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THE SUPERSONIC TRANSPORT

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FOREWORD

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CHAPTER THREE—THE SUPERSONIC TRANSPORT

I. INTRODUCTION

This chapter examines some of the considerations governing public acceptance or rejection of the supersonic aircraft (SST) as a commercial transportation vehicle.

Mass public transportation by air has been a development of the last half-century. It is today the primary mode of long distance commercial travel. Its primary characteristic is speed. Each successive generation of passenger aircraft has achieved higher speeds coupled with larger carrying capacity than its predecessor. The issue at hand is whether by action of the United States Government this process should be continued beyond a natural barrier, the speed of sound.

The purpose of this study, based on a review of the literature of the controversy, is to provide a factual perspective from which to assess tangible and intangible costs and benefits of the SST.

The underlying question: Static versus dynamic technology

The controversy over the SST may not be so much over the political question as to the social worth of a particular technological innovation as over the broader question as to whether the processes and results of technological innovation generally are a social good that should be continued into the indefinite future. The literature of "technology assessment" has identified this question as salient for the United States today. Studies of the issue, most notably that by the Committee on Science and Public Policy (COSPUP) of the National Academy of Sciences,[1] suggest that even if the achievement of a stable condition is the goal, the level of technological achievement of today's society is inadequate to provide it, so that further technological progress is indispensable in any event. The findings of students of technology assessment reach a consensus on two further points:

(1) Each major technological innovation needs to be assessed in greater detail than ever before, and not once but repeatedly, to assure that its second- and third-order consequences are tolerable to society; and

(2) The social consequences of a technology need to be assessed along with the technical and economic consequences.

Opponents of technology appear to take various positions: (1) that technology is itself undesirable because its side effects are inescapably adverse, (2) that the pace of technological change is too fast to be accommodated to the socio-political structures of human organization, (3) that technological innovations occur so rapidly that human organizations are unable to sort out the good from the bad, or (4) that the variety of innovations produced by technology imposes such a burden of choice in the individual as to impair the quality of life.

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[1] U.S. Congress. House. Committee on Science and Astronautics. "Technology: Processes of Assessment and Choice." Report of the Committee on Science and Public Policy, National Academy of Sciences, July 1969. (Washington, U.S. Government Printing Office, 1969), page 118.

Any substantial body of thought that opposes technological innovation per se, would be inclined to join forces with those who oppose specific innovations on their own merits. While this study is concerned with the specific advantages and disadvantages of one technology, *viz.*, the SST, the issue as to the general merit of technology needs to be disposed of. The NAS Committee on Science and Public Policy has put the matter in perspective with its conclusion:

> The future of technology holds great promise for mankind if greater thought and effort are devoted to its development. If society persists in its present course, the future holds great peril, whether from the uncontrolled effects of technology itself or from an unreasoned political reaction against all technological change.[2]

Although the economic aspects of technology tend to be decisive in determining whether or not some particular innovation should be pursued, the ultimate values and costs—which are hard to quantify—are environmental. As the COSPUP Report notes, "* * * technology * * * is nothing more than a systematic way of altering the environment." Accordingly, the report states:

> The choice * * * is between technological advance that proceeds without adequate consideration of its consequences and technological change that is influenced by a deeper concern for the interaction between man's tools and the human environment in which they do their work.[3]

Moreover, the assessment of technology requires—

> * * * not [for society] to conceive ways to curb or restrain or otherwise "fix" technology but rather to conceive ways to discover and repair the deficiencies in the processes and institutions by which society puts the tools of science and technology to work.[4]

If it be granted that technology should not—and indeed cannot—be generally arrested and frozen in today's mold, then the question of accepting or rejecting a particular innovation rests on two subsidiary questions. One is whether the system itself is or can be economically self-supporting. Will it pay for itself? Is there an economic demand for its services, sufficient to justify the investment? This issue needs to be answered quantitatively, and if the finding is adverse, the issue usually becomes academic.

The second question is whether the adverse effects of the innovation on man and on the human environment negate the beneficial effects, and also the economic values of the innovation. Since the adverse environmental effects (unless they are unmistakably catastrophic) do not automatically generate a negative decision, the issue becomes a matter for policy determination by the Government. This decision rests nationally with the Congress. Also, there is a residual regulatory concern, now being delineated in the courts, that rests with the States and municipalities. No mechanism is yet available for the international assessment of a technological innovation.

With respect to the SST, since a substantial outlay of funds is required of the Federal Government, and since the asserted environmental effects are national—indeed global—the technology assessment decision of whether or not to proceed with this innovation rests with the Congress. It is both an economic and an environmental issue. Meanwhile, two other projects are already well along toward development of commercial supersonic aircraft, one jointly by the British

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[2] Ibid., page 118.
[3] Ibid., pages 2-3.
[4] Ibid., page 15.

and French, and the other by the Soviet Union. To some extent, these competitive activities seem likely to reduce the scope of the decision: it may be not whether the global environment is to receive a civil SST, but rather whose SST.

Economic considerations of SST development

The economic questions that confront the Congress are for the most part those of straightforward cost/effectiveness and demand forecasting. They are similar, for example, to aspects of the long-range planning problem that annually confronts top management in the automobile industry.

What will be the costs of achieving commercial supersonic air transportation?

What level of engineering design risk is involved?

What dollar benefits will accrue from this capability, to the carriers, to the aircraft industry, to the using public, and to the United States Government—in other words, to the taxpayer?

How reliable are the estimates of future demand for the use of the proposed hardware?

What economic adjustments are implied by the introduction of supersonic flight, and what costs and benefits are implicit in these?

What is the proper form of management of the enterprise, if it is decided upon?

What is the appropriate method of funding of the enterprise?

What would be the effect of banning the Concorde and TU–144 from the U.S.? Would the countermeasures in international economic competition caution against such a unilateral action?

Is participation of the Federal Government in the funding of the enterprise the best use of its fiscal resources? Is there an adequate financial return? In essence, does the SST assure an appropriate net advantage in both tangible and intangible factors, to the Nation and its citizens?

Environmental considerations of the SST

The environmental consequences of the SST appear to be both complex and controversial. Some of these tend to interact with some of the economic issues. For instance, perhaps the most salient environmental question grows out of the fact that the supersonic aircraft, by virtue of its capability to move at supersonic speeds, causes sonic booms. The question is thus raised as to whether these high-altitude effects will be an intolerable nuisance; the tacit understanding has apparently been established that the proposed aircraft would travel at supersonic speeds only over the oceans—a constraint that would seem to deprive the vehicle of a part of its potential economic advantage and flexibility.

The high power requirements for supersonic flight, and the consequent large consumption of fuel, imply that the aircraft should be large in size and carrying capacity if it is to pay its way. This requirement leads to environmental questions which involve the effects of the effluent of the aircraft: air pollution resulting from the necessarily high level of effluent during take-off, and the conjectural climatic consequences of high-altitude discharge of water vapor and particulate matter. The noise of the (necessarily highly powered) SST engines on and near the ground is also cited as an environmental degradant.

Against these allegations of undesirable effects, there are such positive factors as the reduction in number of aircraft per thousand passenger miles (or per number of passengers transported), the saving of time, the general benefits that are alleged always to result to a nation's technology from a large effort in some one direction, the undeniable benefit to the nation's technological posture where technology correlates increasingly with diplomatic influence, and the probability that increased speed capability of aircraft in the air would generate pressure on the airlines, as well as other participants in transport services, to improve the lagging efficiency of on-the-ground operations, toward making air travel a true system.

Another consideration, often overlooked, is that a vigorous effort in the advanced technology of large-scale, supersonic flight, aiming to make it compatible with the preservation of a congenial environment for man, can be expected to yield many beneficial developments in environmental science and technology that can be useful in other problems and activities of environmental enhancement.

II. Breaking the Barrier of Sound

The first manned vehicle to explore the regime of supersonic speed was the Bell X–1, an American aircraft piloted by Charles Elwood Yeager.[5] During a sequence of 41 flights, all of brief duration, he took the rocket-powered X–1 to speeds exceeding Mach 2,[6] and to altitudes above 70,000 feet. The first flight through the sound barrier occurred Oct. 14, 1947.

The shape of an airplane is a combination of blunt and shallow curves, sloping planes, and edges. Air flows over each surface at a different speed, all related to the speed of the aircraft. The shape of the aircraft is designed so that the air will flow smoothly by it, whether the aircraft is moving slower or faster than the speed of sound. However, there is a critical range of speed, the transonic region, which extends a few miles per hour on both sides of Mach 1. In this region, parts of the air flow move subsonically and others move supersonically. While in this regime, the aircraft is buffeted by shock waves and turbulence. Yeager found it advisable to pass through it quickly: to remain in it too long was not only uncomfortable to the passenger but hazardous to the structural integrity of the aircraft. However, once the aircraft passed through this "transonic zone," the air flow became smooth again.

Yeager's flights resolved the long debate among aerodynamicists over the possibility of controlled flight beyond the sonic barrier. Also, he opened the supersonic domain as a useful realm to any aircraft

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[5] Numerous claims were made by World War II pilots that they had broken the sonic barrier with their propeller-driven aircraft in full power dives from high altitude. Speeds as high as 800 mph, sometimes accompanied by sonic booms, were reported. However, during World War II, methods were not available for measuring accurately the speed of diving aircraft. Although these claims seemed plausible at the time, knowledge of compressibility effects was limited, and nothing was known about the transonic regime. Subsequent analysis has established that none of the World War II propeller-driven aircraft, designed for subsonic flight, could have exceeded 550 mph, a speed well below the speed of sound.

[6] Speed is often given in multiples of, or fractions of, the speed of sound. Mach 1 is the speed of sound. The name is that of the Austrian scientist, Ernst Mach, 1838-1916. The speed of sound (m–1 or Mach 1) in air is not a constant: it varies primarily as a function of temperature and to a lesser extent as a function of pressure. With increasing altitude, the air pressure declines linearly, but temperature reverses direction several times. As temperature declines, so does the speed of sound. The relationship is expressed by the formula:

$$\text{Mach 1 (in mph)} = 33.5\sqrt{T} \text{ (in degrees Rankine)}$$

At a cruising altitude of 60,000 feet, (the cruising altitude proposed for the SST), the normal temperature is minus 70° F. Mach 1 at this temperature is 680 mph. At an altitude of 150,000 feet, temperature has risen again, and is normally about 50° F. At this temperature, Mach 1 is about 750 mph, which is nearly what it would be at the earth's surface on a 50° F day.

with enough power to reach it. His experiments signaled the beginning of a vigorous research program to achieve supersonic flight routinely. Military advantages of this capability seemed obvious; although the commercial advantages were less so, aeronautical enthusiasts observed that just as subsonic aircraft had drawn the four corners of the United States conveniently close, supersonic aircraft would do the same for the whole globe.

Importance of turbojet engine for supersonic flight

The key to general supersonic flight was the turbojet engine. A principal obstacle to the achievement of supersonic speeds with propeller-driven aircraft had been the aerodynamic limitations of the propeller itself. The tip of the propeller entered the transonic regime long before the speed of the aircraft did; at that point, loss in efficiency through turbulence wasted power so that a speed ceiling of around 500 mph was generally accepted by aeronautical engineers as the ultimate top for propeller aircraft.[7]

Concern over the inherent speed limit imposed by the propeller led two independent investigators to seek and find a solution in the turbojet engine. The first successful turbojet-powered aircraft, the He 178, was produced by Ernst Heinkel in 1939; soon afterward, Frank Whittle's engines were used, in 1941, to power the Gloster E-28. The Heinkel and Whittle engines both used a centrifugal compressor as a first stage: air was compressed, expanded by burning fuel in it, and then discharged through a turbine which drove the compressor; forward impetus was provided by the jet thrust of the hot combustion products after they passed through the turbine.[8]

The turbojet engine offered a solution to the problem of propeller speed limitation. Thrust and efficiency of this new system, contrary to that of the propeller, were actually increased with increased forward speed.

Early in World War II, Whittle's insistent warnings to U.S. military authorities, together with the appearance in combat of the ME 262 (a twin-engined German fighter whose top airspeed exceeded by 100 mph the speediest planes of the Allies), persuaded the Army Air Force that the turbojet was worth examining. A Whittle engine was obtained and after a brief test, the Air Force asked the General Electric Company to produce an improved version compatible with U.S. industrial practice. An airframe was designed and built to receive the engine. The project was conducted with incredible speed under high security, camouflaged by preempting the project nomenclature of another secret aircraft development, the Bell XP-59 which was subsequently shelved. In 1942, the Bell new XP-59 received its engine, flew successfully, and introduced U.S. military and industrial aviation to the jet age.

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[7] As of August 16, 1969, the official speed record for propeller-driven aircraft was 483 mph. The record was achieved by a modified Grumman F8F "Bearcat." Almost 7 feet of wing was removed, leaving a span of 27.5 feet; weight was reduced from a normal gross of 10,400 to 5,800 pounds, of which almost half was contributed by the oversized engine. The prior record, 469 mph, had been established 30 years earlier by the German ME 209R, which took it from the Italian Macchi Mc 72 seaplane (440 mph in 1934). Thus in 35 years the speed of propeller-driven aircraft had been raised 43 mph. The heroic measures required to accomplish this small increment of extra speed make further advances with piston-engined, propeller driven aircraft, unlikely.

[8] The Italian engineer, Campini, in 1940 tried a workable but impractical alternative in the Caproni N-1. He used a piston engine to drive a large air compressor, air from the compressor was discharged through the open tubular body of the aircraft where additional fuel was sprayed into the air blast and ignited. This was a true jet, but the system was inefficient and was abandoned.

It took 11 years from that point to bring about the first U.S. military aircraft capable of routine supersonic flight. This was the first of the so-called "Century" series, the North American F-100[9] which flew in 1953, six years after the brief flights of the rocket-powered X–1A had breached the sonic barrier for the first time.

III. Scaling up the Technology of Supersonic Flight

Military efforts to extend the application of supersonic aeronautical technology to larger aircraft produced an uninterrupted sequence of misfortunes and controversies. When the Air Force undertook a supersonic replacement for the subsonic B–52 bomber, the first result was the short-lived B–58. This three-man bomber could reach Mach 2.1 at 44,000 feet; it could cover its full range of 2000 miles in less than 2 hours. However, the B–58 was marginally useful; it fell short in payload as well as in range for its intended mission as an intercontinental strike vehicle.

The development span of the B–58 overlapped that of the B–70, of which only 2 units were actually built and flown before the program was dropped. More will be said of this development, which had considerable significance for the evolving proposal later on to build a prototype commercial transport for supersonic flight.

Meanwhile, efforts of the U.S. Navy to produce a large supersonic seaplane centered on the P6M, under development by the Glenn L. Martin Company in Baltimore. This design encountered several tragic misfortunes in flight before the project was terminated.

The last stage in the sequence was the F–111, a smaller supersonic fighter-bomber system intended (in various versions or modifications) for both Air Force and Navy use. The F–111 has remained controversial since its inception.

In view of the fact that large commercial aircraft traditionally grew out of military antecedents, it may be useful to examine the fate of one of these large supersonic bombers.

The development of the "all-purpose" B–70 bomber

Proposed as the world's first large aircraft capable of long-range, sustained, supersonic flight, the B–70 was envisioned as the logical replacement for the subsonic B–52. It was also seen as fulfilling the need for a super-performance surveillance aircraft. The further possibility was later suggested that the general prototype might be modified into a commercial version to compete with contemporary (1959) European schemes to produce a family of short-range, intermediate, and long-range supersonic aircraft for commercial service.

Initial design specifications for the B–70 were issued by the Air Force in October, 1954, with an invitation to aircraft companies to compete for the job of prime contractor. The Air Force plan was to develop and deploy a fleet of these aircraft as long-range, multi-mach bombers by the mid-1960's. The plan fell victim to prolonged controversy. At first, problems centered on the wide variety of technical approaches advanced by the bidders. Then, as these were resolved,

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[9] The North American F-100 was a single seat fighter powered by a Pratt & Whitney J57 turbojet. Its top speed was 925 mph at 35,000 feet altitude. Its engine could produce 10,000 pounds of static thrust in cruising, and was equipped with an "afterburner" which increased the thrust to 16,000 pounds for short periods, such as on takeoff. (An afterburner is a tubular extension or tailpipe, added to a jet engine. In its use, fuel is sprayed into it and ignited; the already hot exhaust gas is thus further heated and expanded, greatly increasing the exhaust velocity and resulting thrust of the system.)

the project next came under attack as an expensive and unnecessary military alternative to the intercontinental ballistic missile. Development of the intercontinental ballistic missile, armed with a nuclear warhead, had provided a weapon competitive in destructive capability with the long-range strategic bomber. It also reduced the striking time of an intercontinental attack from hours to minutes. The military commitment to bomber aircraft was undoubtedly lessened by this alternative technology, and with it the willingness (or necessity) to make the heavy investment required for its successful development.

Opposition to the B-70 program grew steadily from the time the Air Force released its Request for Proposal in 1954. By 1959, the embryo aircraft was under attack by both missile advocates and others who saw it consuming an increasing share of the declining aircraft budget in the (also declining) budget of the Department of Defense. Presidential action came to terminate the program, November 30, 1959, although the President later granted the Air Force permission to continue the B-70 as a minimum-cost, aerodynamic research program. Some Members of Congress were critical of this decision to drop the program. The development was viewed as both an essential replacement for the aging B-52, and a prototype for a commercial SST.[10] However, the President's decision was firm, and the program came to a close with a few experimental and test flights of the two prototype vehicles.

Efforts to commercialize the B-70 technology

The possibility of a commercial version of the B-70 was raised in 1959 when General Elwood Quesada, then Administrator of the Federal Aviation Agency, called the President's attention to plans of the British aircraft industry to build two models of commercial supersonic SSTs, one for short-range domestic service and another for intercontinental service; as well as the plans of the French aircraft industry to build a medium-range SST, to be called the "Super-Caravelle." [11]

General Quesada noted that the beleaguered B-70, by then jocularly referred to as the "paper airplane which would fly in a cardboard sky," was in fact superior in technology to either the British or the French SST concepts (independent at that time). The B-70 design called for continuous Mach 3 flight over a range exceeding 7000 miles; the foreign firms were proposing smaller vehicles, to cruise at speeds of less than Mach 2. He therefore urged the President to consider the possibility that a commercial version of the B-70 be designed to be the U.S. entry in the emerging international competition.

In Quesada's view, the civil application would be derived from a technology developed to satisfy a purely military requirement. This had historically been the conventional pattern of innovation of commercial aircraft. As he put it—

> Ever since the Wright brothers' memorable accomplishment in 1903 the Military Establishment had had a vigorous development program designed to meet their needs for increasingly high performance aircraft. The pressing demands

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[10] For example, the Preparedness Investigating Subcommittee of the Senate Armed Services Committee, chaired by Lyndon B. Johnson, reported at the time: "Transportation of people and cargo at three times the speed of sound and above the weather could be attained through the utilization of B-70 technology in a commercial air vehicle." (Cited in "Congress and the Nation, 1945-1964," Congressional Quarterly, page 307.)

[11] The Caravelle, built by the Sud-Aviation company, was France's first commercial jet transport airplane. Its first flight was May 27, 1955. It entered commercial service May 18, 1958, with Air France. The world's first commercial jet transport was the De Havilland Comet, DH-106, which first flew in 1949 and entered commercial service with BOAC May 2, 1952.

of national defense have characteristically given precedence to military budgets for this purpose.

After designs were fixed and quantity production established to meet military requirements, it was often possible to build adaptations for purchase by air carriers and use in the civil fleet. This has been especially true in the development of crucial components such as engines and propellers, as well as materials and techniques of design. Thus, for over 55 years commercial aviation has had the advantage of leaning on and borrowing from a strong military development program.[12]

Evaluation of the B-70 conversion plan

There were technical advantages and disadvantages of this proposed course. The value of the B-70 as a prototype lay in its advanced aerodynamics, control methodology, high-temperature-resistant structural design, and techniques of fabrication. These were all gains that derived from a substantial history of applied research sponsored by the Department of Defense. Application of these advances, acquired at considerable cost, would give an American SST a significant edge over the foreign competition. However, Quesada's proposal had disadvantages as well. The long, slim body of the B-70 would not convert well to civilian use. In the various proposals for this conversion, the passenger seating capacities ranged from 15 to a very crowded 100. A converted version with the required upgrading for reliability and design modifications for airline service was judged likely to cost about the same as a completely new design for the specific purpose of commercial service. A study for FAA, by United Research, Inc., reported in October, 1960, that the development of a civil SST, based on the B-70 prototype, would require about $1 billion, a figure beyond the financing capability of individual firms in the aircraft industry, even if based on a backlog of firm orders.[13]

At the close of his tenure as FAA Administrator, Quesada placed contracts with two engine companies for SST power plant studies, and recommended an acceleration of the FAA program of studies of the entire system.

When President Kennedy took office, in January, 1961, he named Najeeb Halaby as Quesada's replacement. At the request of the new President, March 3, 1961, Halaby organized a team to develop a statement of national goals for aviation in the 1960s. One of the findings of this team was a recommendation for intensified efforts to produce a "Mach 3 transport." It called for an SST design with double the possible passenger accommodation of the B-70, featuring a swing-wing concept.

As to funding, the study proposed that—

> Government funds should be utilized through the research, design, development, prototype and probably production stages. Every effort must be made to recoup the Government's financial investment through some type of royalty system to be paid by the operators.[14]

Changing role of military technology

Beginning with the aftermath of World War I, civil aeronautics in the United States (and elsewhere as well) had leaned heavily on

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[12] U.S. Congress. House. Committee on Science and Astronautics. "Supersonic Air Transports," Hearings before the Special Investigating Subcommittee of the . . . , 86th Cong., 2nd sess., May 18, 1960, (Washington, U.S. Government Printing Office, 1960) page 43.

[13] Don Dwiggins. "The SST: here it comes, ready or not." (Garden City, New York, Doubleday and Company, 1968), page 117. (294 pages.)

