisscrossed by highways.

One would think that in small cities, where the average travel time to work is shorter than in large cities, the total travel time per person would be much less than in large cities. However, this does not seem to be the case; people seem to compensate for short commutation with more noncommuting travel. Figure 17 shows some data on auto trips that illustrate this point. Eighteen cities ranging from New York with 16 million area residents to Rapid City, S. Dak., with **73,000** are identified. It would appear that in smaller cities in which shorter distances shrink the average trip, people use the time saved to make more trips. *

Figure 17.—Average Auto Trip Rate v. Trip Time



SOURCE. Vacov Zahavi, *Traveltime Budgets and Mobility in Urban Areas,* May 1974.

*If this effect could be transferred to the market associated with supersonic travel, one would expect that the AST would increase the travel market on account of the timesaving of higher speed travel.

Commuter parking at airports

Photo credits Environmental Protection Agency

Passengers waiting at airport terminals

THE FUTURE ENVIRONMENT

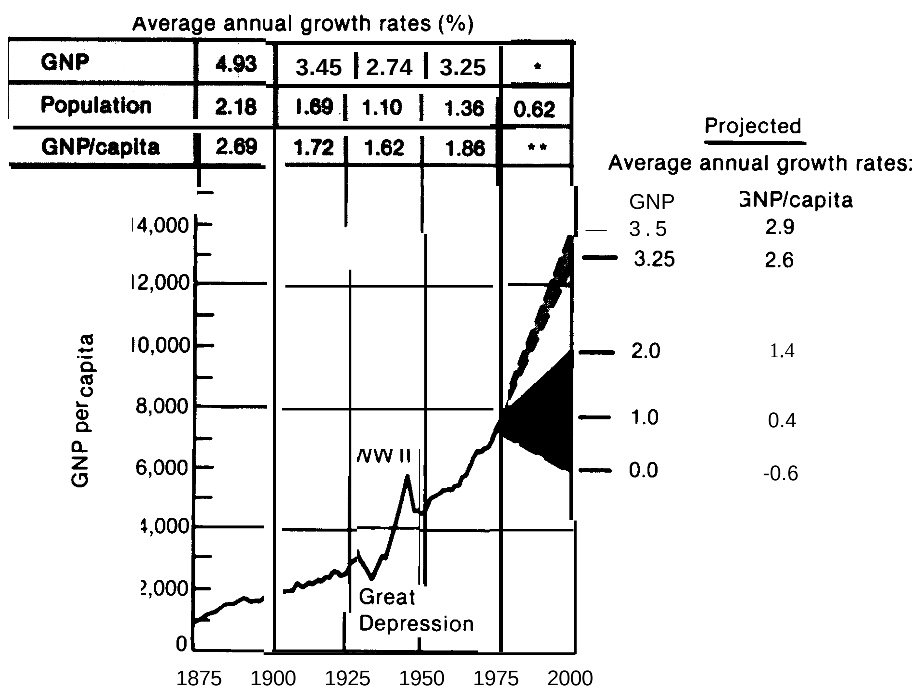
One approach to future projections is to implicitly assume that the world of the next **30** to **50** years will contain no long-term deviations from past trends. In Dr. Herman Kahn's expression, it is the "surprise-free scenario, " at least the "big surprise-free scenario. " Given our current concerns over the shortage of petroleum, is it reasonable to assume that we will somehow cope with the energy problem, possibly by providing substitutes, albeit at higher costs, that national economies will continue to expand, albeit slowly, and that world order will remain largely intact? These are necessary assumptions for growth in the air system. If these assumptions fail, the issues addressed in this assessment are moot.

Historical precedent supports the reasonableness of these assumptions. The economic system of the world and the Nation has shown a remarkable ability to weather many other crises that in the context of a quarter-century could be considered short-term. Figure 18 shows a 100-year history of economic and population trends for the United States. Under any economic growth rate that reasonably approximates past trends, we will be a more affluent nation by the end of the century. At the right of figure 18 are five hypothetical annual growth rates that show alternative outcomes in gross national product (GNP) per capita for the next 25 years. The total wealth should increase: at 2-percent annual growth in GNP, the Nation would generate $48 trillion in GNP (1975 dollars) between the years 1975 and 2000, compared to the $27 trillion between 1950 and 1975. At a 3-percent growth, the figure would be nearly $55 trillion. Whatever the growth in population, it should not be a drag on GNP because the labor force is expected to increase more rapidly than the population as shown.