[14] This was "Project Horizon," a report of a task force consisting of Fred. M. Glass, Stanley Gerwitz, Selig, Altschul, Leslie A. Bryan, Gerald A. Gusch, Frances T. Fox, John F. Loosbrook, and Paul Reiber. The report of Project Horizon was submitted to the President Sept. 5, 1961, and made public Sept. 10, 1961.

surplus military equipment and on military-trained personnel. By November of 1918, the United States possessed 10,510 aircraft—6,972 at home—and a large inventory of engines and spare parts. Military trained personnel in the air arms, being demobilized, numbered 228,368. All this surplus aeronautical hardware deterred new development or production, but provided an inefficient means for a precarious and subsidized air transport industry. Meanwhile trained fliers and mechanics sought ways of using the skills they had been taught. Further military development of aircraft in the United States lagged, and most of this activity was conducted in Europe and later Japan.

During the two decades between the two World Wars, considerable progress was made toward the development of commercial transports. Gradually, designs departed from the straitjacket of military prototypes. This trend was epitomized in the development near the end of that period of the DC-3. This was a true trail-blazer, remarkably economical for its time to operate and maintain. It spurred the proliferation of many new feeder airlines and contributed immeasurably to the spread of air service all over the world. Although it was a far cry from combat aircraft, the military services made extensive use of it for transport purposes in World War II (the C-47).

The translation of the military advances in World War II into civil aircraft designs was more involved and complex than it had been 20 years earlier. Under the spur of military necessity the principles of aeronautical design had been vastly improved. These principles, of course, were the same, regardless of whether the function of the design was military or civilian. However, the configuration of an aircraft was profoundly influenced by its function, so that the same aeronautical design principles led to different final products. Speeds of postwar propeller-driven aircraft were not notably different for military or commercial service but cabin space was.

The powerplant as key to aircraft evolution

From the Wright Brothers to the present day, developments in heavier-than-air craft have derived most importantly from innovations of engine and power-train. Without the gasoline-fueled reciprocating engine, the Wright Brothers' aircraft would not have been possible. During the period following World War I, important progress was made in improving the horsepower-to-weight ratio of engines, culminating in the turbo-compound reciprocatory power plant that made Coast-to-Coast nonstop flight a commercial practicality. Again, military requirements justified and paid for the advances in engine technology. The civil market was an eager but secondary outlet for these products.

With the advent of the aircraft gas turbine engine, however, the suitability for commercial purposes of military power plants become less obvious or practical. The turbo-prop engine,[15] while first used in military aircraft, in England, in 1945, was quickly discarded for military purposes. Its efficiency was highest at moderately low altitudes. The aerodynamics of the propeller limited the speed of prop-jet aircraft to the subsonic regime. However, because of its fuel economy, freedom

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[15] The turbo-prop engine has a propeller attached through a gear box to the front end of the shaft that extends through a compressor stage, a fuel burning stage, and a turbine stage. The turbine provides the power to rotate the entire assembly. There is also some residual thrust from exhaust gas emitted from the turbine into the tail pipe.

from vibration in flight, and capability of delivering many times the horsepower of reciprocating engines of comparable weight, it moved successfully into the commercial field. The Viscount, powered by four Rolls-Royce turbo-prop engines, became operational in 1953. The commercial utility of the turbo-prop, it should be noted, was not and still is not fully exploited because its performance characteristics did not warrant substantial military R&D investment.

The primary form of military gas turbine engine for aircraft is the turbojet.[16] This engine, which was operationally employed in both British and German military aircraft by 1942 (the Gloster Meteor and the Messerschmidt 262), derives all of its thrust from the exhaust. At low altitudes, the turbojet is inefficient but at high altitudes its efficiency is excellent. The principal problem is that it pumps in more air than it can use, so that—especially at low altitudes—adjustable restrictions are needed to limit the air intake. Although this kind of engine is now being proposed for use in the SST, which would operate predominantly at high speed and altitude, its fuel consumption at the lower speeds and altitudes of post-World War II commercial air travel have made it marginally useful for lower-performance civil aircraft. The first commercial transport to use the engine was the British Comet, in 1952. (Faulty cabin design of the Comet caused its withdrawal after two years of service; a redesigned model appeared in 1958, still using turbojet engines.) The first U.S. airliner to use turbojet engines was the Boeing 707, in 1958; it was followed in a few months by the Douglas DC-8. In the early versions, both aircraft used unmodified military jet engines. The engines were turbojets ("pure" jets) which were fine for high speed flight (speeds beyond the design capability of the 707 and DC-8) but, in stressing this vital military asset, the engines were not designed for fuel economy.

Fortunately, a sideline investigation of little military interest was to appear. One early device to deal with the surplus air which all jet engines must either use or deflect once in flight, was the "by-pass"; in this model of engine, surplus air is ducted around the combustion chamber and then added again at the tail pipe. The result is augmented thrust and reduced fuel consumption especially at moderate speeds and low altitudes.

Further increases in efficiency were offered by tapping the surplus energy in the turbine system to increase the mass flow of air by accelerating it with a large, front-end fan and then ducting it around the rest of the engine assembly. This was the turbo-fan. Now in general service in U.S. airliners, it has an engine front that is larger in diameter than the rest of the engine.[17]

A belated commercial development, the turbo-fan appeared in the United States in 1961 when the Pratt & Whitney Company modified their military engine, the J-57, by adding a fan to the front end and ducting the air stream around the body of the basic engine. This

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[16] The turbojet, or true jet engine, derives all of its thrust from its exhaust. Air is scooped into an intake aperture, is compressed by a compressor, has fuel injected into the compressed air and ignited, and then the combustion products force their way through a turbine stage which powers the compressor stage. (Compressor and turbine are tied directly to the same central shaft.) Finally, the combustion products are expelled through the tail pipe to provide the jet thrust.

[17] The turbo-fan was introduced by the British Metropolitan-Vickers Company, in 1943. This was done by modifying a turbojet engine, adding a two-stage, contra-rotating fan. This rather primitive engine increased the thrust of the basic turbojet by 66 percent, without additional fuel consumption. However, for military purposes, this concept was not attractive. The large frontal area would have too much drag for speeds approaching Mach 1. Conversely, the economy and power provided by the turbo-fan at lower speeds made it important for commercial applications. But since the development of gas turbine engines was funded almost entirely by the military services, the turbofan was late in coming into use.

modified version, designated the JT 3D, increased thrust 50% while simultaneously decreasing fuel consumption 13%. The commercial airlines quickly moved to take advantage of the innovation. Existing equipment was retrofitted, and new aircraft were equipped with turbo-fans. By 1965, virtually all non-propeller-driven civilian jets, foreign and domestic, were using the turbo-fan.

The rapidity with which the turbo-fan was adopted, once available, suggests the importance of a substantial R&D capability for the purpose of advancing the state of the art of commercial airframes and engines. Although the military version of the turbo-fan had been investigated more than two decades earlier, its failure to offer significant military advantage had resulted in a long and costly technological lag in commercial application.

IV. DETERMINING NATIONAL POLICY ISSUES OF THE SST

When President John F. Kennedy took office, early in 1961, the SST came into sharper focus. Describing himself as determined to "get America moving again," the new President invited opportunities for active causes. Responding to this opportunity, Najeeb Halaby, FAA Administrator followed his predecessor's initiative and urged consideration of a civil supersonic transport program. He found the President receptive.

As the SST project began to take a more tangible form, three interlocked questions became salient: (1) Should the Federal Government assume responsibility for the program? (2) If so, who should be in charge? (3) What fiscal arrangements would be appropriate? All three questions, of course, hinged on the overriding issue of Should there be such a program?

Previously, in the development of aeronautical hardware the military services had made all these decisions, subject of course to ultimate congressional ratification through the appropriation process. Military procedures followed a well-worn path: preparation of a strategic requirement, survey of technological alternatives, feasibility studies, preliminary design competition, selection of a prime contractor, negotiation of a contract with time-phased target objectives, and concurrently the presentation of an over-all bill to the Congress in which the specific project would be only one small element among many. But the SST project could not take this route.

Necessarily, it was a commercial project that needed to be compatible with the commercial environment. Instead of satisfying a strategic military requirement, the SST proposal was offered to match the less structured requirements of meeting and surpassing foreign competition operating from a different economic and political base, on a different time scale, with a different state-of-the-art. It raised the kinds of questions that private business organizations normally try to answer—and profit only by answering perceptively, such as:

> Would the end product find an adequate market for sufficient numbers of units to go above the break-even point?
>
> At the time it became available for scaled-up production, would it be able to compete successfully in price, performance, and maintenance with rival aircraft already on the drawing board?
>
> What level of improved performance would be needed for it to supersede existing subsonic aircraft and outperform the new

foreign competition without incurring an excessive degree of engineering risk?

Risk is an inherent element of the commercial environment. But in the appropriation of public money, elimination of risk is a compelling consideration. With the magnitude of the SST investment exceeding the capacity of available sources of private funds, to make the project go would require Government funding. How was the aspect of risk to be dealt with?

Criteria for the decision to proceed with the SST

President Kennedy announced the SST as a national objective in a Commencement address to the Air Force Academy, June 5, 1963. He had taken time out for this visit in the middle of the delicate maneuverings that preceded the negotiation of the Limited Nuclear Test Ban Treaty. Five days later, he would deliver his detente proposal at The American University, in Washington, D.C., that he hoped would lay the groundwork for an era of global peace and understanding. It is possible that he saw in the SST a dramatic illustration of the "plowshare" principle, as well as a peaceful alternative to occupy the aerospace industry. However, he also expressly interpreted the SST as evidence that the technology of manned flight—military as well as commercial—retained its vitality. The commitment to the SST, he declared, was "* * * essential to a strong and forward-looking Nation, and indicates the future of the manned aircraft as we move into a missile age as well."

The President sketched briefly the terms of reference of the project. It should be a partnership of Government with private industry. The project management should be pressed to "develop at the earliest practical date the prototype of a commercially successful supersonic transport superior to that being built in any other country of the world."

> An open, preliminary design competition will be initiated immediately among American airframe and powerplant manufacturers with a more detailed design phase to follow. If these initial phases do not produce an aircraft capable of transporting people and goods safely, swiftly, and at prices the traveler can afford and the airlines find profitable, we shall not go further.[18]

Soon after his visit to Colorado Springs, the President sent a letter to Congressional leaders in which he discussed the criteria and the method of financing of a Government-sponsored SST. He enlarged somewhat on the last item.

> The cost of such a program is large [said the President]—it would be as great as one billion dollars for a development program of about six years. This is beyond the financial capability of our aircraft manufacturers. We cannot, however, permit this high cost, nor the difficulties and risks of such an ambitious program to preclude this country from participating in the logical next development of a commercial aircraft. In order to permit this participation, the United States, through the Federal Aviation Agency, must proceed at once with a program of assistance to industry to develop an aircraft.

The program proposed would call for a participation to at least 25 percent of the development costs by the manufacturers, and a further contribution (amount unspecified) by the airlines through royalty payments. The ceiling on the Government investment would be $750 million, although additional credit assistance might be extended to

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[18] U.S. President. John F. Kennedy. "Remarks at Colorado Springs to the Graduating Class of the U.S. Air Force Academy, June 5, 1963." Public Papers of the Presidents of the United States, 1963. (Washington, U.S. Government Printing Office, 1964), page 441.

manufacturers during the production process. The President stressed that "participation by industry as a risk-taking partner is an essential of this undertaking." The objective was to build a commercially sound aircraft, as well as one with superior performance characteristics. The test of its economic soundness would be measured by "industry's willingness to participate in the risk-taking."

Thus, the project would be "principally a commercial venture," although it would "yield much technological knowledge." The President summarized the further objectives of the SST as—

To "maintain the historic United States leadership in aircraft development";

To "demonstrate the technological accomplishments which can be achieved under a democratic, free enterprise system";

To "expand our international trade" through both its manufacture and operation;

To "strengthen the United States aircraft manufacturing industry * * * and provide employment to thousands of Americans."[19]

The lag in U.S. aeronautical technology

The President's decision that the Government should participate in the development of an advanced civil aircraft had followed several expressions of concern that civil aviation was failing to advance at a rate commensurate with the domestic and international markets. On September 1, 1961, President Kennedy received a report prepared at his request by the Task Force on National Aviation Goals (Project Horizon).[20] The report was intended to "define the technical, economic and military objectives of the Federal Government throughout the broad spectrum of aeronautics." It identified the emergence of the space program and the reduced emphasis by the military on the development of manned combat aircraft as major causes for the lag in civil aeronautics development. Said the Task Force:

> An adequately funded, prudently managed, continually updated research and development program is essential to the maintenance of U.S. world leadership in aviation. Federal Government responsibility for aviation research has long been recognized and its participation in such research has been extensive. However, in the past Government-sponsored aeronautical research has largely been stimulated by military requirements for advanced manned aircraft. In recent years this stimulation has declined as a result of the growing concentration on development of missiles and space systems by the military and by the National Aeronautics and Space Administration. It is no longer possible for civil aviation to progress mainly by reliance on the byproducts of military-related research and development programs.
>
> There is no question that aeronautics is running a poor second to space technology in the time, talents, facilities, and funds expended on it within NASA. Steps must be taken to upgrade recognition of an activity in support of this national requirement.
>
> With the decline of military emphasis on manned combat aircraft, some shift toward a more centralized coordination of civil aviation research and development in the United States appears needed. This need is sharpened by the forthcoming requirement for more extensive Government financial participation in essentially civil aeronautical development programs, such as the supersonic transport.[21]

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[19] U.S. President. John F. Kennedy. "Letter to the President of the Senate and to the Speaker of the House on Development of a Civil Supersonic Transport. June 14, 1963." Public Papers of the Presidents of the United States, 1963. (Washington, U.S. Government Printing Office, 1964), pages 475-77.

[20] U.S. Task Force on National Aviation Goals. "Project Horizon." Report of the . . . Federal Aviation Agency. September, 1961. (Washington, U.S. Government Printing Office, 1961), 239 pages. See especially page 17.

[21] Ibid., pp. 48-49.

These views were echoed in Congress where a staff report of the Senate Committee on Aeronautical and Space Sciences noted that U.S. aeronautical technology was falling behind: "Other countries of the world, with less responsibility than the United States for peacekeeping and international prestige, have continued developments in aeronautics which could command substantial markets and adversely affect our balance of trade." [22] The report expressed concern over the assertedly diffused responsibility for national policies for aeronautics and particularly the want of a federal policy for sustained technological development of civil aeronautics. The need for an integrated national system of air transportation was real, un-met, and under-valued. Said the report, in part:

> An obvious contrast may be noted when the research and development program for aeronautics is compared with the total NASA appropriation ($124 million out of $5,012 billion or about 2 percent for fiscal year 1967). A more meaningful question is whether the funding and the program for aeronautics are adequate, regardless of the magnitude of the space program.

Also—

> Civil aeronautics is an increasingly important part of our economic system with great potential for our international balance of trade and technological prestige. [Moreover], There is a notable absence of national transportation system policy to define the role of various modes, to study the problems of interfaces between modes, and to choose among technological alternatives.[23]

Operationally, civil aeronautics seemed on the threshold of an unprecedented potential for growth, both in the United States and abroad. The United States dominated the world market for aeronautical goods and services, yet, aeronautical services, domestically, were steadily declining in quality as unsolved problems of congestion intensified. New development activity seemed to be stagnant. The Nation, Congress was told, could ill afford either the decline of domestic service or the relinquishing of its position in the world aeronautical market.

Representative Ken Hechler, speaking for the House Subcommittee on Advanced Research and Development, warned that the U.S. position in world aeronautics could easily be lost:

> The impact of aeronautics on our Nation and on our global society over the past two decades is dramatic. Those areas we once called independent geographic regions have vanished. Self-sufficient nations are also a part of the past. The art of flight has drawn the world together and whether we like our close neighbors or not, the effect is not reversible. To the contrary, the effects of aeronautical technology on the way our world functions will become even greater with time. This is an enviable position for a technology. It is enviable because it provides a view of the future in which the world's societies can accept nothing less than the rapid growth and improvement in all aspects of aeronautical products and services.
>
> This committee looks at this prospect of great growth and development with enthusiasm but also with deep concern. These bright prospects are predicated on the rising world requirements for aeronautical products and services. However, the number of participants in the aeronautical community, competitors if you will, is also rising. This bright period, as it applies to the aeronautical future of any nation, including our own, is neither automatic nor inevitable.[24]

Studies by the executive branch and in both Houses of Congress found the rate of progress in aeronautic technology inadequate for future domestic requirements or to preserve the Nation's position as

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[22] "Policy Planning for Aeronautical Research and Development," op. cit., page 1.

[23] Ibid., page 3.

[24] U.S. Congress. House. Committee on Science and Astronautics. "Aeronautical Research." Hearings before the Subcommittee on Advanced Research and Technology of the . . . December 1, 2, 4, 8, 9, 10, and 11, 1969. 91st Congress, first session. (Washington. U.S. Government Printing Office, 1970), pages 2-3. (400 pages.)

the world's prime exporter of aeronautical goods. Hitherto, the flow of advanced technology into the civil sector from military R&D had nourished civil aeronautics and had enabled it to dominate the world market; in the decade of the 1950's the flow of military R&D no longer served this function. To an increasing extent, military aircraft were being developed as one component of a completely integrated weapons system. The "systems approach" was a sharp contrast to the former practice of developing an advanced aircraft and then outfitting it with weapons. Highly specialized military aircraft as system components were inappropriate for conversion to civil uses. Moreover, missile systems were far more competitive than complementary to aircraft. Advocates of new missile systems challenged manned aircraft as obsolete. The impetus for missile development and employment was a major factor in diverting emphasis from aircraft development. (Certainly, it had contributed to cancellation of the B-70, originally scheduled to replace the aging B-52 in the early 1960's.) With demise of the B-70, Air Force interest in large supersonic aircraft was blunted for almost a decade.

Other areas of military aeronautics in which developments would have served civil needs were also set aside. These included VTOL and STOL systems for tactical fighter support, as well as for heavy aerial logistics to locations lacking conventional runways.

NASA (and its precessor agency, the National Advisory Committee for Aeronautics) had served both the military and the civil sector as a resource for research, but not for the development of whole aircraft. Here too, aeronautics was now being superseded by the space program.

Studies leading to the President's SST decision

President Kennedy in his Air Force Academy speech and the subsequent messages to Congress had resolved for the time being the three policy issues (1) There was to be an SST; (2) the program would be under the direction of the Federal Aviation Agency, and (3) it would be funded mainly by the Federal Government, with private industry assuming one-quarter of the risk, and the Federal funds ultimately recaptured from user royalties. Many studies and analyses had led to these decisions.

The first of these was the Task Force on National Aviation Goals. Its study, "Project Horizon," had recognized in 1961 that support funds by the Government would be necessary, but also that they should be recovered:

> Government funds [said the report] should be utilized through the research, design, development, prototype, and probably production stages. Every effort must be made to recoup the Government's financial investment through some type of royalty system to be paid by the operators.[25]

Even before the Task Force had made its formal report, a separate three-member "SST Steering Group" had proposed separately that a Supersonic Transport Authority be formed either independently or within the structure of an existing agency.[26]

In November, 1961, Halaby established another advisory body to serve the SST steering group. It was called the Supersonic Transport

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[25] Don Dwiggins, "The SST: Here It Comes, Ready or Not." (Garden City, New York, Doubleday & Company, Inc., 1968), page 122. Members of the steering group were Najeeb Halaby, FAA Administrator; John Stack, NASA Director of Aeronautical Research; and Brockway McMillan, Assistant Secretary of the Air Force for Research and Development.

[26] "Project Horizon," op. cit., page 17.

Advisory Group (STAG).[27] This group recommended Federal management for the SST program and repeated Halaby's recommendation for a Supersonic Transport Authority, headed by an individual appointed by the President with advice and consent of the Senate. The SST Authority, it said, should be placed within the FAA.

> As between the FAA and NASA [reported STAG], we believe the choice is a close one. NASA has the greater experience in aerodynamic research and in managing large research and development programs. FAA has the greater knowledge and experience in the design criteria for efficient transport aircraft, and in the difficult problem of integrating such aircraft into the air traffic patterns already under FAA supervision. [Accordingly, FAA should assume primary responsibility for SST development, but not in the sense of competing with either NASA or private industry.][28]

The SST design visualized by STAG[29] was quite different from the version finally selected for construction. The Group judged speed rather than size to be the primary criterion for market competition with the Concorde, and accordingly recommended an aircraft of similar size and weight (about 175 tons) but capable of Mach 3.5 as against Concorde's design speed of Mach 2.0 (2360 mph versus 1350 mph). STAG predicted a range of 2400 miles, too short for non-stop transatlantic service. They forecast a pre-production development cost of $1 billion, recommending that industry furnish 10 percent. Finally, they suggested an early announcement by the President that the development of an SST receive the status of a national objective.

STAG's report came to the President in January, 1963, at about the time Congress appropriated $31 million for SST studies. He asked Vice President Johnson to form a Cabinet committee for a final assessment; a favorable report was returned June 1, 1963. Four days later, at the Air Force Academy he announced the SST as a national objective.

Repeated Presidential endorsement of the SST program

Lyndon Johnson as Vice President was instructed by the President to continue the effort, which he had begun in the Senate, to foster plans leading to the development of the SST. To aid him, the President established a Cabinet-level committee, chaired by the Vice President, whose mission was the coordination of plans to initiate the national program to build an SST.

Johnson assumed the Presidency on Nov. 22, 1963, only a few months following initiation of the program. In January of 1964, adhering to the timetable established by President Kennedy, a 210-member, governmental evaluation group, drawn from FAA, NASA, USAD, Navy, CAB and the Dept. of Commerce reviewed the proposals submitted by three airframe and three engine companies. The review team found all designs inadequate and reported their findings to the President.

In April 1964, President Johnson announced the negative results and simultaneously announced the formation of the President's Advisory Committee on the Supersonic Transport to be chaired by

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[27] STAG was chaired by Orval R. Cook, General, U.S.A.F. (ret.), president of the Aircraft Industries Association.

[28] "The SST: Here It Comes, Ready or Not." Op. cit., p. 123.

[29] The STAG report discussed an SST of Mach 3.5 as against 2.7 for the current SST version, the Boeing 2707-300. Aside from this difference, the STAG report envisioned lower estimated performance criteria. In fact, the current Boeing version under consideration at the close of the calendar year 1970 is designed to have twice the range and payload of the model judged feasible by STAG in 1963.

the Secretary of Defense. He instructed his committee and the Administrator of FAA (a member) to provide further recommendations.[30]

He received an interim report, recommending design study awards to Boeing and Lockheed May, 1964. Then, May 21, 1964, he asked Halaby, FAA Administrator to make the awards.[31]

On July 1, 1965, at the swearing-in ceremony of General Wm. McKee, to replace Halaby as FAA administrator, President Johnson's welcoming speech to General McKee was also a mandate to proceed with the SST program. The President stressed the importance of the SST as a part of his new assignment. That assignment, he said, was "* * * to develop a supersonic transport which is, first, safe for the passenger, second, superior to any other commercial aircraft, and third, economically profitable to build and operate." [32] The President devoted most of his welcoming speech to detailed instructions for the program over the following 18 months. He explicitly reconfirmed FAA's responsibility for the guidance and full management of the program.

The final selection of Boeing and General Electric as the preferred airframe and engine suppliers for the SST was announced by McKee on Dec, 31, 1966, On April 29, 1967 President Johnson authorized the Secretary of Transportation, rather than the FAA, to award prototype contracts to these firms.[33]

This action transferred the primary responsibility for management of the SST from the FAA. Presumably it was in recognition that as a regulatory agency over air transportation, the FAA would encounter a conflict of interest if it engaged in the development of a vehicle for use in air transport which it would later be called on to certify and regulate. This problem had been foreseen by the Supersonic Transport Advisory Group (STAG) in urging that an independent office be created to manage the program. However, during President Johnson's terms of office, management of the SST remained with FAA.

The 1967 design offered by the Boeing Company encountered an unexpected set-back in final design evaluation. It offered a "swing wing" or variable geometry airfoil structure which, at the present state of the art, was judged to present an insoluble problem of excessive weight. President Johnson's goal of an economically sound and competitive vehicle would be jeopardized by the design constraints imposed by the swing wing. Accordingly, the Boeing engineers asked for a year's delay to go "back to the drawing board." This delay, through 1968, ran to the end of the Johnson Presidency.

On coming to office, in January, 1969, President Nixon asserted the same favorable view of the SST as had his two predecessors in office and established an Ad Hoc Committee to review the status of the program for him.[34] On January 15, Boeing submitted a new design,

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[30] U.S. President. Lyndon B. Johnson. "The President's News Conference of April 25, 1964." Public Papers of the Presidents of the United States, Lyndon B. Johnson, 1963–64. Book I. (Washington. U.S. Government Printing Office, 1965), pages 550–1.

[31] U.S. President. Lyndon B. Johnson. "Statement by the President in Response to a Report on the Supersonic Transport Program." *In* Ibid., page 702.

[32] U.S. President. Lyndon B. Johnson. "Remarks at the Swearing in of General McKee as Administrator, Federal Aviation Agency." July 1, 1965. Public Papers of the Presidents of the United States. Lyndon B. Johnson, Book II, 1965. (Washington, U.S. Government Printing Office, 1966), page 714.

[33] U.S. President. Lyndon B. Johnson. "Statement by the President Upon Authorizing Construction of a Prototype Supersonic Transport Aircraft. April 29, 1967." Public Papers of the Presidents, 1967, Book I. (Washington, U.S. Government Printing Office, 1968). page 478.

[34] "Supersonic Transport Program," February 27, 1969. Weekly Compilation of Presidential Documents (March 3, 1969), pages 329–330.

calling for a "fixed wing", and FAA commenced a design review. This design satisfied the criteria and on April 1, 1969, the Secretary of Transportation sent program recommendations to the President. After further study in the Executive Office, the President sent to Congress, September 23, a request for $96 million for the fiscal year 1970 and for an authorization of $622 million for use through the fiscal year 1964, to support the SST program. In answer to criticisms that were beginning to be expressed in the Congress, the President said:

> What is involved here is not just 150,000 jobs which will be lost if we don't build it, not just the fact that billions of dollars in foreign exchange will be lost if we do not build it; but what is lost here is the fact that the United States of America which has been first in the world in commercial aviation from the time of the Wright brothers decides not just to be second but not even to show.
>
> Now not out of any sense of jingoism but because this plane is going to be built, because it's going to bring, for example, Asia, not only Japan but China, in the last third of this century 3 hours from the West Coast to Asia—I think the United States should build it and I believe that we can answer the arguments of the conservationists.[35]

Transfer of Government responsibility for SST management

On April 1, 1970, an Office of the Supersonic Transport was established as an independent entity within the Department of Transportation, reporting directly to the Secretary. As its Director, the President designated William M. Magruder,[36] with a background as an aeronautical engineer and experimental test pilot, and experience in executive management with Douglas Aircraft Company and the Lockheed California Company. Formation of the new Office coincided with completion of preliminary phases of the SST design, up to the point at which commitments could be made for actual construction of prototype aircraft.

Establishment of the new Office of the Supersonic Transport was consistent with the responsibility of the Secretary of the Department of Transportation to conduct programs to advance the transportation art. It also complied with the recommendations of various presidential advisory groups that the SST should be under a separate office. The possibility of conflict of interest was also removed, since under the previous arrangement the FAA would be in the position of certifying for commercial service its own aircraft.

Although the authorization of President Johnson for prototype construction had gone to the Secretary of Transportation, the management role of FAA had not been changed in response to this redirection of authority. However, it should also be noted that the involvement of Presidents Kennedy and Johnson in the SST program had been so deep that they, in effect, along with various special advisory groups reporting to them, were practically managing the program. Both Presidents had turned to FAA as the only aeronautical office in the Department of Transportation, and as an agency under the immediate supervision of directors appointed by them, as an appropriate resource to carry the program through its formative stages without the loss of impetus that reorganization might cause. President Nixon came into office as this formative stage drew to a close. Accordingly, establishment of the new Office and the transfer of the program from FAA constituted a maturation process along lines envisioned from the start.

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[35] "The President's News Conference of December 10, 1970." Weekly Compilation of Presidential Documents (December 14, 1970), page 1652.

[36] From 1967 until the joined the SST program, Mr. Magruder was chief preliminary design engineer of Lockheed's TriJet L-1011 program. Prior to that, he served as technical director of Lockheed's SST design in competition for the prototype contract, awarded in 1967 to Boeing Company.

Change in national aeronautics policy evidenced by the SST program

Although both NASA and FAA had long participated in or supported research, FAA in navigation aids and NASA in the proving of aircraft concepts by the use of experimental aircraft and design systems, they had always stopped short of actual development of civil aircraft. Historically, the burden of cost had been borne first by the military services, and then by the private sector of the aircraft industry. The formative years, during which aeronautical systems had developed to their present technical level and economic status, while never smooth, had been reasonably effective.

However, by the mid-1960s, parts of the air transportation network became overcrowded. Acute congestion began to distress the public and erode airline profits. Passenger safety became of concern to the public and to the Congress.

Out of this evolving concern there emerged a new national policy for aeronautics, more tacit than explicit. In essence, it called for civil aeronautical development as well as research to be funded and managed by federal agencies, for joint analytical and anticipatory studies of needs and solutions by NASA and DOT, and a redirecting of advanced research and development to meet needs and solve problems.

As the policy took concrete form, it represented a funded attack on three sets of tasks: (1) improved productivity of aircraft through the large, supersonic transport, (2) improved compatibility of aircraft with the environment through improvements in engine acoustics and combustion, and (3) evolution of an air transportation system on a point-to-point basis instead of from airport-to-airport; this task implied the evolution of "short-take-off-and-landing" (STOL) and "vertical-take-off-and-landing" (VTOL) aircraft. The economic and environmental aspects of the SST, the first target objective of the changed policy, is the subject of the rest of this chapter.

V. ECONOMIC CONSIDERATIONS OF SUPERSONIC FLIGHT

This section assesses the economics of the SST in the overall context of the air transportation industry, applying the cardinal principles which have determined the evolution of today's aerial transports. Since the earliest days of the SST program, the rationale for building the aircraft has been a major issue. Is the program driven by an economically wasteful desire to win in an international competition or is the SST an essential part of a strictly practical business venture? The price tag for the Boeing SST as now envisioned is nearly twice that of the most expensive subsonic jet.[37] Can such an investment pay—or does it represent a generous gift to the affluent air passenger?

Capacity and speed as prime determinants of profit

Some of the single engined mail planes of the 1920's could carry a paying passenger. It quickly became obvious that a slightly larger plane would have about the same fixed costs, shelter, maintenance, and crew, but could carry more paying passengers. Since the fixed cost would be about the same, the higher price of the plane could be weighed against the work it would do. If it could carry four fares instead of one, the higher earning rate would usually more than justify the higher purchase price.

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[37] The SST is estimated to cost about $42 million (with spares) as compared with $22 million (with spares) for the Boeing 747 (1968 dollars).

Successful operators (those with enough available payload to merit the purchase of two aircraft) discovered another advantage of larger capacity: A slightly larger aircraft could carry the payload which now required two aircraft. The price, however, might be almost double that of small ones. Even so, the larger aircraft was usually more economically attractive for two reasons: (1) a saving of about half of the fixed costs because maintenance and crew costs would be for one instead of two aircraft; and (2) flexibility because idle space in a large aircraft is less costly than the fixed costs related to owning twice as many aircraft. In essence, increased payload capability was proportionately more important than the purchase price of the vehicle, as long as the larger aircraft enabled the operator to reduce the numbers of his fleet.

Similar benefit was conferred by aircraft speed. If payload capability of all aircraft was equal and a higher purchase price bought higher speed capability, then the operator could analyze his routes and workload to learn whether the faster aircraft might make two trips per day or at least do enough additional work to permit operating a smaller fleet.

Thus, airline income was tied to aircraft productivity: numbers of passenger miles or ton miles per day. Costs were determined more by number of aircraft needed than by their purchase price.

Maximum return on investment therefore favors owning the fewest possible number of high productivity aircraft. An operator whose payload for a given route doubled, could accept this additional business by buying a second aircraft. But a more economical solution would be to dispose of his small aircraft in favor of one with twice the payload capability. In practice, he would look for somewhat more than the doubled payload capability so as to have a margin for future growth.

Aircraft costs as minor factor of airline economics

As aircraft get larger and faster, price rises sharply. The impression may be general that the price of a new plane today has already risen completely out of proportion to its slightly smaller predecessors. But the operator is buying a piece of production equipment in which price is related to how many revenue units (seat miles and ton miles) it can produce an hour. Each time aircraft have increased their size and speed, the purchase cost per seat mile yielded in an hour has become less, not more,

The price of a Boeing 747 is about $20 million, almost twice the price of the Boeing 707. Yet it is slightly faster and can haul more than twice the payload. The purchase price in terms of revenue units yielded per hour is therefore lower, not higher, than the Boeing 707. In addition, the operator has reduced his fixed costs by trading two aircraft for one.

Actual financing status of U.S. airlines

Meeting the rising market for air travel with the smallest possible fleet has merits that extend far beyond the economic health of the operator. Table 1 shows actual passenger miles for 1959 and projects totals for future years. (It is only illustrative, being based solely on passenger-mile requirements).

TABLE 1.—NUMBER OF AIRCRAFT OF VARIOUS TYPES NEEDED FOR ANNUAL TRAFFIC

	Number of aircraft of each type required to carry annual traffic[1]			
	1959	1971	1980	1990
Aircraft:				
DC-3	10, 167	47, 416	145, 150	284, 833
DC-6	1, 794	8, 378	25, 615	50, 265
707	469	2, 188	6, 699	13, 146
747		786	2, 406	4, 721
SST (Boeing 2707-300)			1, 469	2, 887

[1] Office of Supersonic Transport Development, Department of Transportation. "U.S. Supersonic Transport—Grey Book." Prepared by the Office of the Supersonic Transport. (July 2, 1970), p. 6.J.5 (mimeo).

In spite of the fact that the increased capability of aircraft has expanded service faster than fleet size, many of today's airports and part of the air traffic control system are saturated by today's fleets of 2,500 aircraft. The growth in domestic air travel compared with that of the commercial fleet is illustrated below.

TABLE 2.—GROWTH OF AIR TRAVEL VERSUS SIZE OF COMMERCIAL FLEET

	Aircraft fleet	Percent jets	Billion passenger miles[1]
1959	1, 827	16	29. 3
1969	2, 403	94	95. 9
Increase	576		66. 6
Increase percent	31		230. 0

[1] Table derived from information contained in Air Transport Association of America, "1970 Air Transport Facts and Figures," official publication of the * * * (Washington, D.C.), p. 43.

Step function gains in aircraft productivity

The first leap in productivity of the postwar transport aircraft was the transition from the small twin engined aircraft like the DC–3 to the four engined aircraft in the DC–6 class. Speed was doubled and passenger capacity was multiplied by more than five.

Growth of air transportation shows a characteristic step function. Each new generation of vehicles has produced significant increases in capacity, performance, and economy of operation over its immediate predecessor. The decade chosen for comparison in the preceding tables covers the second leap in productivity—the transition from the piston engined plane to the jets. Both passenger capacity and speed were doubled over that of the DC–6's and DC–7's. Productivity per aircraft therefore rose by a factor of 4.

In each transition period, purchase prices of aircraft rose sharply, but the additional cost was small in relation to their capability to produce revenue. The effect of the more productive equipment was reduction in operating costs despite the steady overall inflationary factors which tend to drive all costs upward. Table 3 shows the point at which the effect of cost reduction of the new aircraft, and the effect of cost inflation cross.

TABLE 3.—AIRLINE REVENUE VERSUS PASSENGER MILES, 1959-69[1]

	Total operating revenues	Total operating expenses	Revenue passenger miles flown (millions)	Net profit or loss	Rate of return on investment (percent)	Profit margin on sales (percent)
Total industry:						
1959	2,618,471	2,496,122	36,371.8	72,881	6.2	2.8
1964	4,250,838	3,780,741	58,493.7	223,172	9.8	5.3
1965	4,957,851	4,285,923	63,676.5	367,119	12.0	7.4
1966	5,745,038	4,969,541	79,889.3	427,633	10.9	7.4
1967	6,864,726	6,156,532	98,746.6	415,388	7.6	6.1
1968	7,762,683	7,237,612	113,958.3	216,130	5.0	2.8
1969	8,792,027	8,396,219	125,414.2	55,308	3.3	.6

[1] "1970 Air Transport Facts and Figures," op. cit. pp. 26–34.

The transition to the jets began in 1959 and was completed by the middle of the 1960's. Profit rose steadily and peaked during 1965. The advantage of the improved equipment and the effect of steadily rising inflationary costs crossed during 1966 and profit began to decline even though demand continued to rise steadily. By 1968 the advantage of the improved equipment, in terms of airline operating profit had largely vanished. The financial status of the airline industry in 1969 reveals a marginal status for survival.

A general decrease in the amount of service now available could preserve profit margins for a time. A decrease in the number of flights could increase the load factor on remaining flights. Single-flight-per-day routes having light loading could be cancelled. Remaining flights could be rescheduled to use the uncrowded midnight to morning hours to reduce losses due to congestion. In the long term, however, the operators face the alternative of fare increases or new aircraft designs which will permit another transition toward higher productivity (larger and faster aircraft).

In the ten year period between 1959 and 1969, inflation decreased the purchasing power of the dollar by 28%. Nevertheless the average passenger fare remained about the same. When this factor is considered, and 1969 fares are adjusted for constant purchasing power based on the 1959 dollar value, it may be seen that the average air fare has decreased in price by more than 25% during the decade.[38]

Passenger amenities—A derivative gain of design advances

The little mailplanes of the 1920's, with an extra cockpit for a paying passenger were replaced by larger single engine aircraft with closed cabins which would accommodate from 2 to 6 passengers. A few twin engined and three engined fabric-covered planes appeared in the late 1920's, offering up to twice as many seats. Passenger comfort rose markedly with each change. One aircraft of the late 1920's even featured a toilet. (Unfortunately its only door was an exterior one. It was for use at refueling stops which might not have terminal accommodations).

With the all-metal twin engined aircraft of the early 1930's, the Douglas DC-2, the Boeing 247, and the Lockheed Electra (the first Electra), the prerequisite of courage and fortitude was greatly reduced for the air passenger. With these aircraft up to 14 passengers could be carried with a fair degree of comfort.

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[38] "1970 Air Transport Facts and Figures," op. cit., page 16.

In the mid 1930's, the sumptuous, transoceanic, four-engined flying boats of Sikorsky, Martin, and Boeing appeared. These giant aircraft were limited in payload because of the fuel their flights required. Their prime function was to carry mail, passengers being allowed to use up whatever margin of payload left after loading the mail and varying amounts of extra fuel to meet expected weather. Ten or fifteen passengers might be allowed. However, they enjoyed a degree of spacious luxury never again approached on any aircraft.

The next evolutionary step in passenger capability came in 1939 with the first pressurized aircraft, the 33-passenger Boeing Stratoliner and the unpressurized 40-passenger DC-4. These aircraft cruised at speeds around 225 mph and were the first to offer the security of long-range flights; the Boeing was even able to offer "above the weather" flying.

Incremental advances followed throughout the next two decades. The DC-4 was replaced by larger pressurized versions, the DC-6 and then the DC-7. The Lockheed Constellation appeared in competition to the DC-6 and grew in size and speed until Lockheed's second Electra (turbo-prop powered) appeared. These propeller driven transports had reached cruise speeds somewhat higher than 350 mph and passenger capacities more than double that of the 40-passenger DC-4.

Both Douglas and Boeing introduced turbojet transports in 1958. In one step, these aircraft more than doubled the productive capacity of any previous propeller-driven transport. In their "high density" seating versions, either aircraft could carry 177 passengers across the country at 500 mph. The earliest model of either jet could do the work of 3 DC-7's, thus offering unparalled savings in terms of productivity.

In the mid and latter years of the 1960's, growth versions appeared, adding vehicle productivity through extra size without notable increases in speed. Similar modifications have extended the productivity of the Boeing 747, the Lockheed 1011, and the Douglas DC-10. They have more than doubled the productivity of the 707 and DC-8 through increases in size alone.

Throughout this entire period, the price of air travel has remained almost constant. The prime consequence of the growth in size and speed of aircraft has been the economic gain of higher productivity. However, the circumstance that higher productivity, throughout this history, has also yielded improved consumer appeal, comfort and safety, has been a rewarding one to both the industry and the passenger. A decade ago the passenger miles accumulated by trains and busses exceeded air travel by 137 percent; today, air passenger miles exceed those of surface travel by 300%.

The SST as the next major increment in vehicle productivity

Although in the past, major increases in productivity resulted from the combined effect of higher speed and larger capacity, future gains for the subsonic air carrier depend on larger size alone. Except for marginal[39] improvement, the modern subsonic jet has reached upper

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[39] NASA research on the "Whitcombe wing" is expected to prove the feasibility of transport applications which permit operation within the transonic region. This would add from 50 to 100 mph to the cruise speed of transport aircraft.

end of its speed capability. The remaining option, greater size, remains open; the Boeing 747, the Lockheed 1011, and the DC-10 exploit this option. The table which follows compares the productivity related to increased size alone with that related to increased size combined with higher speed. It also reveals the reasoning which led to the large capacity of the Boeing SST. When the SST is operating at speeds comparable to the 707 and 747, its productive capacity becomes a size comparison, and it appears midway between these subsonic aircraft. When it flys supersonically, however, its productivity is 500% greater than that of the Boeing 707 and almost 300% greater than that of competing SSTs under development abroad.

The index in the following table relates only passenger capacity and speed. Other payload is not considered. For comparative purposes, the Boeing 707 is rated as "one." Turn-around time is approximately a constant for all models. Downtime for periodic maintenance is not considered but in fact maintenance is based primarily on hours flown and therefore is less of a penalty to a fast aircraft than to a slow one so that a fast aircraft can do more work than a slow one between overhaul periods.

TABLE 4.—RELATIVE PRODUCTIVITY INDEX IN SEAT MILES PER HOUR[1]

Aircraft	Subsonic index	Supersonic index	Passenger capacity	Cruise speed m.p.h.
Boeing 707-320	1.0		179	600
Boeing 747	2.1		370	600
Boeing SST 2707-300	1.7	5.0	298	1,786 600
Concorde I	.7	1.6	128	1,350 600
TU-144	.67	1.7	120	1,550 600
B-70	.56	1.7	100	1,800 600

[1] Subsonic cruise speeds shown are approximate. Supersonic cruise speeds may also vary slightly from these design figures. Cruise speed data furnished by the Department of Transportation.

Early economic feasibility studies of the SST

Since 1960, the FAA, various manufactures, and the airlines have conducted virtually a continuous series of studies on supersonic transportation as capability and as a market. United Research, Inc., of Cambridge, Mass., conducted a preliminary FAA study contract in 1960. In 1963, President Kennedy initiated a study aimed at providing an economic overview of the feasibility of a national program to build a supersonic transport. The study was conducted by Eugene R. Black and Stanley J. Osborne. Completed in December of 1963 the Black/Osborne report provided a review of the economic aspects of the program and included recommendations as to the roles of the manufacturers, the airlines, financial institutions, and the United States Government.[40]

The FAA consolidated the more usable portions of prior studies and incorporated their own statistical materials. Their study, the *Economic Feasibility Report, U.S. Supersonic Transport,*[41] April 1967 provided "baseline" analysis and a format that subsequent studies could update.

Two independent studies prepared as a part of the overall economic evaluation were also completed in mid-1967.

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[40] Eugene R. Black, and Stanley J. Osborne, "Supersonic Transport program." (New York, 1963), 105 pages.