Whatever happens in this country is likely to approximate generally the economic well-being in other advanced nations of the world as the United States has become intertwined in the world economy.

Obviously, the future is uncertain. In the context of the issues of this technology assessment, it seems that the most useful assumption about the nature of evolving high-speed air transport is not cataclysmic or revolutionary, but is generally a broad continuation of the trends of the last two centuries.

Figure 18.—Long-Term Economic Trends (1975 dollars)



SOURCE: "Toward 2000: Opportunities in Transportation Evolution," report No DOT-TST-77-19, March 1977.

Chapter IX

COMPETITIVE CONSIDERATIONS AND FINANCING

The costs of a new commercial aircraft program—research, development, and production—are very large. In the case of an advanced supersonic transport (AST), no one really knows the cost, though estimates range from $6 billion to $10 billion in 1979 dollars. The figure could be much larger. Much of the investment is essentially independent of the number of aircraft built, so that scaling back production plans is not an option for reducing the financial risks.

A particular drawback is that a very large investment must be made even before testing has proceeded far enough to verify the technical soundness and performance of the product. Figure 19 shows how much an initial investment must be made before there is any possibility of a return. On the positive side, although the negative cashflow trough is very deep, it is followed in the later years of a successful program by large positive cash flows.

Figure 19 also indicates how initial investments have been escalating over time. The Douglas Aircraft Planning Department has estimated that since the 1940's these costs have risen at about 11 percent annually in constant dollars, the result largely of growing size and complexity of various aircraft. (For example, the cost per *pound* has escalated from $83 for the DC-3 to $6,300 for the DC-10 in constant 1975 dollars.[1]) By comparison, the net worth of the company has *only* grown at an annual rate of 6.6 percent. The discrepancy gives a crude measure of the ability of the company to finance new programs. As another example, the DC-10 front-end costs were 155 percent of Douglas equity, though the same costs for the DC-6 were 42 percent.

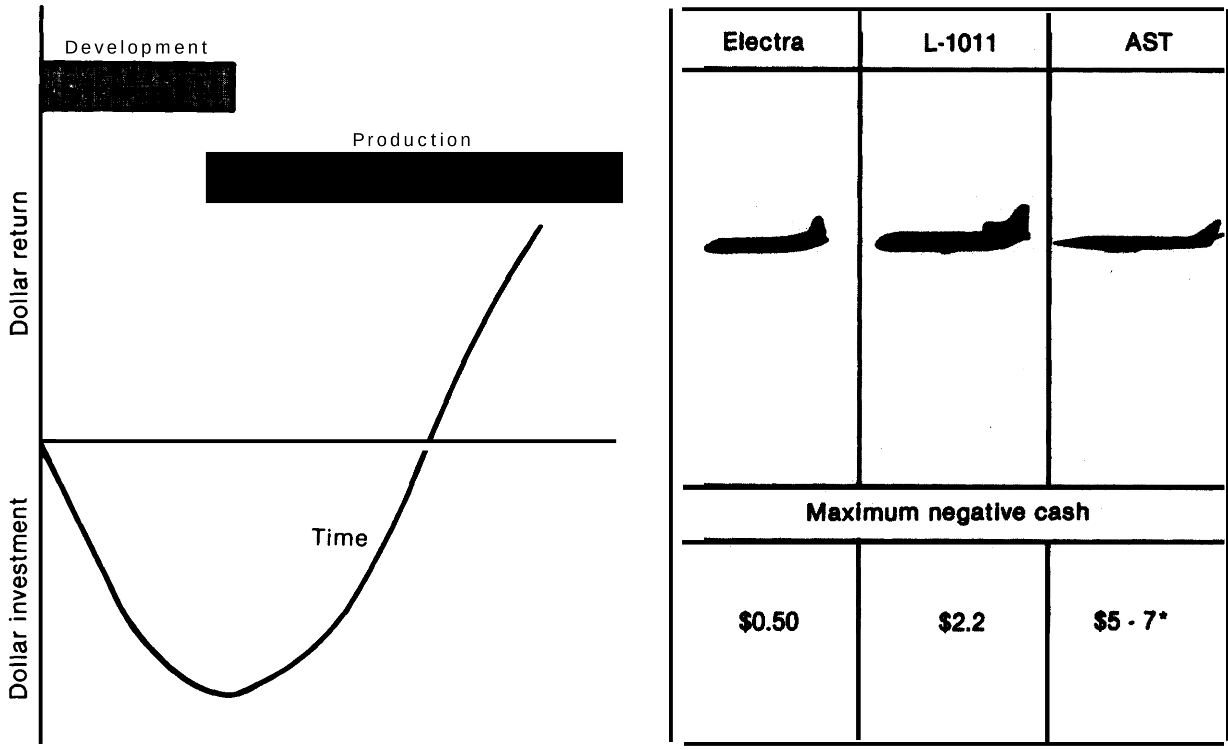
The magnitude of the required investments and the delay in any substantial returns would induce a company to time any new program to take advantage of positive cash flows from prior programs to help finance the initial costs of new ones. The periods of positive cash flows—and relatively smaller commitments of technical skills—are the "windows of opportunity" for a commercial aircraft manufacturer. Determining when such "windows of opportunity" are likely to occur is important in the intelligent pacing of any precursor technological readiness programs.