[41] Federal Aviation Administration. "Economic Feasibility Report, U.S. Supersonic Transport." Report of the * * *. (April, 1967, Mimeo).

(1) Review of the Economic Feasibility Report for the SST and Supporting Materials, 3 April 1967, Charles River Associates.[42]

This report was the result of a review of the aircraft demand sections of the FAA *Economic Feasibility Report*. It included revised methodology from the IDA report and recalculation of certain basic input data on costs and yields for the aircraft mix expected in the 1975–1990 time period.

(2) SST Financial Planning Study, May 1967, Booz, Allen and Hamilton.

Discussion and analysis of the production financing problem in terms of order of magnitude dollar requirements to the manufacturers and airlines, risk factors, potential sources of capital, and evaluation of the various means by which the program might be financed including alternative methods of Government support.

Progress and design decisions for the final size and operating characteristics of the SST continued to replace the assumptions in the studies with firm data. Plans to use a "swing wing" were dropped in favor of a fixed wing. Payload and number of passengers as well as range and other operating data were determined.

In May 1969, Boeing issued a study of the dynamics of SST introduction into commercial operations, based on a detailed analysis of 142 international routes. Overland flights were assumed to operate below boom producing speeds and revenues were based on current economy fares, with yields varied in relation to the degree of market penetration. The study concluded that a fleet of 500 SST's by 1990 was economically feasible and that the currently defined SST would not require increases in the current fare structure to produce a reasonable profit for the airlines.[43]

The Boeing study has a special significance in that, for the first time, the SST was evaluated in terms of real, not hypothetical data. Actual routes, curfew restrictions, and time zone differentials were analyzed. Operating characteristics and cost data were based on a firm design rather than a range of assumptions.

The updated study predicted a market potential of 515 aircraft, very close to the FAA estimate of 500 to be sold by 1990. (Charles River Associates had predicted that 805 would be required within this time period.[44]) It assumed a sixfold traffic increase for the 22 year period between 1968 and 1990. All studies assumed the sonic boom restrictions, barring flights at boom-producing speeds over populated areas.

There was uniform agreement among the various later studies that by 1990 the SST would constitute approximately a sixth of the world fleet. The range of these estimates has a variation based primarily on size of aircraft sold rather than available load factors. Estimates for the total fleet (Western world) of long range aircraft (short haul aircraft for flights of 700 miles or less are omitted) are as follows:

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[42] Charles River Associates, Incorporated. "Review of the Economic Feasibility Report for the SST and Supporting Materials". (Cambridge, Massachusetts, April 3, 1967).

[43] Data furnished by D.O.T.

[44] Charles River Associates, Incorporated. "Review of the Market for the Supersonic Transport, Methodology and Sensitivity Analysis." (Cambridge, Massachusetts, April, 1969), 87 pages.

Range of 1990 market estimate

SSTs	500– 800
Concordes	200– 400
New and replacement subsonic jets	2, 425–3, 870
Total airplanes	3, 125–5, 075

Selected highlights of the physical and operating characteristics of the Boeing and foreign SSTs along with the Boeing subsonic 747 are shown below:

TABLE 5.[1]—WEIGHT, PAYLOAD AND OPERATING COST COMPARISON OF SSTs AND THE BOEING 747

	B2707-300 (281 B)	Concorde	TU-144	747
Aircraft characteristics:				
Gross weight (lbs.)	750, 000	385, 000	330, 000	710, 000
OEW (lbs.)	327, 660	710, 000		353, 621
Airframe weight (ibs.)	275, 260	139, 600		320, 021
Engine weight (lbs.)	13, 100	7, 600		8, 400
Number seats (10/90 split)	281	126	120	384
Total payload (lbs.)	[2] 60, 200	28, 000	26, 400	98, 200
Range, seat miles (standard day)	4, 000	4, 000	4, 000	4, 375
Operating cost per seat mile on comparable basis (in cents):				
2,644 seat miles:				
Direct operating cost	1. 12	1. 54		0. 93
Indirect operating cost	1. 30	1. 25		1. 40
Total	2. 42	2. 79		2. 33
3,565 seat miles:				
Direct operating cost	1. 06	1. 60		0. 90
Indirect operating cost	1. 14	1. 20		1. 33
Total	2. 20	2. 80		2. 23

[1] Data obtained from Department of Transportation, Dec. 30, 1970.
[2] Based on 200 lbs. per passenger and 4,000 lbs. cargo.

Pros and cons of international finance

Items with high export potential are viewed historically as positive [45] contributions to the balance of payments. The SST, as a manufactured item with high export potential, would become the latest and highest priced contribution to the world aviation market, 84% of which is now held by the United States. In the case of the SST, however, question has been raised as to whether or not the balance of payments would benefit from sales.

Some opponents of the SST program, have contended that the project would fail and thereby waste the risk capital loaned by the Government. Other opponents, expressing fear that the SST program would be successful, suggest that its very success would result in a net outflow of funds.

The contribution of the proposed Boeing SST to the international balance of payments position of the United States—along with other factors, not all economic—has received considerable adverse assess-

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[45] "Positive" contributions add to the export account and "negative" ones add to the import account. Neither word has a good or bad connotation. Most economists prefer whatever balance of visible and invisible imports and exports facilitates desired flows of goods, services, and capital without undue strain on prices, employment, and fiscal stability among all the nations affected. In general, a high total value of reciprocal trading indicates economic health. In essence, the concept is that high productivity and high employment go with a high total in reciprocal trading.

Goods produced for domestic as well as foreign sales are produced in higher quantities than goods intended for only one of these markets. High quantity production tends to lower the cost of most items. Hence, they become available to more people and may contribute to a higher standard of living.

Conversely, the lack of an export market results in a lower production of perhaps costlier goods. If the same items are available at a lower price overseas, there is a temptation to increase imports, which could reduce domestic manufacturing even more. The nation may then seek to sharply encourage the development of exportable goods, or to limit imports. Often both are done.

ment by a number of leading students of economics. Surveyed during the summer of 1970 by the Sierra Club (itself a center of opposition to the SST on environmental protection grounds), the economists [46] offered such criticisms as the following:

It had failed the test of the market-place;

It was not necessary as an investment for the United States to achieve full employment;

Its effect on the U.S. balance of payments position would be minor;

Its economic consequences were purely speculative;

Its speedier transit to Europe was of doubtful attractiveness to passengers;

There were alternative uses for Federal funds of greater importance, such as to fund critical social programs;

There would be adverse environmental effects;

The present program was purely opportunistic; it would be preferable to catch up with the European developments, later on, rather than to assume the lead now;

Federal funds were drawn from the whole population, while the SST would benefit only a part, which was an inequity;

If the risk was too high to attract private capital it did not warrant Federal spending;

It was a subsidy for luxury spending;

It was a sophisticated version of "leaf-raking";

Its costs would be defrayed by raising fares on large subsonic aircraft.

Only Professor Wallich was ambivalent on the question. While opposed to the SST on environmental grounds, he observed that in any event the Concorde was being built, and if it proved commercially viable, then the United States should follow suit "to capture such economic advantages as are to be had by building the plane." He continued: "Failure to build would inflict lasting balance of payments damage with little compensating environmental gain."[47]

The question as to whether the U.S. balance of payments would be affected by the SST positively, negatively, or not at all, hinges on two sets of assumptions:

(1) The prospect of future overseas sales of the aircraft (or, conversely, of purchases by U.S. airlines of foreign SSTs); and

(2) The net effect on overseas travel, both business and pleasure, of the U.S. supersonic transport, with or without the existence of a foreign-made SST, and the net derivative effect of such travel on the U.S. balance of payments.

On the second issue, it seems fruitless to speculate, although many have. Perhaps the most trenchant observation to be made is that a large increase in interchange of persons across international boundaries might contribute to international understanding and thus further peace. If true, the investment in a means to facilitate international travel would be worthwhile at many times the cost. But to speculate about the future effect of crossing the Atlantic in two hours instead

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[46] They were Kenneth Arrow, Francis Bator, John Kenneth Galbraith, and Wassily Leontief of Harvard University; Richard R. Nelson, Merton J. Peck, James Tobin, and Henry C. Wallich of Yale; W. J. Baumol of Princeton; Milton Friedman of the University of Chicago; Walter W. Heller, of the University of Minnesota; Robert M. Solow, Paul Samuelson, and C. P. Kindleberger of Massachusetts Institute of Technology; and Arthur M. Okun, former chairman of the President's Council of Economic Advisors.

[47] "The SST." Remarks of the Hon. J. W. Fulbright on the floor of the Senate. **Congressional Record,** (September 15, 1970), pages S15398-S15405.

of six on the rate of travel or the flow of business investment can produce no useful guidance.

On the other hand, the prospect of sales of an American SST abroad is an issue of substance and consequence. Is it preferable as a matter of U.S. policy that U.S. airlines equip themselves with costly SSTs produced in England-France, or the U.S.S.R.?—Or that foreign airlines equip themselves with costly SSTs produced in the United States? If the Concorde project is abandoned should the U.S. project be also? And if one is continued, should the other be? Some measure of the quantity and flow direction of dollars associated with potential sales of the U.S. SST is shown below.

On the assumption that the American SST is competing only with the first generation Concorde (and neglecting altogether the question of the Soviet SST), it is estimated that 60 Concordes would be purchased by U.S. airlines and that 270 Boeing SSTs would be exported, yielding a net $10.1 billion in *exports*. If the Boeing SST were not built, it is estimated that U.S. airlines would acquire 300 Concordes, yielding a net $7.0 billion in *imports*. The total effect of the U.S. SST on the U.S. export-import trade balance under this assumption would be $17.1 billion.[48]

Corresponding figures under the assumption of a second-generation Concorde by 1990 are: with an American SST, $10.1 billion of net *exports*; with no American SST, $12.0 billion net *imports*, a swing of $22.1 billion.

The issues of risk and the test of the market place

It is necessary to recognize that any technological innovation involves engineering risk. That such a risk is involved in the SST is obvious; the long history of military troubles with large supersonic aircraft shows this. On the other hand, the very considerable experience of the aircraft industry with such military aircraft has done much to reduce the magnitude of the engineering risk for the future.

The fact that Government funding has been found necessary for the SST—a source of criticism for some economists—is not, however, primarily attributable to the degree of engineering risk. Rather, the primary factor is the sheer magnitude of the investment required. Even if there were no engineering risk, the raising of the substantial development funds required would be difficult. In addition to engineering risk, there is also the matter of economic risk—the chance that economic conditions might be unfavorable to market reception of the SST when it is ready, the chance that a superior Soviet SST or some unforeseen political development might present a future obstacle, and the sheer difficulty of managing such a large engineering development. However remote, this economic risk must be acknowledged as a possibility, and thus a handicap to low-interest-rate capital funding. These two risks and the size of the investment and the size of the project are not additive, but factors to be multiplied in assessing the difficulty of private funding.

However, the investment of Federal funds to support large-scale, high-cost, technological development beneficial to private enterprise is an activity with many precedents: agriculture, irrigation works, atomic energy, titanium, synthetic rubber, research in coal utilization, and hydroelectric projects all come under this category. Govern-

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[48] "U.S. Supersonic Transport—Gray Book," op. cit., page-G-12.

ment investment to support transportation have included many commercial-type developments, of which the following are illustrative: steamships, the nuclear ship, the hydrofoil ship, the St. Lawrence Seaway, the Panama Canal, the Inland Waterways, U.S. Barge Lines, the high-speed train, the Panama Railroad and the Alaskan Railroad.

Such precedents afford assurance that U.S. funding of a potentially attractive (or essential) but high-cost technology is a reasonable course. Whether or not it is an economic success would seem to depend on the engineering skill of the builder and the managerial skill of the airlines. And whether it constitutes a serious hazard to the global environment is a question remaining to be discussed. However, it seems reasonable to conclude at this point that there is a good chance that the SST affords an economic opportunity to the airlines and perhaps also the U.S. balance of payments. Undeniably, it is an important source of job income with a tangible product.

VI. The Issue of the Environmental Impact of the SST

Whatever the nation of the aircraft that first extends supersonic travel into the civil sector, its introduction seems likely to come at a time of growing concern over the impact of technology on the environment.

The traditional use of machines and technological processes has shown little regard for the environmental burden or hazard they might offer. Today, this burden is no longer deemed acceptable as an inevitable penalty of civilization. Contaminants, unwanted noise, thermal energy, and radiation now signify impairment of the quality of life. Sentiments in favor of preserving or restoring the quality of the environment are expressed in the United States, the Soviet Union, Western Europe, Japan, and doubtless elsewhere.

In the recent past, the increasing use of civil aircraft and the increased burden of environmental consequences of such use, have brought air transportation under scrutiny—even attack. Air travel is a great consumer of space; in terms of large airports and service facilities, traffic holding patterns around large terminals, and airlanes criss-crossing the continent. Almost all engines are noisy. The soot and smell of combustion products of kerosene and gasoline fuels contribute to air pollution. Other problems are created by imperfections of air transportation as a system—the separation of passengers and luggage, the annoying sequences of transport stages, problems of aerial congestion over terminals and busy air lanes, and the conflicts over airport zoning.

With the prospective advent of the SST, attention has turned to the question as to its special effects on the environment. The question can be approached from many directions, depending on the point of view of the analyst. Not all critics of the SST are "anti-science" and not all advocates of technological advance are uncritical of its consequences. The study by the Committee on Science and Public Policy of the National Academy of Sciences of "technology assessment" encapsulates the issue in these words:

> Whereas a few years ago, for example, the idea of a supersonic transport seemed to many the obvious fulfillment of man's airborne destiny, today some who might once have greeted the SST with unbounded enthusiasm are asking whether it is

truly a sign of progress to fly from Watts to Harlem in two hours, vibrating millions of ears and windows in between.[49]

This reference goes on to suggest that the rational choice facing men—

> * * * *Is between technological advance that proceeds without adequate consideration of its consequences and technological change that is influenced by a deep concern for the interaction between man's tools and the human environment in which they do their work.* [*Italics in original*][50]

In other words, technology should be assessed not from the point of view of an assumption that it is guilty, but rather to identify possible problems to be dealt with in a systematic, orderly, and effective fashion, to ensure that the final product achieves an acceptable, optimum compromise among the many objectives subsumed under "environmental quality."

There have been many criticisms of supersonic aircraft as an impairment of the environment. Supersonic vehicles offer new levels of power and a new variety of sonic disturbances. They propose to occupy a stratum of the atmosphere quite new to civil aircraft. Clearly, environmental compatibility takes its place with other more traditional performance criteria to be satisfied before this new vehicle can be accepted as useful.

A tabulation of the issues that have been raised regarding the SST in its relationship to the environment would include the following:

1. Micro-environmental issues:
    a. Sonic boom
    b. Engine noise on and near the ground
    c. Air pollution
    d. Toxic effluents
    e. Radiation hazard to passengers
2. Macro-environmental issues:
    a. Oxygen balance upset
    b. Excess of global carbon dioxide in the global atmosphere
    c. Weather modification from water vapor and particulate matter
    d. Radiation hazard (ozone layer depletion)

Apparent resolution of the sonic boom issue

Sonic boom test programs[51] conducted by the Air Force have provided a practical and a theoretical understanding of the boom and its effects. These tests also gave several million civilians a practical education in the phenomenon. Even when the booms were reduced far below any destructive potential by altitude or distance of the source they proved hard for some people to tolerate.

The announced national policy and the "FAA Notice of Proposed Rule Making," issued April 16, 1970 (39 FR 6189) would prohibit operation of civil aircraft over the United States at speeds which would cause a sonic boom on the ground. The ruling is supposed to apply to all civil aircraft, domestic or foreign, but not to military aircraft over which the Authority has no jurisdiction. .

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[49] "Technology: Processes of Assessment and Choice," op. cit., page 1.

[50] Ibid., page 3.

[51] For example. "Sonic Boom Experiments at Edwards Air Force Base." Prepared under contract by Stanford Research Institute, For the United States Air Force through the National Sonic Boom Evaluation Office, (Arlington, Virginia, July 28, 1967).

A sonic boom created by a jet fighter flying "on the deck" can cause pressure changes exceeding 100 lbs. per sq. foot, enough pressure to damage certain types of buildings. Air Force tests, in which the pressure rise ("overpressure") of sonic booms was gradually increased, revealed that damage first appeared when the overpressure reached 7½ lbs. per square foot. At this pressure, several panels of glass in a greenhouse were cracked.[52] The greenhouse was the most fragile of the test structures and the overpressure of 7½ lbs. per square foot [53] was therefore regarded by the Air Force at that time as the lower edge of the pressure range at which point there is one chance in 100,000 of structural damage.

The civil aircraft ruling proposed by FAA which forbids the sonic boom over land has relaxed public concern over this aspect of the SST to some extent. However, on transoceanic routes, the SST's fly supersonically and the power of the sonic boom is therefore pertinent.

The Boeing SST is planned to reach its supersonic cruising altitude at slightly more than 60,000 feet. It will then create a boom having a nominal overpressure on the ocean of 2 to 2½ pounds per square foot.[54] This is the pressure change experienced when one rises approximately four floors in an elevator. Fish or the hull of surface vessels in the ocean experience pressure of this magnitude from the passage of a ripple about ½″ in height, an insignificant pressure change. However, even in the most intense of sonic booms the actual change in pressure is not particularly high. The phenomenon is noteworthy because of the suddenness with which it occurs. The low altitude pass that can damage certain types of buildings with an overpressure exceeding 100 lbs. per square foot (5% of the normal atmospheric pressure) does so because the change in pressure occurs so rapidly. A far greater change in pressure, spread over a longer time period, would go unnoticed. For example, a rise from sea level to 5000′, the altitude of Denver, Colorado, for example, creates a pressure change of 355 lbs. per square foot.

If a marked change in air pressure occurs in 1/20th of a second or less, the change is detected as sound. The SST overpressure of 2½ pounds per square foot occurs in milliseconds and is like a sudden clap of thunder, not painful but certainly startling, especially when heard from a clear sky under conditions in which the boom is not masked by background noise. On an ocean voyage the startle effect would be present if the passenger was becalmed in a quiet sea. However, on an ocean liner, only those on the open deck would be likely to hear it because there its effect would largely be lost in the background sounds of the ship and the ocean.

Noise: Measuring jet engine sound

The jet aircraft engine is not only a powerful sound generator, but also a generator of sounds to which the ear is particularly sensitive.

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[52] John A. Blume and Associates Research Division. "Structural Reaction Program National Sonic Boom Study Project." Report prepared for the Federal Aviation Agency, April, 1965. (Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, 1965), pages 11-12. (Report no. AD-474-778).

[53] The dimension is in pounds per square foot and not per square inch, which is the more familiar measure of pressure. Thus sonic boom units are 1/144 of those usually encountered in air pressure reports.

[54] Under certain atmospheric conditions, the boom pressure could be amplified to double the normal 2 to 2½ psf overpressure.

A shrill whine can stop conversation and irritate to the extreme even when its energy value is quite low. The persistence or duration of the sound also adds greatly to its irritation value.

The decibel scale, however it may be weighted to accommodate special aspects of sound measurements, is logarithmic. In essence, the scale relates acoustic energy to sound perception or loudness. Each increase of ten decibels signifies a tenfold rise in energy, but because the ear responds in a logarithmic manner, the tenfold rise in energy indicates only a doubling of loudness. Conversely, if a sound is reduced by ten decibles (e.g., a reduction from 130 dB. to 120 dB.), the lower level has only 10% of its former energy, but its loudness has been reduced to 50% of the former value.

The decibel ratings for sound energy have turned out to be inadequate in studies of jet engine noise. The irritation value of jet engines remained higher than that of the deep toned piston engines even when the decibel ratings of the jets were lower.[55]

New measuring systems were devised to scale the intensity of the tones present in accordance with the sensitivity of the ear to each tone, and also to consider their duration. The basic decibel system is still used, but when properly weighted for jet aircraft engine studies it is called *Effective Perceived Noise Decibels* (EPNdB).

When the main concern is noise intensity but not duration, the "E" is not used and the unit becomes "PNdB". The Department of Transportation uses both the PNdB and the EPNdB in its sound research. New FAA regulations limiting the intensity of jet aircraft noise apply the EPNdB.

Reduction of jet noise by categories of operation

There are three phases of flight (all of which are on or near the ground) in which the sound of jet aircraft can become objectionable. These are: 1) the approach to landing, 2) the take-off and, 3) the climb-out.

Federal Aviation Regulation part 36 (FAR 36) has limited the noise level of large subsonic jets to 108 PNdB. The regulation, however, does not apply retroactively to include aircraft certified prior to date of issuance. The McDonnell Douglas DC–10 and the Lockheed L–1011 are certified under FAR 36. However, these new aircraft are not yet in service. The familiar jets, the Boeing 707 and 747, and the McDonnell-Douglas DC–8, do not comply with the 108 PNdB stipulated by FAR 36. In some cases, such as the approach phase of a 707, the sound produced is double that permitted by FAR–36.

Existing subsonic jet noise is a continuing source of controversy. Retrofitted acoustical treatment is extremely costly, but despite the cost, the process is being considered as the only recourse to gain public acceptance.

The much larger engines of the SSTs, on both the Boeing and foreign aircraft, might be expected to produce much more unwanted sound than the noisiest of the subsonics now in service.

Several sets of unofficial decibel ratings have been associated with both the Boeing and the Concorde aircraft. No information is available concerning noise levels generated by the engines of the Soviet SST.

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[55] The problems of correlating sound energy levels with human perception are discussed in "Noise abatement: summary of the issues", by Migdon R. Segal, (Multilith Science Policy Research Division, Legislative Reference Service, Library of Congress, November 4, 1970), 44 pages (See especially "Quantifying noise: sound vs. loudness", pages 4–11.)

The ratings have indeed indicated high noise levels (exceeding FAR–36) on one or more phases of flight. In the case of the Concorde, real measurements were possible, but changed as the engines and nacelles, guide vanes, and other devices were modified. In the case of the Boeing, the decibel ratings were either calculations or were based on tests of the engine before its installation in a prototype.