The magnitude of the required investments would either limit or preclude the possibility of two new aircraft programs being started at the same time by one company, or possibly by the entire industry. Thus, from the industry's perspective, a new supersonic aircraft program must be seen as competing directly with new subsonic aircraft programs. The freedom of the developer is impinged by the fact that the next "window of opportunity" is at least a decade or so in the future. Developers of large new commercial aircraft are motivated to act in accord with what they perceive as their long-term interests, not to assume high risks for the sake of flaunting technological glamour.

Current financing trends are making it increasingly difficult, and perhaps impossible for a single company to undertake a large new commercial aircraft program. The sheer size of the financial commitment required to enter the supersonic transport market means there will not be many competitors, even if ways, such as subcontracting and consortium arrangements, are found to mitigate the financial burdens. Whereas there is the potential for many entrants in the general aviation and small transport market in countries around the world, the potential competitors for an AST market are only from a few of the most technologically advanced nations and from a few industrial organizations. (Of course, the list of potential collaborators is much larger.) It should be remembered that competition offers its own set of risks: the potential for one economically successful program

[1]A. J. Gellman and J. P. Price, *Technology Transfer and Other Public Policy Implications of Multi-National Arrangements for the Production of Commercial Airframes*, NASA CR-159890, July 1978.

Figure 19.—Typical Aircraft Cash Flow Curve (billions of 1976 dollars)



*$6 billion to $10 billion, in 1979 dollars.
SOURCE: OTA Working Paper, Lockheed California Co , January 1979.

of, say, 400 aircraft might, with two competitors in the field, turn into two more expensive and/or unsuccessful programs of perhaps 150 aircraft each.

Balancing the forbidding size of development investments is the prospect that it pays to be the first to introduce a major new kind of aircraft. It is often observed that a large proportion of orders for a new aircraft are placed within the first several years before and after its introduction. Certainly, if an AST, reasonably competitive with subsonic aircraft, were introduced by one airline on a route, enormous pressure on competing airlines to follow suit would ensue. If the competitors fail to follow the lead, they stand to lose a major share of their markets. An airline can only afford to wait for a second offering if a later aircraft is sufficiently superior to recapture the lost competitive advantage.

Another reason that the first manufacturer to offer a new aircraft product will stand to gain is that airlines prefer operating a homogeneous fleet. A mixture of airplanes not of the same basic technical family complicates maintenance and parts inventory and demands a more diverse standing array of labor skills—all of which increase costs. Thus, though there are simplifications here, once an airline has committed itself to a given aircraft, only the very marked superiority of an alternative will induce the airline to switch to other manufacturers for subsequent orders as the fleet expands. The risks of a homogeneous fleet, such as greater vulnerability if flaws appear in the chosen aircraft, do not appear to deter this inclination toward a high degree of homogeneity.

Once any manufacturer commits to production and begins accepting orders for a new AST, in an international market where sales and competition are not constrained politically, the "window" for a second competitor with only a marginal technical advantage may be open for a very short time, perhaps less than 2 years. How long the "window of opportunity" is kept closed after this initial opening depends on the rate of growth of both the market and the increment of technical, and therefore economic, superiority the later aircraft might embody.

The time and expense required to build a technological base will depend on the degree of advancement set as a goal. No U.S. manufacturer now feels the necessary technology is available and sufficiently validated to prudently commit billions of dollars for an AST development and production program. What further degree of advancement is necessary to meet environmental standards and reasonably assure an economically successful aircraft is still a matter of judgment, although attention has been devoted to defining the investment in money and time required to fill the existing deficiencies. The National Aeronautics and Space Administration's (NASA) technology validation program that has emerged, described in chapter II, could cost $0.6 billion to $1.9 billion depending on various suggested plans and require from 5 to 8 years to complete.

The large financial demands and the need to ensure a large market for the aircraft are pressures to spread the manufacturing, and possibly some of the development costs, of an AST internationally. This can be accomplished either by extensive subcontracting or through the formation of some kind of consortium. For nations where the state partially or wholly controls both airlines and aircraft manufacturing there is a motivation to exert pressure for a quid pro quo: "I will buy your airplane instead of X's, if you will let us manufacture the hyperthrockels."

One consideration in regarding such internationalization would be technology transfer licensing. Another would be cost. The impact of a multinational program would probably be to raise the price of development on account of the costs of coordinating and bridging the distance between participants. In addition, sharing the program would probably attenuate the balance-of-payments impact of each aircraft. On the other hand, an internationally diffused program would enlarge the assured market which might offset any such reduction in the balance-of-payments impact.

IDENTIFICATION OF THE TECHNOLOGY

The military has traditionally been of great service to the commercial aviation industry. For one thing, the military has led in researching and developing aircraft technology and has been responsible for such developments as all-metal construction, radar, navigation systems, high-strength lightweight materials, and various jet engines (the JT3, JT8, C-5 which led to the CF-6, and also the B-1 which led to the CFM-56).[23] Furthermore, the military has enhanced the economic viability of the commercial sector by ordering a large number of transport aircraft, such as, in the past, the DC-3, DC-4, and DC-6, the Constellation, and to a lesser extent the KC-135 and B-707, and, in the present, modifications of the DC-10 (KC-10 tanker), B-707 (AWACS), B-737, and DC-9.

However, the situation has changed. The military is no longer leading the way in aircraft developments and thus spinoffs to commercial aircraft areas have been reduced or eliminated. The main reason for this change is that the goals of military aircraft are no longer compatible with those of commercial transports. What this means is that if it is desired to keep improving the U.S. technology base, other ways of supporting aeronautical technology should be considered.

For subsonic aircraft, improvements are expected to continue in propulsion-system efficiency (through higher temperatures and pressures achieved by advances in metallurgy and materials), noise suppression, structures and weight technology (through composites, increased use of titanium, and advanced fabrication techniques such as superplastic forming), and aerodynamics (through airfoils, winglets, and active controls). Improvements are also an-

[2?] "Future of Aviation," Committee Report, House Science and Technology, U.S. Congress, October 1976.

[23] "Research and Development Contributions to Aviation Progress (Washington, D.C.: Federal Aviation Administration, 1972).

Photo credit Boeing Aircraft Co

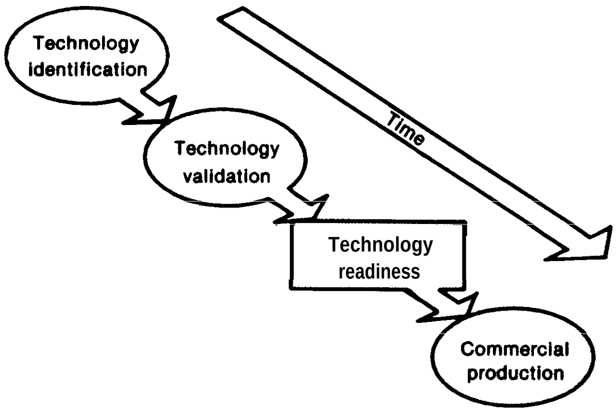
B-707– AWACS

ticipated with respect to cost, safety, and maintenance.

If the Government's role in funding research for subsonic technology continues as it has in the past, there will be further technological advancements in subsonic aircraft, Some funds will continue to be used to assess far-term technologies—generally the high-risk technology items—including composite primary structures, laminar flow control, advanced avionics, and alternative fuels. Industry R&D funds are primarily directed at near-term technologies applicable to both new aircraft and derivative versions of existing aircraft. These include: active controls, composite secondary structures, aerodynamics, and improved applications of current high-bypass-ratio engines.

In the supersonic area both NASA and the aerospace industry have been involved with improving the "state-of-the-art" for supersonic aircraft. As discussed in chapter II, NASA has proposed a supersonic cruise research (SCR) program divided into four phases, shown in figure 20. Two initial phases, of technology identification and validation, led to a phase of technology readiness—and a decision whether to precede with any commercial aircraft production. To date, approximately 90 percent of the SCR program funds have been allocated to technology identification and the question now is how much should the Federal Government invest in the validation and readiness phases. The potential technology solutions include blended wing/body designs, further propulsion improvements (coannular nozzles, advanced inlet design), improved noise suppression, titanium sandwich construction, increased structural efficiency, active controls, advanced flight controls, flight management systems, and greatly

Figure 20.— Phases of Advanced Transport Development (SCR)



SOURCE: NASA · OAST, "A Technology Validation Program Leading to Potential Technology Readiness Options for an Advanced Supersonic Transport," September 1978.