Both Boeing and the Concorde makers are aware of the necessity to quiet their high thrust engines. This seemingly formidable challenge is rapidly being resolved and noise levels equal to or less than today's subsonic jets appear to be within reach.

In a recent public disclosure [56], Boeing commits their SST to the subsonic requirements of FAR 36:

> Prior to production commitment, the capability of the commercial SST to achieve noise levels consistent with those required for certification of new four engine intercontinental subsonic transport aircraft will be demonstrated.

The British Aircraft Corporation (B.A.C.), are similarly encouraged with the progress of their acoustic research. In one way, their challenge is less than that faced by Boeing in that their engines are much smaller. However, in another sense, it is more difficult because their acoustical treatment must be retrofitted into a design which was "frozen" 8 years ago.

Nevertheless, their progress has already given them the assurance that their earliest commercial models will produce less noise than today's subsonic jets, and their later models will be even quieter. B.A.C. will shortly release a public statement to the effect that the Concorde will comply with all existing noise regulations at the time it enters service.[57]

So much has been said in recent times about the noise of the SST—specifically, high "sideline" noise—(the sound of the takeoff), that some discussion of the statements is appropriate. The most widely quoted comment equated the sideline noise of the SST with that generated by 50 Boeing 707's departing simultaneously. The basis for the comparison was an early decibel rating of the SST engine, taken without acoustical correction.

Such a figure is misleading as a final sound rating of the aircraft. A person who is unfamiliar with the peculiarities of sound measurement systems or with the physiology of hearing would be misled into thinking that when the SST released its brakes to depart, he would hear a sound 50 times as intense as that of a single 707. The fact is that he would not. In the situation described, he would hear a sound about twice as intense, not 50 times as intense. The figure of 50 refers, not to what the ear hears but to energy level, and energy has only a logarithmic relationship to perceived sound, not a linear one.

It must be recognized that neither Boeing nor Concorde has as yet reached their target sound emission levels. The outcome of any research can not be known with certainty before the fact.

Acoustical correction of jet engines is a new field, about five years old. However, the early results of this research are now being applied to new jet engines. The noise of the new engines is about half that of the older ones despite a fivefold increase in thrust over the past 12 years. Boeing's commitment to a target sound emission level much

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[56] Boeing Corporation. "The Supersonic Transport and the Environment," (Boeing Corporation, January 1971 (revised)), page 6.

[57] Letter from B.A.C. to G. Chatham, Feb. 9, 1971.

lower than today's subsonic jets may stem from this rapid progress and also from the fact that their schedule does not foresee commercial production for another eight years.

The problem of air pollution

Within the city, the work efficiency obtained from fuel becomes a matter of environmental quality. Table 6 compares fuel consumed per horsepower/hour for various types of power sources.

Table 6

Power Source vs. Fuel Efficiency [1]

	lb. fuel/hp. hr.
1. Draft Horse	10. 0
2. Coal fired locomotive	4. 0
3. Automobile	. 9
4. Diesel-Electric Locomotive	. 6
5. Aircraft Piston Engine	. 5
6. Fan Jet (Subsonic Aircraft)	. 4
7. Jet engine (supersonic aircraft)	. 3

[1] Table furnished by Department of Transportation.

Aerial commuter systems like VTOL and STOL offer the city high production vehicles equipped with higher-temperature, cleaner-burning engines as compared with standards for surface vehicles. Of more importance to the city is the fact that exhaust from these vehicles, except while landing and taking off, is released at an altitude which gives the normal air movement a much more effective dilution rate than it can have for slow moving, densely packed, surface vehicles. It should also be noted that pollution from surface vehicles, while related to efficiency, is even more related to speed of traffic movement. Traffic congestion multiplies the running time (hence effluents) of all vehicles involved. Aircraft are not immune to the problem of traffic congestion, but increased capacity of aircraft works to reduce numbers required.

The effluents of combustion emitted outside of a city do not present a serious pollution problem when compared with those allowed to concentrate within a city. However, they can not be ignored.

Aircraft, particularly jet engined aircraft, emit the lowest quantity of pollutants in relation to the weight of fuel used on any vehicle. Also most of their effluents are released high in the air where they are readily dispersed.

The following table shows the pollutant yield for various vehicle engine systems, based on using the same quantity of fuel.

TABLE 7.—POUNDS POLLUTANT EMITTED PER 1,000 POUNDS OF FUEL CONSUMED [1]

Vehicle	Carbon monoxide	Oxides of nitrogen	Hydrocarbons	Particulates	Sulfur oxides	Total (rounded)
Auto	200. 0	20. 0	40	1	1. 0	262. 0
Piston airliner	100. 0	50. 0	15	2	1. 0	168. 0
Ocean liner	(2)	10. 0	. 01	1	20. 0	31. 0
SST	. 9	3. 5	. 5	1	1. 0	6. 9
Subsonic Jet	. 1	3. 0	. 5	1	1. 0	6. 5

[1] Table furnished by Department of Transportation.
[2] Negligible.

To compare the work potential obtained, that can be done from the same fixed amount of fuel, Table 8 places the comparison on the amount of effluents released per 1,000 seat miles for the same vehicles.

TABLE 8.—EMISSIONS PER 1,000 SEAT MILES [1]

[Pounds of pollutants emitted per 1,000 seat miles]

Vehicle	Fuel pounds (thousand miles)	Carbon monoxide	Oxides of nitrogen	Hydrocarbons	Particulates	Sulfur oxides	Total (rounded)
Auto	100	20	2	4	0.1	0.1	26.0
Piston aircraft	133	13.3	6.6	2	.2	.1	22.3
Ocean liner	660	(2)	6.6	.1	.6	13.2	20.5
SST	193	.17	.68	.10	.19	.19	1.3
Subsonic jet	170	.17	.51	.1	.17	.17	1.1

[1] Table furnished by Department of Transportation.
[2] Negligible.

Finally, the more productive a vehicle becomes, the lower the number of vehicles required to handle a given workload. A reduction in the number of vehicles required is of great importance to transportation economics as explained earlier. It is also a pollution variable.

In all comparisons, the turbine engine powered aircraft is superior to other systems considered. The piston engine, particularly when used in automobiles, is clearly the worst.

Jet aircraft account for 3 times the intercity passenger miles of all other carriers combined. In local travel and commuting, however, the automobile remains unchallenged.

Research to develop low cost automobile exhaust treatment systems is progressing, but must necessarily be regarded as a first step. These systems will improve air quality by removing a percentage of the more toxic effluents from the exhaust. However, they do not alter the total quantity of fuel consumed nor the extremely low vehicle productivity.

The comparative data shown suggest that the technology of the high temperature turbine used in modern aircraft if applied to automobiles, would significantly reduce exhaust concentration and toxicity. The aircraft turbine, as compared with the automobile engine, produces less than 3% the toxic effluents for the same amount of fuel consumed. The amount of fuel required per hp/hr is also reduced by more than 50%.

The approach taken in the preceding discussion of the impact on the urban environment of transportation effluents has employed the criterion of effluent quantity per unit of transport service. From the engineering point of view, this is a valid approach. It poses for the city dweller the question: if technology has maximized transport service with minimized effluent, but the service still produces unacceptable pollution, the city dweller has only the remaining option of foregoing whatever amount of service required to restore an acceptable quality of environment.

However, from the political point of view a different set of criteria may be judged preferable. Different economic classes use different categories of transportation. Residents use different patterns of transportation from non-residents. Economic interests in the central city have different transportation values from interests elsewhere. Claims of these different groups for transportation services are unlikely to relate to the engineering criterion of least effluent per seat-mile. The suburbanite, for example, cannot substitute SST service for his automobile, any more than the central city dweller would prefer an auto to the faster and cheaper rapid transit system.

In spite of these considerations, there is still merit in establishing the engineering criteria of effluent/service. It serves the purpose of putting a price tag, in terms of environmental quality, on each transportation mode, so that political claims can at least be evaluated against tangible degrees of environmental degradation. On this basis, the SST does not appear to impose an unreasonable penalty relative to the service it provides. The same statement would apply to all aircraft.

Elimination of urban air pollution

Congestion in cities results in local concentrations of airborne pollutants from industry, households, electric power stations, and transportation systems. Local microclimates differ widely; some of these tend to concentrate and others to disperse the effluents produced locally. Still other urban areas trail a wide band of polluted air downwind. The air has long been regarded as a "free good," that can accept limitless pollution and quickly restore itself by rain and wind. However, as cities have grown in size and in the volume of pollutants they generate, the self-purification capacity is sometimes exceeded and local smog conditions result.

It is not evident that the airplane, whether subsonic or supersonic, is a significant contributor to air pollution over American cities, or that it needs to be. There have been episodes of air pollution caused by aircraft: emergency dumping of fuel, soot trails from badly adjusted engines, clouds of smoke from coolant injection on take-off, and even normal operation at busy airports during conditions of temperature inversion. Some of this effluent is preventable by proper regulation. Location of airports warrants closer attention to conditions of local microclimate. But size and speed can help reduce air pollution caused by aircraft. As the tables in the preceding subsection demonstrated, fuel consumption per seat mile declines with increasing size of aircraft.

Another consideration is the relationship between rate of pollution and air speed. The faster an aircraft (or any vehicle) moves through the air, the less the quantity of effluent per mile traversed.

In simplest terms, if there could be less transportation, then the machines used for transportation would consume less fuel, thereby reducing the quantity of pollutants released into the air. If, on the other hand, the movement of goods and people has become an essential part of our ecological system then the goal of cleaner air is best served by fostering technologies which raise the productivity of transportation systems and equipment so that fewer units will be needed. Simultaneously, improvements to power sources can be made which will reduce the release of noxious combustion products in relation to the quantity of fuel consumed.

Effects of miscellaneous toxic effluents from the SST

In assessing the relative pollution of various vehicles, three considerations dominate: 1) quantity of fuel for a unit of work, 2) quantity of pollutants released per unit of fuel consumed, and 3) the impact of the pollutants on the biosphere.

The turboject engines of the SST are essentially the same as those of subsonic jet aircraft. If the afterburners of the SST engines are in use, on take-off, fuel consumption and exhaust emission per passenger mile rises by about 14% above those of the subsonic jet. However, an article in Aviation Week, February 15, 1971, raised the possibility that General Electric Company would abandon the afterburner concept, with a slight increase in the size of the basic engine to compensate.

Where the toxic effects of combustion products are of interest, the following points may be considered:

1. Toxic conditions do not occur unless there is a concentration of exhaust effluents. This condition occurs only when exhaust emission rates exceed the rate of dilution due to air movement. Some studies[58] have shown that aerial commutation as opposed to surface modes would reduce city pollution by 87%. Communication with the investigators revealed that the conclusion was based on relative efficiency of surface and aerial power plants. The most significant variable was omitted: viz., dilution of the exhaust from aircraft by the flight of the vehicle at an altitude where natural air movement is not constrained by buildings and surface topography. In other words, the results of the study were understated, apart from the relative efficiency of the propulsion systems.

2. A comparison of the toxic effluents of the turbo-jet engine with the conventional automobile piston engine is relevant. The following comparison is made on the basis of a seat mile with the automobile moving steadily at 60 mph, while the figures for the turbojet engine are based on the SST engine with after-burner in use.[59]

	Turbo-Jet engine	Auto engine
CO	1	109
NO_x	1	3
SO_x	2	1
Hydrocarbons	1	40

The comparison illustrates the relatively primitive technology of the conventional surface vehicle power plant. Even with improvement, however, exhaust products from surface vehicles must still be identified as the primary vehicular source of pollution to the biosphere due to the inherently lower dilution power of the atmosphere at the surface.

The foregoing analysis is essentially a "worst case" approach. It considers the toxic contaminant effect near the ground, with afterburner, an operational mode in which the jet engine is least efficient. It should be evident that these same effects when the aircraft is operating at high altitude, and at supersonic cruising speed, would be vastly more diffused. Moreover, the turbulence and cross currents always present in the stratosphere would assure the functioning of the process of atmospheric self purification through intermingling with the tropospheric layer and the subsequent scrubbing effect of rainfall.

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[58] Rutgers University, Center of Transportation, "Study on pollution reduction potential of aerial commutation," FAA report, (July 1970).

[59] Data furnished by Department of Transportation.

Radiation exposure in stratospheric flight

One environmental issue of the SST concerns only the passengers and crew in flight; this is the question of exposure to penetrating, ionizing, solar radiation at the high altitudes of supersonic flight.

The blanket of atmosphere provides a shield that largely absorbs the charged particles and x-ray-like radiation emitted by the sun, thus shielding the earth's surface. But at altitudes of 60 or 70,000 feet some of this protection is removed. (Fortunately, almost ⅔ of the intensity of radiation at 80,000 feet is removed by descent to 60,000 feet.) Solar radiation is not constant, but is known to reach peaks of intensity resulting from solar flares. Variations also occur because the earth's magnetic field tends to deflect the particulate part of the solar radiation toward the poles and away from the equator and temperate zones. A "worst case" exposure would therefore be an SST flying over a polar route in sunlight at very high altitudes, and especially during a period of intense solar flare activity.

The question is whether the exposure to solar radiation in a high-flying SST would be serious enough to cause concern. In general, it can be said that except for the infrequent, intense solar flare, the risk is minor. However, the issue is complicated enough to warrant extended discussion.

Controversy has persisted ever since the early days of the atomic energy program, as to the statistical consequences of radiological damage to man. It is generally agreed that all penetrating, ionizing radiation produces biological change in human tissue and that at some level of exposure the change is significant enough to be called "damage". What is less certain is the rate and extent to which the body is able to repair this damage. The consensus is that some repair of radiation effects does take place, and therefore the evaluation of radiological effects must be performed in relation to rate of exposure. (In other words, if the rate of exposure greatly exceeds the rate of repair, serious damage can be expected.)

The effects of ionizing radiation are measured in terms of the unit of exposure called the REM.[61] In evaluating the extent of exposure of SST passengers and crew to solar radiation, many questions need to be resolved, such as: how many flights are made? During how long a period? What is the probability of any unusually intense solar flare activity? It is also germane to ask how much other ionizing radiation the passengers might have been exposed to.

The established standards for radiation exposure used by the Federal Government deal separately with the general population and occupational exposure. X-Ray technicians and others whose work exposes them to ionizing radiation may not be exposed to more than 5 REM per year. Individual members of the general public are not to be exposed to more than one/tenth of that amount.[62] Radiological health philosophy is to keep exposures well below such limits and not to regard them as "speed limits".

Wide differences in exposure from naturally present or "background" radiation on the earth's surface have been observed. Back-

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[61] The REM, or "Roentgen Equivalent, Man", is derived from the RAD, multiplied by a bio-damage constant. The RAD is equal to 100 ergs of absorbed radiation energy per gram of matter. The bio-damage constant depends on the measured amount of bio-damage resulting from each specific kind of radiation. Numbers of REM indicate, directly, the extent of damage resulting from the exposure, per indicated time period, expressed as REM per year or millirem per hour.

[62] The exposure rates set by various Federal agencies are based upon guidelines prepared by the Federal Radiation Council in 1960 and subsequently approved by the President.

ground radiation exposure varies because of the differing distributions of radioactive materials in granite, brick, monazite sands, and other stony materials. The extremes range between 0.055 REM/year in the mid-Atlantic Ocean to 17.5 REM/year at Guarapara Beach, in Brazil. Measurements taken in New York City have ranged from 0.07 to 0.13 REM; measurements in Stockholm from 0.15 to 0.52 REM.[63] (This normal background radiation level would, of course, be subtracted from the level to be encountered by an SST passenger, in order to determine the difference at high altitude flight.)

Medical x-rays constitute the largest single source of population exposure to x-ray-like radiation. The range of possible exposure varies from 0.05 REM for a chest x-ray to as much as 60 REM for a gastrointestinal examination by fluoroscopy.[64] The U.S. average annual medical x-ray exposure per person is probably between 0.05 and 0.07 REM/year according to the National Council on Radiation Protection and Measurement.

The "worst case" exposure for an SST flight over the polar regions at an altitude of 70,000 feet would represent an average inside exposure of .0018 REM/hour or about .005 REM for a three-hour flight at altitude. A pilot flying all year long on such a route would be in the air for about 900 hours, and at cruising altitude about half the time. His dose per year would be significantly less than 1 REM/year.[65] A passenger who accompanied this "worst case" pilot on half of his flights would not exceed his "maximum permissible dose" of 0.5 REM/year.

The most severe solar flare recorded, 23 February 1956, would have resulted in a significant increase in dose rate. A flight during such an event would have resulted in a dose rate as high as about 4 REM/hour. Although such events are infrequent, it would be necessary to provide against them. This could be accomplished by the use of radiation monitoring instruments aboard the aircraft. Should such an event occur, the increase in solar radiation would be immediately detected and the aircraft could descend to a lower altitude where the atmospheric shielding would be sufficient to keep the intensity within acceptable limits.

The SST as a cause of unwanted weather modification

In the last five years ago or so, the attitude of an outspoken public segment toward the environment has emerged to challenge the idea of the environment as an immutable free good, and to contend that the environment is a delicate and fragile structure that man's technology threatens to shatter. There are cases where man has unwittingly or callously upset ecological balances. The interdependence of dwindling wild-life shows this. The introduction of the water hyacinth into Florida (purposeful); the rabbit plague in Australia (accidental); the proliferation of the prickly pear cactus in Australia (purposeful); the war waged against the remora fish in the Great Lakes; all serve warning of the serious consequences of uninformed tinkering with sensitive ecological balances.

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[63] Comparative Evaluation of the Radiation Environment in the Biosphere and in Space, Hermann J. Schaefer. (Naval Aerospace Medical Institute and NASA, December, 1968) NAMI-1054, p. 2.

[64] Fundamentals of X-Ray and Radium Physics, Joseph Selman, M.D., third edition. (Charles C. Thomas, Springfield, Ill., 1961) p. 329.

[65] This exposure includes "normal" solar flare activity but does not include the giant flare of 23 Feb. 1956

Accordingly, the public has been led to the conclusion that many impacts of man's technology on the global environment offer the possibility of disaster unless there is proper management of "Spaceship Earth."

Something of this attitude has led to the conclusion that the flight of 500 SSTs across the stratosphere may threaten to alter some sort of fragile balance upon which the earth's climate depends. Extreme statements offer such possibilities as the following: That clouds of contrail vapor will shut out the sun or seal in the Earth's heat; that combustion of petroleum fuels will release enough carbon dioxide to turn the atmosphere into a sultry greenhouse, in which ferns will replace firs, and ice caps will melt to swell the oceans and inundate the lowlands; or that particles of solid effluent from jet exhausts will disrupt thermal balance between earth and sky, perhaps to cause the onset of a new ice age. Since past geological eras have witnessed such extremes of climatic condition, and since their causes are not fully understood, these apprehensions have received some credence.

But the important balances in the atmosphere are remarkably durable. Examination of the effects of water vapor, carbon dioxide, and particulate matter from a flight of SSTs, and comparison of the magnitude of these effluents with those of recent historical diastrophisms is one way to test this durability. Another is the analysis of the quantative relationships of air, water, and carbon dioxide. Still another is the functional analysis of the physics of meteorology.

Of course, one can never point to any variable and say that "there is no effect from this item". The reason for this is known in philosophy as the impossibility of proving a "universal negative". It is also virtually impossible to prove such a negative scientifically as many researchers have discovered.[66] Science is probabilistic. Events or effects are considered trivial or important to varying degrees based on their probability of occurrence, the entire analysis based in turn on a given state of knowledge. As knowledge is gained, estimates of probabilities become more reliable. New questions may be answered.

However, when it is shown that some specific impact of a technology under study is quantitatively minor in comparison with the same impact from some other source, and when the derivative of *that* effect is also shown to be minor, it would seem appropriate to write off the issue as closed, and to turn to other issues less fully resolved.

The Boeing SST, weighing 350 tons, carrying 170 tons of fuel and 30 tons of payload 1800 miles an hour at an altitude of 62,000 feet, over regularly scheduled routes, introduces new conditions into the discussion of technology versus environmental quality. With some 500 of these vehicles in service, [67] some of their effects on the environment have been viewed as global in scope, adverse in character, and persistent if not indeed irreversible in duration.

The SST is designed to operate at high altitudes. The stratosphere begins about 8 miles above the earth and subsonic jets usually operate a few thousand feet below this height. However, the SSTs will operate best at altitudes from ten to twelve miles above the earth, four miles above the subsonic jet traffic and well within the lower part of the stratosphere.

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[66] For example, see the AD-X2 Battery Additive Case—Chapter Three, Part I.

[67] The figure of 500 SSTs has been accepted and used by the Department of Transportation as a conservative average of a series of independent marketing projections.

The freedom from traffic and from the kind of weather experienced at lower altitudes makes the stratosphere an attractive location for supersonic airline routes. However, will this high stratum be adversely affected by the products of jet engine combustion? It is known that the stratosphere receives water from thunder storms, meteoric debris and dust, as well as complex chemicals and gases from volcanic emissions. What is the rate at which these substances are received by the stratosphere? How soon are they cycled out? Is the cycling-out rate of the stratosphere constant or does it vary with the quantities of material inserted? What is the quantitative relationship of these ingredients of the stratosphere to the potential SST effluents?

Such questions are typical of many, the answers to which constitute an assessment of global environmental impact. They are complex questions and in some cases require new research to derive answers. It has been suggested that the water vapor released from the SST into the stratosphere will cut off some of the thermal energy from the sun, causing the surface of the earth to cool off and bring back an ice age; or alternatively, that this same insulation will capture and retain solar heat, causing a possibly lethal rise in global surface temperature. The possibility of enlarged atmospheric content of carbon dioxide is also alleged to contribute to the latter effect. Another notion is that water vapor in the stratosphere might destroy the ozone layer. (The ozone layer filters out certain lethal frequencies of the ultraviolet spectrum, which if allowed to penetrate to the earth's surface might challenge the survival of land life.) One somewhat extreme view is that the consumption of fuel for industry, electric power generation, and surface and aerial transportation threatens to consume all the oxygen in the atmosphere.