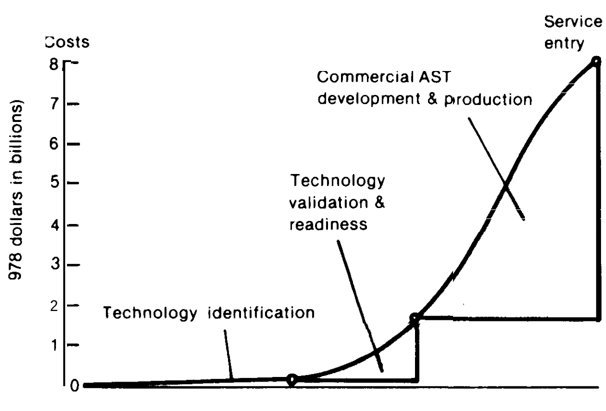
improved aerodynamic efficiency at subsonic and supersonic speeds. Along with the variable-cycle engine concept, these technology solutions could provide a basis for achieving the desired economically viable and environmentally acceptable AST. However, as discussed in chapter II, work is only beginning on validating these advanced elements, identified in the first phase of technology research.

ALTERNATIVE STRATEGIES

The immediate issue is not a go or no-go decision on an AST, but rather the selection of a desired level of commitment to technology readiness. (Such readiness in the context of an assumed $8 billion total program is shown graphically in figure 21.) Selection must weigh the attractiveness of future possibilities that a given level of technology might create or maintain against the cost of achieving such readiness.

One strategy would be to concentrate on the subsonic market and not attempt to compete

Figure 21.— Cost of a Representative AST Program



SOURCE. F E Mclean, OTA Working Paper, "Advanced High-Speed Aircraft."'

with a supersonic aircraft—the base case discussed earlier. This strategy would be appropriate if a significantly worse energy situation in the 1980's makes an AST less attractive. It would also be appropriate, regardless of energy considerations, if the potential competitors of the United States also hold back from significant investment in technological advancement. If a new foreign supersonic transport were introduced without benefit of further advancement in technology, it may well capture enough of the market to be successful—say, $20 billion—but it is less likely to be so successful as to make the subsonic market unattractive.

The no-supersonic strategy has the great short-term advantage of saving the money that would be invested in technological development. However, its risk is long-term. If a supersonic transport were developed and it were sufficiently successful, it could capture the lion's share of the market. Once there is a successful supersonic, the market for a third-generation aircraft could very well expand tremendously, especially if over land supersonic flights were permitted. If the United States refused to join the market at an early point, it would find it both difficult and expensive to catch up. Among other impediments, it would be very hard to train a new generation of specialists with competence in supersonic technology. How difficult and how expensive such catching up might be has not been evaluated.

The second strategy open to the United States would be the opposite of the above—a commitment to a fairly vigorous supersonic technology development program of perhaps $100 million to $150 million annually. This path could lead to a U.S. AST program or a major U.S. role in a cooperative international program. The ramifications of these possibilities have already been discussed. The risk is that the investment might lead to nothing except perhaps application of the technology to subsonics, military aircraft, or space transport.

The third alternative might be called the hedge strategy. The United States might invest a certain amount—perhaps $50 million per year—in technological R&D. Such a strategy could serve as an adequate base to negotiate a cooperative international program. It also would retain the option of future acceleration as a basis for a U.S. program.

It seems plausible that, whichever strategy is taken, the industry response would roughly parallel the national program. A vigorous supersonic R&D program sponsored by the Federal Government would probably evoke a much larger private sector financial commitment than a weak effort at the Federal level. The national "signal" is very important to the aircraft manufacturers.

If some commitment is made to a supersonic program, it would appear that there is no short-run alternative to continuing the past and current practice of funding NASA. As noted, NASA has a relatively modest SCR program underway, funded at about $10 million annually.

In the long run, however, there may be preferable approaches for the continued development of aeronautical technology. Such alternatives have not yet been seriously identified and evaluated, but certain principles that should guide the identification of alternatives should be noted. Any alternative should ensure a healthy competitive posture for the aircraft industry. It should also encourage innovation.

Any alternative to the NASA arrangement should seek to internalize the costs of aeronautical research to the air system. This would require, first, identifying appropriate sources of funds and, second, determining the best method for their allocation. The former is probably easier to accomplish than the latter. For example, each one-tenth of a cent levy on each domestic revenue passenger-mile would provide $200 million annually. Defining an allocation process would take time. However, in this and other regards relating to an alternative to the NASA research program, the general principle of limiting Government involvement should be followed.

BEYOND TECHNOLOGY READINESS

During the conduct of this study, concern was expressed about the manner in which the phase following technology identification, validation, and attainment of technology readiness would be funded. Though this area is addressed as a subsequent activity of this study, it is relevant here to present several alternatives which may be appropriate under different circumstances for financing the development and production of advanced supersonic aircraft:

- A U.S. aircraft manufacturer could undertake the effort as a private venture and have suppliers develop components on a risk basis in the same manner as the large subsonic transports are now developed. In addition, funds could be obtained through advanced payments by the airlines.
- It may be possible for several U.S. manufacturers to combine efforts or to form an independent organization supported by

several companies involved in the technology development phase. If two or more U.S. companies combined efforts, they would run the risk of antitrust threats which would have to be removed before this option could be considered, A recent NASA publication discusses some of the antitrust policy questions. It states:

> Among the most significant barriers to the formation of both domestic and multinational consortia is antitrust policy. The U.S. Department of Justice is not presently receptive to the suggestion that there may be a need for rationalization of the commercial airframe industry without which effective market competition may be reduced in the long run and U.S. interests may suffer materially in several ways. The only means currently available to a firm contemplating participation in any consortium to ascertain formally the acceptability of that consortium to the antitrust authorities is the Business Review Procedure of the Department of Justice. However, even a positive opinion by the Justice Department does not grant a permanent exemption from prosecution. The competitive impact of any proposed cooperative arrangement will be gauged by the Department of Justice primarily by: 1) the extent to which market competition in the United States between commercial airframe producers would be foreclosed in both the short term and the long term, and 2) the way in which the arrangement proposes to treat the issue of technology transfer. The competitive effects of proposed airframe consortia are largely indeterminate ex ante, particularly in the long run. However, given the present and prospect, both multinational and all U.S. consortia have *at least* as great a likelihood of enhancing competition as of thwarting it.[4]

- The possibility also exists for a collaborative effort between a U.S. company and one or more. foreign companies or governments. A principal reason for such a consortium would be to reduce the amount of money committed unilaterally to finance a new aircraft project through sharing the costs, benefits, risks, and responsibilities.

[4]A. J. Gellman, op cit

NASA has offered various motives for becoming involved in either intranational or international consortia:

> The mechanism of a consortium can be expected to reduce the resources required for the development, production, and marketing of a transport aircraft below what would be required if any individual participant were to undertake the project alone. However, the consortium device will probably increase markedly the total resources required for its project. Neither multinational consortia with U.S. participation nor all-U. S. consortia automatically imply either a reduction or an increase in domestic aerospace employment opportunities, in either the short run or long run. Each case must be analyzed on its own merits.

For example, some may argue that if *a* U.S. and foreign manufacturer formed a consortium, a certain amount of employment would be lost to foreign countries. However, it may be argued that, if such participation served to strengthen the domestic industry, a net improvement in employment could result in the future. A case in which this would apply would be one in which a U.S. manufacturer saw a potential for a family of aircraft, but would not engage in this venture on its own.

> The primary motive of U.S. firms for considering participation in multinational consortia is the enhancement of their individual financial resources. The consortium mechanism might also provide a means for a U.S. firm to pursue contemporaneously more than one transport aircraft development project. Preservation of market access is a secondary, but perhaps at times important, motive for commercial airframe manufacturers to join multinational consortia.[6]

While this discussion is by no means exhaustive, it does indicate some potential ways in which consortia can aid in the AST programs.

This chapter has only preliminarily addressed some of the major financing concerns with respect to validating the technology and developing and producing ASTs into commercial service. The intent was not to evaluate options for financing but only to suggest some alternatives.

[5]Ibid
[6]Ibid

A further examination of the alternatives as well as possible funding mechanisms is planned as a subsequent activity in this assessment, to be documented in a later report "Financing and Program Alternatives for Advanced High-Speed Aircraft."

U.S. GOVERNMENT PRINTING OFFICE : 1980 0 - 60-285