Global atmospheric pollution versus local air pollution

To generalize from the conditions in a smoggy urban area to the whole earth disregards the enormous differences in scale. In the city, man's technology is the primary and indeed virtually the only source of air pollution. But globally, man's technology is only one of many sources of pollution—a relatively minor one—while a number of natural phenomena contribute vastly larger quantities of pollutants than any from human activity.

There are several ways to analyze the causes, effects, and rates of global atmospheric pollution. One way is to compare the contaminants released by human activity with similar contaminants natural to the earth's atmosphere, or contributed by natural events.

Another criterion is the relationship between the quantitative effect of some specific pollutant from a particular source in question and the range of differences measured in the naturally-occurring level of the same pollutant. (The rates at which the natural occurrences or concentrations of particulate matter, gases, ice particles, aerosols, and the like fluctuate yields information on the tendency of the stratosphere to retain or reject them.) Oxygen and carbon dioxide occur naturally in the atmosphere, but are constantly in the process of being recycled, in nature. Plant decay combines oxygen from the atmosphere with carbon from the organic matter, producing carbon dioxide; then, in the presence of sunlight, green plants consume carbon dioxide and water to produce more organic material, with oxygen as a byproduct of this process. Thus, the average content of oxygen in the atmosphere remains very nearly a constant in nature, but man's consumption of fossil fuels (coal and petroleum products) has been thought to upset this balance. One measure of global pollution, therefore, is the relationship between the amount of oxygen consumed in the burning of fuel versus the total available supply of oxygen, and conversely, the total amount of carbon dioxide in the atmosphere. Evidence of a secular (sustained one-way) change in either oxygen or carbon dioxide content of the atmosphere would be a serious matter, especially if it were shown to be substantial or increasing exponentially.

Still another measure of the significance of the seriousness of a particular pollutant is to examine historical episodes in which, by naturally-occurring events, very large quantities of this same pollutant were injected into the atmosphere and then to ascertain whether the consequences were significant and adverse.

Man's use of oxygen versus the atmospheric oxygen supply

Oxygen accounts for 20.95% of the total atmospheric mass, and weighs about 1.3×10^{15} tons. All remaining recoverable fossil fuel reserves total an estimated 2.97×10^{12} tons. If man were to burn all of this fuel, the total recoverable reserves, he would consume 3% of the available atmospheric oxygen. The percentage of oxygen in the atmosphere would be reduced from 20.95% to 20.32%. The concentration of oxygen available for breathing declines by an amount six times as much as then this when one travels from Washington, D.C., to Denver, Colorado, due to the lower air pressure in Denver. It appears that man is incapable of exhausting, or even significantly reducing his oxygen supply.

As to the role of plant life in sustaining this reservoir, Wallace Broecker [68] offers the following comment:

> First of all, each square meter of earth surface is covered by 60,000 moles of oxygen gas. Plants living in both the ocean and on land produce annually about 8 moles of oxygen per square meter of earth surface. Animals and bacteria destroy virtually all of the products of this photosynthetic activity; hence they devour an amount of oxygen nearly identical to that generated by plants. If we use the rate at which organic carbon enters the sediments of the ocean as a measure of the amount of the photosynthetic product preserved each year we find that it is about 3×10^{-3} mole of carbon per square meter per year. Thus, animals and bacteria are destroying all but 4 parts in 10,000 of the oxygen generated each year. The net annual oxygen production corresponds to about 1 part in 15 million of the oxygen present in the atmosphere. In all likelihood even this small amount of oxygen is being destroyed through the oxidation of the reduced carbon, iron, and sulfur being exposed each year to weathering processes. Thus, in its natural state the oxygen content of our atmosphere is exceedingly well buffered and virtually immune to change in a short time scale (that is, 100 to 1000 years).
>
> Man has recovered altogether about 10^{16} moles of fossil carbon from the Earth's sedimentary rocks. The fuels bearing this carbon have been combusted as a source of energy. The carbon dioxide produced as a by-product of this enterprise is equal in amount to 18 percent of the carbon dioxide contained in our atmosphere. Roughly 2 moles of atmospheric oxygen was required to liberate each mole of this carbon dioxide from its fossil fuel source. By so doing we have used up only 7 out of [each] 10,000 oxygen molecules available to us. If we continue to burn chemical fuels at our currently accelerating rate (5 percent per year), then by the year 2000 we shall have consumed only about 0.2 percent of the available oxygen (20 molecules in every 10,000). If we were to burn all known fossil fuel reserves we would use less than 3 percent of the available oxygen. Clearly a general depletion of the atmospheric oxygen supply via the consumption of fossil fuels is not possible in the foreseeable future.

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[68] Wallace S. Broecker "Man's Oxygen Reserves," Science, (Vol. 108, No 3939, June 20, 1970), pages 1537–1538.

The effects of increasing atmospheric carbon dioxide

When carbon dioxide (CO_2) is released as a combustion product, it is distributed throughout the entire atmosphere. Where and how it is released does not affect this dispersion. It is absorbed by the ocean, by plants and other life, and part remains in the air. The division of CO_2 among these three reservoirs holds a fairly constant ratio. Its distribution and absorption rate, therefore, seems to be a function of atmospheric concentration. That is, the more CO_2 there is to absorb, the more that is absorbed. The atmosphere, all living organisms, and the ocean thus become reservoirs for CO_2 and the available quantity released to the air is "partitioned" among them.

Accurate measurements of the partitioning were made for the first time during the period 1958 through 1963.[69]

> Beginning in 1958 and extending through 1963, two nearly continuous series of measurement of atmospheric CO_2 content were made. One of these series was taken at the U.S. Weather Bureau station near the top of Mauna Loa Mountain in Hawaii (Pales and Keeling, 1965), the other at the United States scientific station at the South Pole (Brown and Keeling, 1965). The measurements were carried out on an infrared gas spectrometer, with a relative accuracy for a single measurement of about $=0.1$ ppm. The observing stations are located near the centers of vast atmospheric mixing areas, far from uncontrollable sources of contaminants. Because of these nearly ideal locations, together with the high precision of the instruments, and the extreme care with which the samples were taken, these measurements make it possible to estimate the secular trend of atmospheric CO_2 with an accuracy greater by two orders of magnitude than ever before. Some fifteen thousand measurements were carried out during the five-year period.
>
> The data show, clearly and conclusively, that from 1958 through 1963 the carbon dioxide content of the atmosphere increased by 1.36 percent. The increase from year to year was quite regular, close to the average annual value of 0.23 percent. By comparing the measured increase with the known quantity of carbon dioxide produced by fossil fuel combustion we see that almost exactly half of the fossil fuel CO_2 apparently remained in the atmosphere.

The table below shows the potential increase in CO_2 as a result of the complete combustion of all recoverable fossil fuels.

TABLE 9.—ESTIMATED REMAINING RECOVERABLE RESERVES OF FOSSIL FUELS[1]

	10^9 metric tons	Carbon dioxide equivalent, 10^{18} gms.	As percent of atmospheric CO_2 in 1950
Coal and lignite[2]	2,320	5.88	252
Petroleum and natural gas liquids[3]	212	.67	29
Natural gas[4]	166	.43	18
Tar sands[3]	75	.24	10
Oil shale[4]	198	.63	27
Total	2,971	7.85	336

[1] Ibid., page 120.

[2] Assumed to be 20 percent lignite containing 45 percent carbon, and 80 percent bituminous coal containing 75 percent carbon.

[3] Assumed carbon content of petroleum, natural gas liquids, and hydrocarbons recoverable from tar sands and oil shales=86 percent.

[4] Assumed composition of natural gas by volume: $CH_4=80$ percent, $C_2H_6=15$ percent, $N_2=5$ percent.

Source: Computed from data given by M. King Hubbert, Energy Resources, A Report to the Committee on Natural Resources of the National Academy of Sciences—National Research Council (NAS publication 1000-D, 1962), pp. 1–141.

From these data the following conclusion is reached:

> We may conclude that the total CO_2 addition from fossil fuel combustion will be a little over 3 times the atmospheric content, and that, if present partitions

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[69] U.S. President's Science Advisory Committee, Environmental Pollution Panel "Restoring the Quality of Our Environment" (The White House, November 1965) pages 115–116.

> between reservoirs are maintained, the CO_2 in the atmosphere could increase by nearly 170 percent.[70]

The atmosphere now contains CO_2 in the ratio of 3 parts in 10,000 by volume. Complete combustion of all fuel reserves would increase this by 170%. It would then become 8 parts in 10,000. Since no more CO_2 could be added (from further combustion) the amount would then show a yearly decline as it is partitioned to the biosphere and to the ocean through time.

Estimates of atmospheric CO_2 have been made for the year 2000 based on various rates of fuel consumption. These calculations are summarized as follows:

> Assuming further that the proportion remaining in the atmosphere continues to be half the total quantity injected, the increase in atmospheric CO_2 in the year 2000 could be somewhere between 14 percent and 30 percent [of the amount now present].[71]

In other words an increase of 30% would change the ratio from 3 parts in 10,000 to almost 4 parts in 10,000. This can be regarded as an unimportant effect, and quantitatively less than the margin of error in typical field measurement.

Carbon dioxide and the weather: The "greenhouse effect"

In the quest for understanding of the mechanisms of the climate and the weather, meteorologists sometimes separate out one constituent and explore theoretically the consequences of an increase or decrease in its proportion to the other ingredients of the atmosphere. This has been done with CO_2. One conclusion of the exercise is that an increase in the CO_2 content of the atmosphere sets in motion a complex process that results in the heating-up of the lower atmosphere or "troposphere". This is called the "Greenhouse Effect". The hypothesis is described in the SCEP report in the form of a conclusion as follows:

> Radiative equilibrium computations, including a convective adjustment, suggest that [an] 18 percent increase of the carbon dioxide concentration by the year 2000 * * * would result in an increase of the surface temperature of about one-half degree and a stratospheric cooling of 0.5° to 1°C at 20 to 25 km; a doubling of a carbon dioxide concentration over the present level would result in an increase of the surface temperature of about 2°C, and a 2° to 4° decrease in the stratosphere at the same level.[72]

~20% ↑ = .5°C
100% ↑ = 2.0°C

However, the study follows this comment immediately with a warning that other factors complicate the calculation and raise doubt sufficient to destroy the hypothesis:

> We would like to emphasize [said the report], however, that these computations neglect the important interacting dynamics and thermodynamics of the atmosphere, as well as the ocean-atmosphere interaction. This neglect makes the computed temperature changes very uncertain.[73]

Carbon dioxide, like water vapor, absorbs infra-red radiation. Heat from the sun or heat reflected from the earth can pass through the oxygen and nitrogen in the atmosphere without being absorbed, hence without warming these transparent gases. But both carbon dioxide and water vapor are opaque to infra-red, absorb this heat, and cause the atmosphere to warm up. They differ sharply in the range of their

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[70] Ibid., page 126.
[71] Ibid., page 119.
[72] "Man's Impact on the Global Environment." Report of the Study of Critical Environmental Problems, op. cit., page 88.
[73] Idem.

proportions that occur in the atmosphere and hence in the amount of heat they can retain. The concentration of CO_2 in the atmosphere tends to remain fairly constant despite changes in air temperature, while warm air can hold much more water vapor than cold air can. Therefore the ratio of CO_2 to water vapor varies widely with air temperature, hence with latitude and with altitude.

Water serves as a heat pump both to air masses and to differentially heated areas of the earth. As water droplets change into water vapor (a gas) energy is absorbed. When it reaches a cooler point in the atmosphere, the water vapor condenses and releases this energy. The energy is then radiated equally in all directions, about half into space. The condensate, as a cloud, also reflects downward the heat energy radiated upward from the earth and reflects upward the incoming solar energy. The cloud may then descend as rain or it may re-evaporate, thereby absorbing more energy which can then be carried to still another point.

Seventy percent of the earth's surface is water and most of the earth's weather is produced by this air-water-energy exchange. There is no controversy over this role of water.

The basic role of CO_2 in the atmosphere is similarly undisputed as to its heat absorbing and re-radiating capability. However, the effect of this action is much harder to measure because the warming action of CO_2 is always confounded with other and larger heating and cooling mechanisms. It should also be noted that the net energy absorbed by the earth is related more to the reflectivity of the earth than to air temperature.

Heat absorbed by molecules in the atmosphere is re-radiated, not stored. The radiation is emitted in every direction and part of it is radiated back into space.

Both CO_2 and water vapor produce similar effects in absorbing and re-radiating heat and in warming the air.

Were it not for the stabilizing and counterbalancing effects of larger variables such as water vapor, surface reflectivity, cloud formation, and perhaps others, the warming role of CO_2 in the atmosphere could indeed be computed as suggested in the SCEP quotation above to produce the so-called "greenhouse" effect. But this is a large "if". Moreover, the long-range history of climate and CO_2 content do not confirm but tend to confuse, if not actually to refute, the hypothesis altogether. The overall warming of the atmosphere between 1885 and 1940 was generally felt to be related to rises in the concentration of atmospheric CO_2. Unfortunately, for the hypothesis, although CO_2 insertion has increased markedly since then, temperatures have slightly declined.

In sum, increasing concentrations of CO_2 have not been shown to be a significant variable affecting the climate. It is necessary to conclude from the history of CO_2 in the atmosphere that its effect is unknown, not for lack of knowledge of the infra-red absorption and heating values of CO_2, but simply because the effect of CO_2 in the context of all other atmospheric variables and stabilizing factors, is so much smaller than that of other constituents of the atmosphere.

> As Mitchell * * * has shown, atmospheric warming between 1885 and 1940 was a world-wide phenomenon. Area-weighted averages for surface [i.e., air temperature measured by weather stations as opposed to air temperature measured by balloons or other high altitude systems] temperature over the entire earth show

> a rise in mean annual air temperature of about 0.5°C (0.9°F). World mean winter temperature rose about 0.9°C (1.6°F). Warming occurred in both hemispheres and at all latitudes, but the largest annual rise (0.9°C or 1.6°F) was observed between 40° and 70°N latitudes. In these latitudes, the average winter temperatures rose by 1.6°C (2.8°F).
>
> The pronounced warming of the surface air did not continue much beyond 1940. Between 1940 and 1960 additional warming occurred in northern Europe and North America, but for the world as a whole and also for the northern hemisphere, there was a slight lowering of about 0.1°C (0.2°F) in mean annual air temperature * * *. Yet during this period more than 40% of the total CO_2 increase from fossil fuel combustion occurred. We must conclude that climate "noise" from other processes has at least partially masked any effects on climate due to past increases in atmospheric CO_2 content."[74]

The demonstrated overall stability of the earth's temperature (a rise of one to two degrees between 1885 and 1940 and a fall of a few tenths of a degree over the next 20 years) suggests strongly that the role of CO_2, or the potency of a "greenhouse" effect, is of minor significance.[75]

Possibility of climatic changes from water vapor vented by the SST

A normal fleet of 400 supersonic transports making 4 trips per day will release 150,000 tons of water per day into the stratosphere. In addition to the water, the exhaust gases contain particulate matter, carbon dioxide, sulphur dioxide, and other gaseous products.

Speculations as to the consequences of this intrusion into a relatively unused layer of the atmosphere have included a conjecture that it might induce climatic changes. Both a lethal rise in temperature and a new ice age have been offered as possibilities, both based on the same assumption that the SST would cause a permanent cover of high clouds. Another hypothesis is the destruction of the ozone layer with a subsequent intensification of ultraviolet solar radiation flux at ground level.

The stability of the stratosphere has also been questioned. On the assumption that the steady state of the stratosphere may depend on a critically sensitive balance of natural forces, it is suggested that the water vapor injected into the stratosphere from the combustion products of many SSTs might destroy the critical balance and trigger vast climatic changes.[76]

The National Academy of Sciences, NRC Committee on Atmospheric Science, has evaluated this possibility and concludes that it is without foundation.

> Our tentative conclusion, based on an assumed traffic volume of four flights per day for 400 supersonic transport planes, is that neither additional cloudiness (contrails) nor watervapor absorption of a long-wave radiation will be sufficient to disturb appreciably either stratospheric properties of the large-scale circulations that are influenced by its thermodynamic state.[77]

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[74] "Restoring the Quality of Our Environment," op. cit., pages 122 and 123, citing: Murray J. Mitchell, Jr., "Recent secular changes of global temperature," Annals of New York Academy of Sciences, (Vol. 95, 1963), pages 235-250, and Murray J. Mitchell, Jr., "On the world-wide pattern of secular temperature change." *In* Changes of Climate, Rome Symposium by UNESCO-WHO, Published in Arid Zone Research Volumes, (Paris, Vol. 20, 1963), pages 161-181.

[75] In the broadest sense, all meteorological phenomenan may be regarded as a reactive interface between two heat sources (the earth's internal heat and the solar flux) with the energy sink of outer space. Among these three factors, the most critical and also the most variable is the solar flux. Although short term climatic changes can be coupled to catastrophic volcanic events, longer term changes correlate closely with cyclic variations of the sun. This agreement was shown by S. J. Johnson, W. Dansgaard and H. B. Clausen, in their paper "Climatic Oscillations 1200-2000 AD, Nature, (August 1, 1970), pages 482-483.

[76] See also the section of this paper dealing with particulates and volcanic action, pages 736-741.

[77] U.S. National Academy of Sciences, "Weather and climate modification: problems and prospects; vols. 1 and 2." Final report of the Panel on Weather and Climate Modification to the Committee on Atmosphere Sciences, National Academy of Sciences, National Research Council (Publication No. 1350, Washington, D.C. 1966), page 11.

An analysis of the problem by the Office of Meteorological Research, ESSA, has produced a similar conclusion:

> * * * Although an unequivocal answer cannot be offered, the general opinion of a large group of scientists almost unanimously rejects any significant threat to modification of the weather.[78]

The reasoning in support of these conclusions merits examination.

During 1967, three common sources of combustion in the United States poured about 1.2 billion tons of water into the air, as follows:

TABLE 10

Fuel consumption: Powerplants, automobiles, and aircraft[1]

Source	*Hydrocarbon fuel burned, millions of tons*
Powerplants	447
Automobiles	220
Aircraft	25
Total	692

[1] Table furnished by Department of Transportation.

Since each pound of fuel burned produces about 1½ lb of water, the burning of 692 million tons of hydrocarbon fuels will produce approximately a billion tons of water. This water, ejected as vapor, becomes a factor in the equilibrium of water absorbed or released by the atmosphere.

The average moisture content of the air weighs approximately 150 trillion tons. If the billion tons of water generated in a year by the sources cited could be added to the air in a single second, it would add 1 part in 100,000 to the water normally found in the atmosphere.

A projected fleet of SSTs would traverse a relatively unused part of the earth's air envelope. The cruising height of 12 mi. would be four to five miles above that of conventional jet transports. Consequently, the atmospheric volume used for air travel would be almost doubled. The useful volume of air space is now about 1.2 billion cubic miles. With the SST the useful volume would rise to about 2½ billion cubic miles.

The ratio of the water produced by fuel consumption of the fleet of SSTs to the water normal to the air, would be only 1 part in 1 billion. However, the water in the atmosphere is concentrated in the warmer and more dense air near the earth's surface. The 200,000 tons or so of water expelled by an SST fleet would be ejected over a flight path of some 2 million miles .The water would therefore be dispersed at the rate of about 200 pounds per mile.

If the relative humidity happened to be near saturation in a particular section of the stratosphere, a contrail could form. It would exist until it was dispersed into a volume of somewhat dryer air and then, as water vapor, it would become invisible. However, the stratosphere is normally dry, with only 2 to 3 percent of relative humidity. Accordingly, it is highly unlikely that such a contrail could form.

The diffusion of the water vapor behind the aircraft is rapid and continues until equilibrium with the surrounding air is achieved.

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[78] "Memo report to the Administrator of ESSA," (October 4, 1965.)

Water vapor, like CO_2, absorbs energy in the infrared region of the spectrum. If one attempts to measure the change in radiation intensity on a square foot of earth's surface within about two minutes of the fly-over, he will be seeking a change in sunlight resulting from the light penetrating an expanding band of water vapor which by that time would have merged with the wing tip vortices. These two rotating tubes of air would have a total cross section of about 200,000 square feet.

The SST requires two seconds to fly a mile. Therefore, two minutes after passage the expanding water vapor would occupy a volume of a billion cubic feet of air per mile. Measuring solar energy intensity on a square foot area directly beneath one of the tubes (about 350 ft. in diameter), existing at this instant would require detecting changes associated with the filtering efficiency of .0024 ounce of vapor (if weighed as water). Measurement would be most uncertain, if possible at all.

Gradual accumulation of water in the stratosphere

However small the daily effect may be, the question needs to be considered as to whether it would be cumulative. The SST, once in service, would remain in service. Would the year-by-year deposits of water cause a gradual accumulation which could eventually affect the normal environment? That is, would this normally dry, high layer of air preserve its equilibrium? Would the water from the SST accumulate with time or be disposed of by the natural mechanisms which now preserve the equilibrium of the stratosphere?

A recent symposium at Williams College to study critical environmental problems tentatively concluded that in polar areas, the stratosphere could accumulate enough water to produce an increase in cloudiness during the winter season. In expressing their concern, the symposium recommended that tests and research be conducted to determine, first, whether or not additional clouds would occur, and second, what effect these clouds might have.[79]

It should be noted that the stratosphere possesses natural mechanisms which tend to hold its conditions fairly constant. The higher strata of the atmosphere are not immune from the effects of low-altitude weather. A single, large, cumulonimbus (thunderstorm)[80] cloud can inject as much water vapor into the stratosphere as would a fleet of SSTs making 1600 flights on a given day.

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[79] "Man's Impact on the Global Environment." Report of Critical Environmental Problems SCEP, op. cit., page 17.

[80] The number of thunderstorm injections per day is estimated to be between two thousand and six thousand. Seasonal variations and low altitude weather changes give a wide range to this daily insertion of water from natural causes.

The number of stratospheric penetrations within the continental United States is estimated to be 505 per year, 55 of which reach attitudes higher than 18 km. [R. F. Jones, et al. "World Meteorological Problems in the Design and Operation of Super Sonic Aircraft." *In* World Meteorological Organization, Publication No. 216. (Geneva, Switzerland, 1965).]

The water content of the stratosphere, however, remains quite stable and very low. ESSA data show that over the past five years the water content of the stratosphere has shown a slow increase and is now 50% greater than it was five years ago. In numbers, however, this 50% increase is the difference between 2 parts per million (ppm) and 3 ppm.

About 20% of the atmosphere lies above 38,000 feet. This quantity of air weighs 11.4×10^{14} tons. Stratospheric water would therefore be approximately:

at 2 ppm—22.8×10^6 tons
at 3 ppm—34.2×10^6 tons

Some idea of the water cycling capability of the stratosphere can be obtained by comparing the relatively stable amount of water present in the stratosphere with the amount received from thunderstorms each day.

If we use the ESSA estimate of approximately 150,000 tons of water inserted into the tropical stratosphere from a simple large cumulonimbus cloud, then for each 500 such daily events (a conservative estimate) the stratosphere would receive 75×10^6 tons of water.

This rate of water insertion (500 cumulonimbus clouds per day) would require 45 days to place in the stratosphere an amount of water equal to that now present. This consideration is less important than the fact that the water level in the stratosphere is extremely constant. To remain constant, or approximately so, the stratosphere *must release all the water it receives each day above that normal to its stable state.*

For each 500 large cumulonimbus clouds[81] that occur each day the stratosphere receives, but also releases, seventy five million tons of water. The water injected by a fleet of 500 SSTs would be 0.002 of this amount; this small increment would also be subject to the same cycling mechanisms. The stratosphere is dry, not because it lacks exposure to huge quantities of water, but because natural mechanisms tend to unload excesses so as to stabilize its water content at a low level.

How long does foreign matter remain in the stratosphere? The period of 18 months is often used. The figure was derived from fall-out detection following a nuclear test.[82] The nuclear decay of the fall-out indicated an 18 month period from the initial explosion. This experience has provided meteorologists with a basis for their assumption that water from the SST will remain in the stratosphere for 18 months. Yet the cycle time of water placed in the stratosphere would have little bearing on stratospheric humidity because the water released each day is approximately equal to the amount received. It is neither likely nor necessary that the water either released or absorbed in a given day be the same water. When air is circulated into a cooler region, it becomes less able to carry water. A temperature change can cause condensation of water to occur, and the water will condense without regard to how long it has been there.

If it be assumed that the water placed in the stratosphere by the SST actually did take 18 months to be cycled out, the storage of water in the stratosphere would rise steadily to reach a maximum in 18 months of 8.1×10^7 tons. The Study on Critical Environmental Problems (SCEP), estimates that this quantity would increase the water concentration in the stratosphere from its present average of 3.0 ppm to a global maximum of 3.3 ppm.[83]

The hypothesis of a rise in stratospheric humidity based on a residence time assumption for water is at variance with the observation that the stratosphere does not retain the water to which it is exposed, except for the amount which sustains its steady state humidity. The increase based on assumption of a residence time is therefore a "worst case" hypothesis.

Finally, should the "worst case" be true, the increase would represent a change only one fifth as great as the normal fluctuation noted by ESSA over the past five years.[84]

Stability of the ozone layer

The possibility has been raised that the water released by the SSTs could cause a degeneration of stratospheric ozone. The consequences of this loss have frequently been described as the opening of the atmosphere to the penetration of lethal ultraviolet radiation, capable of killing all living things except marine life.

Molecules of ozone are diffused through a deep layer of the stratosphere, showing a peak concentration at the mid-point of the layer,

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[81] The precise number of thunderstorms that occur each day, and the precise number of thunderstorms that rise high enough to inject water into the stratosphere are poorly documented. According to the McGraw-Hill Encyclopedia of Science and Technology (Vol. 3, p. 180), weather stations, world-wide, record an average of 45,000 thunderstorms per day. These stations record meteorological events over only a small portion of the earth's land mass and almost none of the earth's water surface. A conservative extrapolation of these records would indicate that more than 200,000 thunderstorms occur world-wide, each day. It is estimated that some 5,000 to 6,000 of these are large and high enough to reach into the stratosphere. The figure of 500 storms per day is used in this study as an illustrative figure, arbitrary but conservative.

[82] "Man's Impact on the Global Environment." Report of Critical Environmental Problems, SCEP, op. cit., page 17.

[83] "Man's Impact on the Global Environment," op. cit., page 16.

[84] Lester Machta. "Water Vapor in the Upper Atmosphere." SAE/DOT Conference on Aircraft and the Environment. (February 8-10, 1971), page 107. (SAE Paper 710323.)

which is about 80,000 ft. above sea level (about 4 miles above the cruise altitude of the SST).

Over any given point on earth, seasonal variations in O_3 (ozone) concentration average about 25%. Daily fluctuations over any single point on earth are at least 10% on a given day. Over a year's time the ozone concentration above a single point would therefore vary by a third or more. (The intensity of ultraviolet radiation reaching the earth's surface on a "clear" day varies even more widely since haze and dust are more efficient than ozone in blocking short wave length radiation.) The ozone density over different parts of the earth varies through a range of more than 100%. In particular, it increases with latitude, the polar regions having double the average concentration of the tropical areas.

The SCEP examined the potential of ozone destruction as a function of the insertion of water and other combustion products into the stratosphere. Their study of this issue included the "worst case" assumption of an 18 month cycle for all materials deposited by the SST. They concluded that if any effect could be detected, the effect would be well within the daily variation and would be of no significance.[85]

In summary, the stratosphere is not dry because it lacks exposure to water vapor. It maintains a state of low humidity due to natural mechanisms. Similarly, there is no evidence that stratosphere states or other climatic conditions are dependent on a "critical" or "delicate" balance of forces. To the contrary, much evidence exists that the stratosphere as well as the ozone layer (and the earth's climate) remain stable despite insertions of water and other materials in quantities vastly beyond the remotest capability of any conceivable fleet of SSTs. And, in fact, the amount of water inserted by the "standard fleet" of 500 SSTs is minor compared with the quantity cycled in and out of the stratosphere each day.

The SST, ozone concentration, and the skin cancer hypothesis

During the congressional debate on the SST in March, 1971, the possibility was raised that water vapor in the SST effluent might deplete the protective ozone layer of the upper atmosphere, resulting in an increase in solar radiation of carcenogenic frequencies that reached the surface of the earth. A collection of statements from "some of the Nation's most respected research institutions" was introduced into the Congressional Record, offering a number of opinions generally agreeing as to the plausibility of the reasoning behind the hypothesis, or at least urging that its factual underpinning be thoroughly and scientifically investigated.[86]

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[85] "Man's Impact on the Global Environment," op. cit., page 16.

[86] This discussion is based on a series of prepared statements and communications that appeared in the Congressional Record of March 19, 1971, page S 3483, under the title, "The SST: Could It Increase the Incidence of Skin Cancer?" The initial statement was by Dr. James E. McDonald, an atmospheric physicist at the University of Arizona, who had developed the skin cancer hypothesis. His reasoning and conclusions were supported by Dr. Gio Gori, associate scientific director for program, National Cancer Institute, aided by four consultants in atmospheric sciences, two in epidemiology, and six in photochemical and carcinogenic effects. Four of these consultants had prepared separate communications of their own on the subject. An additional collection of letters and statements were presented from 26 experts in the various scientific disciplines concerned. Of these, five gave indeterminate answers or disqualified themselves for want of familiarity with the technical questions involved; five restricted their comments to an agreement that if more ultraviolet radiation reached the earth's surface, there would be an increase in skin cancer; four gave support to Dr. McDonald's thesis without contributing further data; and 12 said that the questions raised by Dr. McDonald could not be evaluated in the absence of further research. (One said that such research could be performed fairly quickly ,and another said that the question could not be laid to rest in a decade.)

The importance accorded the hypothesis derived from accompanying estimates of additional cases of skin cancer in the United States that might be attributable to the flight of 800 supersonic transports in full-time operations. These were variously given as 10,000 new cancer cases a year, or from 23,000 to 103,000 additional cases. The last-named figure was also described as possibly a conservative estimate, even though it amounted to a doubling of the incidence of skin cancer in the United States.

The hypothesis was that the water vapor in the effluent from a fleet of SSTs in full-time operation would deplete some of the ozone in the stratosphere. Ozone serves as a filter to absorb the particular wavelengths of ultraviolet radiation that are alleged to cause one type of skin cancer, either by themselves or in some kind of synergistic process that has not yet been identified. Due both to the threat to health asserted and the strongly held public attitudes toward all forms of cancer, this hypothesis and the mechanisms it implied, warranted the closest scrutiny and analysis.

The hypothesis that ozone density in the stratosphere will be reduced by SST flights hinges on two assumptions: (1) that the quantity of water injected into the stratosphere by an SST fleet is large compared with injection of water from other—i.e., natural—causes, and (2) that the presence of water in the stratosphere will in fact cause a decrease in the amount of ozone present, and that this decrease will result in an increase in ultraviolet radiation reaching the earth.

As to the first assumption, concerning the ratio of the water naturally cycled into and out of the stratosphere from natural sources as compared with water vapor from the SST, it has been pointed out that the stratosphere receives and rejects water on a daily basis which far exceeds that inserted by the SST. The difference is greater, in fact, by several orders of magnitude.

In addition to the water from thunderstorms, another important source has been identified recently by Dr. Fred Singer, chief scientist to the Department of the Interior. He has pointed out that the conversion of methane gas, generated by marshes and decay of agricultural and forest wastes generally, into water in the stratosphere is a significant but heretofore unnoted source of stratospheric moisture.[57] He calculates that methane conversion in the stratosphere will contribute 3.4 x 10^6 gm/sec of water, an amount more than double that formed by 400 SSTs making four trips a day each.

The sources of moisture to the stratosphere provide water vapor in quantities far exceeding the amount that actual measurements show to be retained by the stratosphere. In order to justify the hypothesis that the SST operation would indeed cause a significant accumulation of this water, the assumption is made that each water injection remains there for an 18-month period before dropping out. Were this same 18-month duration to be assumed as valid for all forms of water injection into the stratosphere, the normal, low relative humidity in the stratosphere could not be explained. It seems probable that the amount of moisture retained by the stratosphere is determined by a stable dynamic balance, and that insertions of water in excess of this natural balance are rejected downward.

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[57] Fred Singer. "Stratosphere Water Vapor Increase Due to Methane." (Paper in preparation, March 18, 1971.)

In the laboratory, water vapor has been shown to reduce ozone concentrations experimentally. Numerous calculations and mathematical models show that when ozone and water vapor are mixed and permitted to react, some of the ozone is destroyed. The second assumption, above, is arrived at by generalizing from laboratory data and calculations. On this basis, the conclusion has been offered that when the water from an SST fleet is inserted into the stratosphere, the water vapor concentration will rise by some factor estimated variously between 7 percent and 10 percent, or from 3.0 to 3.2 ppm. From this reasoning, it is then concluded that the ozone concentration might be diminished, by reaction with this added water vapor, by 1 or 2 percent.

Similar mathematical models were made which predicted that the global increase in CO_2 attributable to a fleet of SSTs would have a heating effect. Both in the case of CO_2 and in the case of ozone destruction, the models while internally consistent appear to have neglected more potent variables present in nature. Evidence is available in nature that contradicts both effects. Thus: (a) despite a steady rise in the output of CO_2 over the past century, the earth is cooling slightly instead of warming; (b) in the case of ozone destruction, an increase in stratospheric moisture of 50 percent has been noted over the past 5 years,[88] yet ozone measurements taken at fixed points over this period of increasing stratospheric humidity varied widely but when averaged indicated an ozone *increase* of about 6 percent since 1961.[89] This increased concentration of ozone in the stratosphere has not been explained, but it would indicate that the mathematical models of natural events on which the entire ozone destruction hypothesis depends, exclude significant variables. Moreover, the variables included in these models—at least in the cases of ozone and CO_2—are of less significance than those that were omitted.

Effects on climate of solid particles from SST effuent in the stratosphere

A solid particle is opaque to most of the spectrum of solar radiation. Solar energy impinging on the particle is partly reflected and partly absorbed by the particle as heat. The warmed particle releases its energy by re-radiating it omnidirectionally and by convection with surrounding air molecules. In essence, the solar energy intercepted by the particle is largely lost to the earth's surface [90] but can contribute a warming effect to the surrounding air molecules.

One hypothesis derived from this observation is that particulate matter ejected into the stratosphere from SSTs might become extremely voluminous or concentrated. The stratosphere might then absorb so much of the sun's warmth that the lower atmosphere and earth's surface would at worst freeze over or at least experience undesirable climatic alteration.

The conclusion of the discussion to follow is that the hypothesis is improbable. Reasons for the conclusion are: 1) that cosmic dust

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[88] Lester Machta. Op. cit.

[89] Personal conversation with Mr. Robert Grass, National Oceanic and Atmospheric Administration (NOAA). The measurements span a 10-year period, taken at 18 stations distributed around the world. Mr. Grass noted that a NOAA report covering this analysis would be prepared, and would include similar results noted in a recent Russian study. The significance of these observations is that intensity of UV radiation has been correlated with ozone concentration in the atmosphere. The 6 percent over-all increase in ozone concentration in the atmosphere over the past 10 years was in fact deduced from the measured reduction in UV intensity at the earth's surface.

[90] The amount of the sun's energy actually reaching the surface of the earth is largely determined by the angle (latitude and time of day) of the earth's surface to the sun, and the clarity of the low altitude atmosphere (determined mostly by weather conditions). The absorption of solar energy by the stratosphere is minute.

constantly falling into the atmosphere exceeds in volume the quantity expelled from any conceivable fleet of SSTs, 2) that historically recorded volcanic eruptions have projected into the stratosphere vastly larger quantities of dust than any fleet of SSTs could provide; and 3) that in any event, the thermal mechanism of water vapor-clouds-rain is much more influential in directing or altering the effects of solar flux than dust could possibly be. Any weather satellite photograph will show about half the earth's surface to be shaded by highly reflective clouds at all times.

Cosmic dust varies in rate of fall from season to season and year to year. Yet its effect on climate has been negligible. The earth has experienced great volcanic eruptions which have sent enormous quantities of dust aloft but the climatic effects, while validating the theory of the cooling effect, do so only to the extent of a few degrees and for a year or two.

In short, the stabilizing effect of atmospheric water has demonstrably operated to refute the hypothesis of significant particulate effects on weather, under repeated and sustained conditions vastly more severe than the SST or any fleet of SSTs could create.

Magnitude of SST particulate effluent

The General Electric Co., manufacturer of the SST engines, estimates that carbon particles from the SST engine will total five pounds per engine per hour. The total carbon emission (20 lbs./hr./plane) would be dispersed over a distance of about 1800 miles.

The highest concentration of carbon would exist about an hour after passage of the aircraft through a calm section of the sky. Most of the exhaust is drawn into the tip vortices formed by the wing. The lift generated by the wing imparts momentum to the air. The energetic air departs from each wing tip as an expanding, whirling mass of air. These two air masses rotate in opposite directions and horizontally to the ground. They depart in a downward direction and spread away from each other. In calm air they will eventually stagnate below and to either side of the flight path. The final diameter of the becalmed horizontal columns throughout which the carbon has been mixed would be a few thousand feet across.

If all the carbon emitted is contained within these two air columns, each will contain 10 lbs. in an hour's flight. Based on a maximum diameter of 1000 feet, each column will have a volume of 7 x 10^{12} cu. ft. through which 10 lbs. of carbon are dispensed, or 7 x 10^{11} cu. ft. of air per lb. of carbon. This is not a detectable quantity. Moreover, the material is chemically inert.

The smaller the particle, the slower it will fall to the earth. As size decreases, gravitational forces become less and less important compared with convective air movements and eddy currents. Finally, particles of extreme fineness become responsive to the random movement of air molecules. The gravitational pull of the tiny particle mass is so trivial relative to the forces in the surrounding air that the particle becomes entrained, its greater density showing only as a slight downward bias in its general random movement.

Unless a stratospheric particle becomes larger[91] for some reason, a year or more could pass before its earthward bias will allow it to

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[91] Reactive particles of sulphur (e.g. sulphurous or sulphuric acid or ammonium sulphate) may grow in size due to photochemical forces which may steadily add additional atoms to the original molecule (e.g. adding nitrogen and hydrogen to a sulphate radical to form ammonium sulphate).

settle. However, the floating lifetime of the particle is shortened, perhaps ended, if it becomes a condensation nucleus.

A "normal" fleet of 500 SSTs, operating ten hours per day, would release a total of 50 tons of carbon per day. If an average stay time of 18 months is assumed for particulates placed in the stratosphere, then the steady state density of the carbon following an 18 month build-up is of interest. Based on an average residence time of 18 months, the carbon particulates would reach a peak concentration of less than 28,000 tons and stabilize at that level. (550 days times 50 tons per day equals 27,500 tons.)

The SCEP study added to this figure for particulate carbon a considerably larger figure for "particulate" combustion products of sulfur. The analysis offered in that study may be open to challenge on that account because sulfur in the exhaust is released as sulfur dioxide, a gas. To become a particle the sulfur dioxide must be either dissolved into a droplet of water or chemically converted into a solid sulfur compound after being released. The SCEP study considered the case of a 100% conversion of all sulfur released into particulates.

For these and other reasons [92] the SCEP assumptions as to sulfur emission products must be considered to represent a "worst case" treatment of the problem. Thus, accepting these generous estimates and considering, as was done, all sulfur products as "particulate", and with a cycle time of 18 months (to reach the stable peak level) the peak concentration of sulfur products would reach 181,500 tons and the carbon total would reach 28,000 tons, a combined total of 209,000 tons of "particles". This sounds like quite a lot of dust to be scattered along the stratospheric airlanes. However, it is considerably less than the dust already there.

Comparison of SST particles with cosmic dust

The dust from space, mostly particles ranging in size from a millionth of a micron to several microns, joins the earth's atmosphere in surprisingly high quantities. The micro size of the particles causes them to fall slowly, like the dust from volcanoes.

The infiltration of meteoric material does not occur at a constant rate but is relatively uniform if compared with volcanic insertions. It is a relatively uniform dispersion to which volcanic material must be considered an occasional, albeit huge, addition.

The quantity of dust received from space has proved difficult to measure and calculations of the total vary through several orders of magnitude. The assumption that a series of measurements taken in one part of the world during a given time period can be generalized to the entire globe is probably not a safe one. Also, some collection and detection methods seem more effective than others. Among the more complex of these are the remote sensing methods employed on satellites. Although the satellites remove all doubt that the materials detected are cosmic and not of earthly origin, interpretation of the sensor signals has introduced new uncertainties.

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[92] Among the others: fuel consumption was improperly assumed to be a constant, instead of decreasing steadily during a trip; the figure used was 66 tons per hr. aircraft whereas a more accurate estimate would be the average consumption of 53 tons/hr. Also, an average sulfur content of .05% was used. Present-day fuels range between .06% and .004%. Sulfur is undesirable in jet engines because it produces corrosive combustion products that shorten engine life. The producers of jet fuel have been steadily reducing sulfur content and the trend is expected to continue. On the basis of past experience with this progress, a sulfur content of somewhere between .01% and .005% would be a reasonable expectation by the time the Boeing SST could become operational. The removal of sulfur from fuels of all kinds may be accelerated by the President's proposed graduated tax on sulfur bearing fuels. (Described in New York Times, (February 2, 1971), page 24).

Estimates of the daily accumulation of cosmic dust now vary through five orders of magnitude (from 100 tons per day to 10 million tons per day).

Rosen and Ney [93] obtained results in the mid-range of this variation:

> The particle flux observed with the photo-electric particle counter is about 4×10^{-2} cm^{-2} sec^{-1} for diameters between 0.5 and 2 μ. This implies a mass flux of about 4×10^{6} meteoric tons per year over the earth.

Studies showing much heavier quantities were summarized by T. Grjebine.[94]

According to a research summary by Grjebine in which a variety of stratospheric sampling methods were correlated, the earth receives enough micron range particles (metallic) from space to show a stratospheric concentration (between 15 and 25 km altitude) of 2×10^{-4} grams per cubic meter. In other words a column of air one meter on a side and 5000 meters high would contain one gram of metallic dust. This is not a significant filter as far as solar energy is concerned. Yet. the quantity of cosmic dust is between 4000 and 5000 times as large as that suggested for an SST fleet under a "worst case" assumption.

Of course, cosmic dust is assumed (for want of better information) to be more or less evenly distributed. By contrast, SST flights would presumably be mainly in the northern hemisphere along established routes. This would mean repeated dispositions along relatively narrow bands in the stratosphere. This flight pattern could be expected to result in more localized concentrations of particles.

Such concentrations however are not likely to occur. The reason for this is as follows:

In their calculations, the SCEP considered the particulates as inserted in a stagnant fashion rather than from high speed flight.[95] The instantaneous mixing characteristics of the SST (not considered by the SCEP) should also be taken into account. Assuming that all the SO_2 would become particulates, the total sulphate and carbon deposition is 67 kg/hr. The mixing vortices of air into which this material is placed totals 4×10^{10} cubic meters of air per hour. The concentration per flight is calculated to be 1.6×10^{-7} grams/m^3.

For the SST effluent to achieve the particulate density suggested by the SCEP of 330 parts per billion would require two hundred flights over precisely the same flight path during which time (50 days) absolutely no natural atmospheric movement along the flight path would be assumed to occur.

These conditions are quite impossible. For example, a (very reasonable) velocity of the upper air of no more than ⅙ mile per hour would prevent the residue left by one flight from mixing with that of the next. Air movement in the stratosphere varies with attitude but is almost never still. Wind movement varies from 25 mph up to several hundred mph.

Comparative magnitude of volcanic particulate effluent

The SCEP, in considering the problem of particulate concentrations resulting from repeated use of regular routes, made a comparison

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[93] S. M. Rosen and E. P. Ney. "Vertical Distribution of Dust in the Stratosphere." *In* "Meteor Orbits and Dust." Proceedings of a symposium sponsored by the National Aeronautics and Space Administration and the Smithsonian Institution, Cambridge, Mass., August 9-13, 1965. (Washington, U.S. Government Printing Office, 1967) page 347.

[94] T. Grjebine. "Concentration of Magnetic Dust in the Stratosphere." *In* "Meteor Orbits and Dust," op. cit., pages 361-364.

[95] Personnel communication with S.C.E.P. participants.

with the band-like dispersion resulting from the volcanic eruption of Mt. Agung. The following conditions were noted:

1. Prior to the eruption, particle sampling by Junge showed a concentration of 12 parts per billion.
2. 1969, several years after the eruption, Cadle et al measured 360 parts per billion (5.8×10^{-5} grams/m^3)[96].

The point insertion of volcanic action can, of course, cause vast increases in stratospheric dust which may persist for several years. Mt. Agung, for example, inserted large quantities of sulphates which diffused around the earth in a stratospheric band located in the tropical latitude. The concentration of the Agung sulphates was great enough to cause a detectable rise in stratospheric temperature along the track of the dust. The amount of energy required to heat this dust and all of the air containing it would be about 0.0005 of the solar flux for each degree rise in temperature. Such an absorption of energy was not great enough to cause measurable effects at lower levels of the atmosphere, nor on the surface, and none were noted.

In the Agung eruption, a quantity of particulate matter was ejected into the stratosphere in concentration about comparable to that given in the "worst case" analysis developed by the SCEP study. No significant climatic effects were detected. In fact, the National Center for Atmospheric Research (NCAR) cites six volcanic events in recent time which injected enough material to cause a decline in world temperature through reflection or absorption and re-radiation of solar energy.

> Volcanic dust has been held responsible for several more recent dips in world temperature means, such as the notable temperature decline in 1787, 1816 [the "year without a summer"], 1837, 1884, 1893, and 1912.[97]

But in all of these cases, the volume of materials ejected was vastly larger than that which would be released from any conceivable SST fleet. For example, the greatest burden placed on the stratosphere in recent times occurred at Krakatoa on August 27, 1883. The Krakatoa eruption replaced an island containing 14 cubic miles of rock with a flat plain a mile across on the ocean floor lying beneath 1000 feet of water. Dr. Melvin A. Cook, an authority on explosives, computes the energy released by Krakatoa as equivalent to 5,000 megatons of TNT.[98]

The column of efflux left the earth's surface at velocities exceeding Mach 3. The resulting sonic boom was audible 3,000 miles away.

The shock wave, detectable on barographs, traveled around the earth, reflected from itself, and returned, repeating the cycle four times before dissipating below the sensitivity of available instruments.

Estimates by Ernst Behrendt indicate that the efflux included a cubic mile of sea water in the form of superheated vapor. Behrendt's account was published by the American Nature Association.[99]

Sightings at the time produced estimates of the altitude achieved by the blast as 150,000 feet. Several cubic miles of materials, rock, lava, steam and water were pulverized and blended by shock waves and heat, and brought night-time darkness to areas within a hundred mile radius.

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[96] 5.8×10^{-5} grams/m^3 based on weight of air at 60,000 feet which is 120 gm/m^3.

[97] NCAR Quarterly (February 1969, No. 22), page 12.

[98] Melvin A. Cook. "The Science of High Explosives." (New York, Reinhold, American Chemical Society Monograph Series), 1958, page 1. (21 pages).

[99] Ernst Behrendt, "Earth's most awful blast", Nature Magazine, v. 39, No. 3, March, 1946, pp. 121–124, 160.

The residue circled the earth, giving the moon a green tint and turning the setting sun blue, gray or green for the better part of a year. Sunsets were noticeably more brilliant all over the world for several years.

Here again it would appear that several cubic miles of water, chemicals and solids, interacting with the sunlight for over a year, as they cycled out of the air, caused no noted or dramatic effects on long term temperature cycles, world weather, or life on earth due to ozone disturbance.

In summary, particulates in the effluents of a fleet of SSTs do not approach the magnitude of routine natural insertions of particulates. Effects on the earth's climate, of even truly massive volcanic insertions (quantities that no conceivable number of SSTs could approach), have been identified as being slight and transient.

Summary of assessment of weather modification possibilities of the SST

Man's technology has been shown to have many different possible effects on his environment. It is not possible to foresee all effects of any innovation. Moreover, as basic scientific research accumulates more knowledge and develops more sensitive measuring devices and techniques, new opportunities and dangers appear. This has been increasingly the course with all environmental questions over the past quarter-century. Skill in detection has disclosed the existence of mercury in many previously unsuspected places. It has identified the presence of pesticides in food chains. It has inspired development of a new science of environmental or ecological chemistry for the analysis of degradants. It has recognized the significance of both acute impacts and long-time, low-level impacts. These undeniable and important contributions of man's ability to preserve and restore his environment have also sensitized the scientific community and the public at large to the many ways in which the environment can be impaired. It is likely that this knowledge can do a disservice in the possession of those anxious to prove an *a priori* case or prone to emotional overreaction. The possibility that an innovation may be harmful in some specific way is not the same as the certainty. Science deals in probabilities, and in the relative significance of variables, but not with certainties.

With respect to the weather modification aspects of the SST, it might serve a useful purpose to consider how difficult it has been for man to achieve any positive results when he was trying to. Weather modification is difficult, precisely because the mechanisms that determine the weather and the climate are so functionally positive and on so large a scale. They have a built-in stability that is extremely difficult to alter.

Evaluation of the possibility of unintended modification should perhaps be examined by those technologists seeking to achieve purposeful modification.

It has not yet occurred, apparently, to those assessing the environmental impacts of the SST to speculate on the possibility that the combined effects of all SST effluents discharged along the airlanes in the temperate zone could establish a permanent pattern of rainfall along these itineraries. Not that this is very probable, but it is no less so than some of the apprehensions that have been expressed.

One approach to the further assessment of the weather modification potentialities of the SST might be to select that aspect of the atmosphere that is most sensitive and at the same time most dynamic, for a searching functional analysis. This is the air-water balance. It is well established that interactions based on this balance control most of the phenomena of the weather and climate. It is also the conclusion of those engaged in the study of purposeful weather modification that the manipulation of the air-water balance offers the best hope of achieving measurable results with least expenditure of effort. The results to date of this effort may not be promising, but they are the least unhopeful. Therefore, examination of the potential SST effects on weather and climate in this context, possibly in synergistic relationship to efforts at purposeful modification, might help to put the issue into clearer perspective. But as with all such issues, this one cannot be completely disposed of. It is not possible to prove a negative—only to indicate its order of probability. The present state of the knowledge is that weather and climate effects of the SST thus far investigated turn out to be unimportant.

VII. Observations and Conclusions

This chapter has reviewed the technological evolution of the commercial airliner from the 1920s to the present day, to provide a basis for the evaluation and assessment of the technology of the proposed supersonic transport. In tracing this history, it became evident that much of the early technology of commercial aircraft leaned heavily on military-sponsored developments. It was also apparent that the goals of military developments were not necessarily compatible with the requirements of competitive commercial vehicles.

The deviation in military versus civilian requirements widened with time, resulting in a lag of technology useful to the civil sector. The pace of development of civil aeronautics became too slow to satisfy rising domestic and international requirements.

The lag in civil development gave rise to an important issue: whether or not the development of commercial aeronautics should become a direct function of the Federal Government as distinct from the traditional indirect support (funding military aeronautics and waiting for the technology to diffuse into the civil sector). The long time lag in the development of powerplants appropriate for commerical jet airliners was cited as a cost of the failure to do this. The long history of Federal participation in the encouragement of transportation facilities, domestic and international, suggests that this function has proved acceptable in the past and warrants consideration for the future.

Another issue is the national attitude toward technology itself. A study by the National Academy of Sciences was cited to suggest that in the future technology can neither be turned loose to proceed untrammeled, nor constrained by arbitrary measures to preserve the status quo. Defects in present-day technology are acknowledged. The importance of screening and assessing further innovations, the subject of this entire study, appears to call for an intermediate, balanced compromise between these two extremes. It calls for systematic and thorough examination to maximize the benefits of a technological innovation, while detecting and correcting undesirable, second-order consequences. Criticisms and assertions of technological imperfections can be expected to be voiced throughout the development of any such large project; they need to be dealt with forthrightly and factually as they appear.

Review of economic aspects of the supersonic transport

Attention was focused on the productivity of commercial aircraft as the primary consideration in the development of competitive transport systems. Productivity is a factor of speed and carrying capacity, while the requirements of maintenance and "down-time" are a negative factor. Historically, each major increment of innovation in design that increased the positive factors or reduced the negative factors provided impetus for growth and increased efficiency of the airlines. Up to about 1968, these innovations had been frequent enough to keep air fares about constant in the face of a general inflation of the economy.

Specifically, each generation of airliners achieved higher levels of speed, and larger payloads; downtime was reduced by the improved engineering of the reciprocating engine, and even more by the advent of the turbojet engine.

On the negative side, the trend toward larger aircraft meant that the airlines needed schedule changes to improve the load factor. The problem they encountered was that competing airlines running large aircraft found their planes operating at half-capacity. The immediate alternative seemed to be to raise fares or reduce the number of flights.

The hypothesis in support of the economic benefit of the SST is essentially that size alone, with its associated problems of load factor, will not accomplish the next evolutionary step in productivity. An aircraft of intermediate size, halfway between the capacity of the 707 and the giant 747, with three times the speed of these subsonic jets, is suggested as the way to fill this gap.

Since the constraint of avoiding sonic booms over land has been accepted—at least unless and until this environmental effect can be shown to be negligible from an aircraft at 65,000 feet altitude—the primary gain in productivity will be for trans-oceanic flights. It is claimed that the SST retains its gains in productivity on such flights, even if they originate in Chicago or perhaps St. Louis, and fly subsonically over land.

The international financial considerations of the SST center on the comparative advantage of selling American-produced aircraft to foreign-owned airlines versus buying foreign-produced aircraft for use in American-owned airlines. Stated in simple terms, as a pure case, the advantage for the United States appears to be a plus of some $20 billion by 1990 for the successful production of the Boeing SST, if the market analyses are reasonably valid. However, there remain a number of uncertainties that cloud the picture. The recent rise of the international corporation, owned jointly by stockholders in many countries, complicates the flow of value. Another uncertainty is as to the probability of economic success of either of the foreign SST projects. This success is called into question by the fact that the foreign SSTs are smaller and slower than the Boeing version, even though they are scheduled for earlier entry into service.

One critically important variable in marketing is airport accessibility and congestion. Although the problem is general to all commercial aircraft, the congestion and surface access problems have steadily grown worse with time. The SST schedule calls for its introduction in eight years. With no change in airport accessibility trends, the SST will be introduced at a time when the number of passengers carried is no longer governed by market growth but has become fixed due to system limitations.

Through the years, plans to relieve the bottleneck of air terminals have made little progress. The nature of the problem requires that planning be national (or at least interstate), but the implementation requires State and local action. Historically, coordinate action of Federal-State-local jurisdictions has proved difficult.

The more promising plans to relieve terminal congestion propose to make use of VTOL/STOL aircraft linking large terminals with smaller and dispersed satellite terminals. This scheme provides directly for the short-haul passenger, the largest single component of air passenger service. By providing for point-to-point travel for the short-haul passenger, the proposed system would alleviate the pressure of passengers and aircraft at the large terminals serving long-haul transportation. If some arrangement of this kind is not incorporated in the U.S. air transportation system, the congestion at major airports will jeopardize the marketability not only of the SST but of all other larger airliners.

The various issues of noise from the SST

The question of noise is, of course, an environmental issue. However, it differs in character from other environmental insults in that it is of brief duration and hence localized in relation to the aircraft that generates it.

Noise from the SST is of five types: (1) the sonic boom, generated when the aircraft moves at supersonic speed at cruising altitude; (2) the engine noise while the aircraft is motionless, taxiing into position for take-off, or holding; (3) the side-line noise while the aircraft is moving down the runway and taking off (up to one mile from the end of the runway); (4) the departure noise, from one mile past the end of the runway until it gains cruising altitude and reduces power to cruise level, and (5) the approach noise made as the aircraft approaches the field to land.

The question of sonic boom has presumably been disposed of for the time being by the assurance that the SST will cruise sub-sonically over populated land. This issue has raised considerable controversy because of the experience of the U.S. population with military jets flying supersonically at lower altitudes.

Engine noise on the ground before take-off does not appear to be a significant factor. During this phase, engines of the SST can run as quietly as those of any other aircraft. Only enough power is required to move the aircraft slowly.

Engine noise while the aircraft is moving down the runway, and up to a mile beyond, or coming in for a landing, presents the principal problem for designers of aircraft and engines of the SST. Without acoustical correction the noise generated during these phases is excessive. However, the Boeing Company has offered assurances that before the SST is certified, its noise level during these phases will be brought within limits judged acceptable for new subsonic aircraft (FAR 36). Similar assurances are offered by the makers of Concorde who say that the Concorde will comply with all pertinent noise regulations extant at the time it appears on the market.

These assurances, of course, do not completely dispose of the issue. It remains to be seen whether the companies can make good on their promise, or whether they will seek an exception or interim adjustment at a later date. On the other hand, the point is made that airports are often located in areas remote from urban centers, with much open land around them. If the land is subsequently occupied by persons seeking to take advantage of convenience, economic opportunities, or sheer rise in land values attributable to the airport, it is at least a reasonable question as to whether they should not be expected to take the bitter with the sweet.

Departure and approach noise is another question. It extends well beyond the immediate locality of the airport. Presumably, the same assurances are offered by the aircraft and engine designers as to noise reduction in this phase. The importance of this phase is that it affects a larger area, and is not associated with any of the advantages of land ownership relative to take-off noise. Since engine efficiency is likely to be impaired by innovations to reduce noise, particularly when retrofitted, there will be an inevitable trade-off between noise comfort and engine efficiency. Determination of this point can be expected to be a source of future controversy. However, the present evidence is that the designers are taking quite seriously the public concern over noise pollution, and are making strenuous efforts to alleviate it.

The micro-environmental issues of the SST

Apart from noise, two broad categories of asserted environmental effects of the SST have come under consideration. One set involves the consequences of its operation as an added pollution-producing element in the urban/suburban air environment. Public dissatisfaction with deteriorating conditions of greasy residues, corrosive chemicals, particulate matter, smog, and other noxious gases, has been exacerbated by the prospect of effluent from the big, high-powered engines of the SST.

It is incontrovertible that turbojet aircraft, whether subsonic or supersonic, add to air pollution around airports. It is not evident that they contribute a significant fraction to the total pollution load in and around cities, with the possible exception of infrequent, unintended effects such as fuel dumping and badly adjusted engines. The economics of aircraft management dictate that these should be avoided.

The questions to be resolved in the category of micro-environmental effects relate to the local geographical, meteorological, and urbanized circumstances rather than to the specific aspect of SST effluent. It is necessary in the local environment to consider such matters as—

the nature of local air movement and its capacity to diffuse pollutants;

the local tendency toward inversion layers in the atmosphere that obstruct upward diffusion of pollutants and smog;

the traffic density at airports;

the load of pollutants from other sources; and

the insulation of the airport and departure lanes from housing.

As a general proposition, it rests with the local metropolitan area to insist upon a tolerable level of pollution of the air from all sources, including aircraft. Presumably, the designers of aircraft and engineers are mindful that failure to maintain progress toward cleaner engine effluents would invite the risk of costly regulatory inhibitions at airports prone to high levels of pollution.

The macro-environmental issues of the SST

The other category of asserted environmental effects of the SST encompasses global or climatic consequences. A long list of questions have been raised as to possible adverse second-order consequences in this area. The distinction is made that the micro-effects of the SST contribute to other effluents generated by man's technology, while the macro-effects of the SST should be related to the pollutants resulting from large-scale natural phenomena.

One assertion is that the big engines of the SST will contribute disproportionately to the consumption of atmospheric oxygen. This issue is not impressive, however, in view of the fact that if all the known organic matter (coal, lignite, petroleum, and standing timber, for example) were to be oxidized to ash, the reduction in atmospheric oxygen would be something like 3 percent. Moreover, there is some reason to believe that one of the products of oxidation—the carbon dioxide—when present in the atmosphere in increased percentage stimulates the process of plant photosynthesis. The process consumes CO_2 and water (the products of combustion) and generates oxygen. How precisely this reverse process counterbalances the process of oxygen depletion from combustion is not a critical problem in terms of the oxygen supply for reasons stated above.

A related hypothesis is that the percentage of carbon dioxide in the atmosphere will be increased by SST effluents to such an extent that the absorption of the infra-red radiation from all sources by CO_2 would cause a rise in the temperature of the troposphere (that part of the atmosphere below about 40,000 feet altitude). However, this "greenhouse effect" has not been confirmed in recent minor changes in atmospheric CO_2 content. Moreover, there are other mechanisms at work in the atmosphere that are much stronger in their effects than is the content of CO_2 and minor changes in it.

Still another contention is that the particulate matter in the SST effluent might reach so high a density as to enable the stratosphere to absorb enough solar radiation to cause the troposphere and the ground beneath to cool. An examination of the quantity of particulate matter that might be generated by the SST (a fleet of 500 on regularly scheduled service) shows that it does indeed reach the impressive figure of 209,000 tons of particles under a "worst case" assumption before stabilizing. (At that point, losses of particles would equal gains.) However, the earth's daily intake of cosmic dust is estimated to be much larger than this. Measurements of the fall of cosmic dust, taken at different times and places, show quantities which vary through three orders of magnitude, the smallest of which is much larger than the stabilized quantity from the SST fleet under a "worst case" assumption.

Another basis of comparison is the climatic effect of the very large quantities of particulate matter injected into the stratosphere by major volcanic eruptions in recent hitsory. Although these natural effluents are many orders of magnitude larger than any conceivable accumulation from an SST fleet, no significant climatic consequences appear to have resulted from them. It might also be noted that the power of dust to affect the solar flux (hence the climate) is minuscule as compared with the reflectance of a cloud, and clouds cover about half the earth's surface at all times.

By far the largest single component of SST effluent is water. A number of possible consequences have been conjectured for this effect. As with CO_2 the hypothesis is that the absorption of solar radiation by water vapor would warm the upper atmosphere, perhaps at the expense of the lower atmosphere so as to cool it and also the earth's surface. An opposite effect resulting in possibly lethal heating of the troposphere and ground is also conjectured to result from this same source. Certainly it is true that the water balance in the atmosphere is the most significant element in determining temperature and climate. It is also the most variable. For this reason, much of the effort in weather modification has centered on techniques to manipulate this balance. However, as far as the SST is concerned, the issue turns on the degree of stability of the water content of the stratosphere: to what extent does the operation of an SST add significant and lasting quantities of water to it?

Analysis of all apparent factors of SST water discharge suggests that the quantity of water normally held in the stratosphere is very low: normally on the order of 2 to 3 percent relative humidity. It is for this reason that high-flying supersonic jets do not make contrails in the stratosphere except on rare occasions in the polar regions where solar radiation is least significant as a factor of climate. Moreover, the quantity of water emitted per mile by a supersonic aircraft would be so small that once it underwent the diffusing action of air turbulence caused by passage of the aircraft it would amount to only .0024 ounces of vapor per square foot column of air.

The final question is: does this water vapor remain in the stratosphere, to be added to by each successive passage of other SSTs? On the basis of the evidence of what happens to the water vapor and droplets injected into the stratosphere by thunderstorms (500[100] of the some 5,000 storms that occur daily around the earth inject some 75 million tons of water into the stratosphere) it appears that the water content of the stratosphere stabilizes at a low level with surplus rejected downward. Over the past few years, the average water content of the stratosphere has risen by 50% (from 2 ppm to 3 ppm). This increase is from 5 to 10 times as great as the maximum possible from a fleet of SSTs. The increase from natural causes has produced no detectable effects on climate or radiation. What has caused this change in water vapor content in the stratosphere is not known. One possibility is that the content of water in the stratosphere fluctuates above and below some very low figure. Another possibility is that the observed increase can be accounted for by errors in measurement. It would be desirable that periodic measurements of this variable (if it is a variable) be made so that if any significant trend can be established, it can be properly analyzed and interpreted.

Recapitulation

Ultimately, the issues of the SST, as with all assessments of technology, depend upon political attitudes and values rather than on the technical issues of the innovation itself. How important is air transportation for the national welfare? How important is the encourage-

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[100] The figure of 500 was selected as an arbitrary but conservative number for illustrative purposes. It represents about 10% of the estimated total of the daily storms capable of penetrating the stratosphere.

ment of the export of high technology for the national economy of the United States? How significant is technological achievement in the civil sector for U.S. international influence? To what extent is public disenchantment with technological innovation a factor in the decision?

There are many uncertainties: as to the verity of the competition from foreign SST developments; as to whether the Boeing SST will produce the economic gains claimed for it; as to the extent of engineering risk this vehicle represents; and as to whether it can stand alone, without other supporting elements of a complete system of air transportation. Many of the defects of present air transportation have nothing to do with air speed or vehicle productivity; the ground sector, for one example, is generally conceded to have been neglected.

The environmental aspects of the SST, and especially the global aspects, have received the bulk of attention of critics. Yet, upon analysis, most of these postulated effects are found to be minor. Of course, some environmental uncertainties remain. As to these uncertainties, it has been pointed out several times, earlier in this study, that it is rarely if ever possible to prove a negative.

But the greater number of uncertainties appear to lie in the field of economics. It is likely that these can be resolved only by actual experience with the product in use. Much hinges on the quality of engineering management in the development of the vehicle, and the system of which it is conceived as a component. Much hinges also upon the quality of management of the airline service and its competition. Of course, these are general considerations and are therefore imponderables beyond the scope of the present study.

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