Dryden Research Lecture

Possibilities and Goals for the Future SST

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I. Introduction

IT is indeed a distinct honor for me to deliver this lecture which is dedicated to the memory of Dr. H. L. Dryden. It has great significance for me because it honors a man whom I admired and knew for many years. I first learned of Dr. Dryden's work at the beginning of my scientific career when, in the early 1930's, fresh from college, I became involved with supersonic and transonic aerodynamic research at Guidonia, Italy. The members of the club of high-speed aerodynamicists at that time were very few, and the names of Dr. H. L. Dryden and Dr. J. Stack immediately acquired great significance in my work. I was fortunate later on when I came to the U.S.A. to have the opportunity of becoming very good friends with these two distinguished men.

It is in memory of this group which contributed so much to the progress of aviation that I have selected for my lecture the subject of the SST. I must state from the beginning that I am supporting strongly the development of an intelligent SST. I am probably qualified to discuss this problem in view of my extensive training. I started about 35 years ago to try to justify the importance of supersonic aerodynamics and the relevance of supersonic aerodynamics to the progress of civilization. If NASA scientists are having difficulty today in justifying advanced research in Congress, they surely can understand the problems we had in 1935 and 1936 in convincing the administration of that time that an experimental activity in supersonic flow was important and relevant and that funds to construct a 24 in. × 15 in. Mach 2 wind tunnel would be well spent.

Everyone here is surely more or less familiar with the political, economical, and more recently, technical debates that have taken place in the past few years in the U.S.A. on the SST. Such discussions in the past did not succeed in resolving the differences between the supporters of a U.S.A. SST and the opposers, nor did they generate a sound plan of action by defining an acceptable goal. In my lecture, I shall comment on some of the arguments used in the discussion. The goal of my lecture is to try to define the type of advanced SST that can be predicted for the near future and the design goals for an SST that could be attractive for the U.S.A. and would eliminate or at least reduce the differences of opinion between the two opposing groups. Then, I shall try to indicate possible directions of research and development that, if successful, would permit us to meet such requirements.

The major objections raised against the original project for the SST were related to the ecological and economical aspects of the project. In addition, comments were made against the SST on the basis that such a project would benefit only a few and did not fulfill any important national goal. I shall discuss this point first because it will justify my selection of one of the important requirements; ie.e., the most desirable range of the airplane.

The first generation SST has been conceived as a competitor of the presently available long-range subsonic airplane designed for maximum ranges of 4500 miles or less. On this basis, the evaluation of the social value of the SST project has been limited to the importance and advantage in reducing the time of flight by a few hours. Such a reduction is already significant from the social point of view and surely is worth more than the dollar value attributed by some of the analyses I have seen, where only the reduction of flying time has been considered as a significant parameter. Everybody who has traveled for 8 to 10 hours or more in an airplane recognizes that the reduction of human fatigue corresponding to a substantial reduction of flying time can have significant value for many travelers. For example, it could reduce the travel cycle by days and not only hours. However, I believe that the SST can have a very important national and social mission above the advantages of reduction of a few hours of flying time in a trip of 2500 to 3500 miles when the range capabilities are substantially extended to permit much simpler and therefore more frequent communication among people living far apart.

If we analyze historically the relations among people, we find that armed confrontations occur periodically among groups that are within reach of one another. This usually hap-

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*Director, Division of Applied Science, New York University, Astor Professor of Aerospace Sciences. Fellow AIAA. (Deceased Dec. 28, 1975) pens when the groups do not have an effective mechanism of mass communication so that a basic understanding of the relative problems cannot be obtained on a large base and "common sense" utilized to reach acceptable compromises. When a broad-base understanding does not exist, the relations among different groups relies mainly on the unilateral decisions of a limited number of representatives that form the governments without an intelligent input from the majority of the people. It is in this case that the possibility of errors due to human failure and sensitivity to other parameters can and do occur and that armed conflicts can take place. The lack of communication and mutual understanding can be produced by political situations or traditions, which are very strong when communication and trade between the two groups are lacking. However, more often these are due to the practical difficulties of having direct knowledge of the other side of the story caused by the difficulty of travel. I believe that this second situation exists today between the USSR and the U.S.A. It is seldom realized that, as a result of the increased mobility due to the improvement of transportation systems, we could not consider possible today a war between two neighboring cities, as has occured in the past, or between two regions of a given nation, such as the North and South in the U.S.A. The development of rapid communication systems has created the community of interests that makes occurrence of conflicts more difficult. I firmly believe that a detailed analysis made by experts would show that the introduction of the present jet transportation system has contributed to decreasing the tension among neighboring regions of a given nation, or among neighboring nations as much as or possibly more than many politically oriented activities. Historically, we found that the first application of progress in air transportation is utilized to extend the capabilities of offensive action of war. Gradually, the means of civil mass transportation reach the same range available to the military systems; then, the possibility of wars among people within range gradually decreases because closer relations are established. At the same time, the possibility of conflict is extended to people living farther away. On this basis, the parameter miles/hour traveled is a significant social parameter surely as important as miles/dollar or miles/calorie which are the only two parameters considered in some analyses of the SST problem.

I am firmly convinced that presently when many nations have the capability of aggression on any continent of the world, a readily usable system of long-range transportation is an urgent necessity in order to generate a better understanding among people and stimulate a rapid increase in homogeneity of standards of living and uniformity of goals. On this basis, I believe that the SST designed for long-range travel has an important societal value that has been overlooked in the past discussions. Such an airplane, if possible, has clearly a mission different from the present subsonic airplanes, would fulfill a need that exists today, and will become increasingly more important during the next decade when this airplane can become available.

In order to define a practical range for such airplanes, it is useful to analyze the distribution of population and resources around the world. As an example, Fig. 1 indicates the distribution of the population as a function of distance from New York, Los Angeles, and Paris. Nations like the USSR, Japan, China, Brazil, and Germany are at a range between 5000 to 6500 miles from the United States. In general, the largest peak of population presently existing is outside the 7000-mile range from the U.S.A. Therefore, a range between 6000 and 7000 miles appears, if possible, to be a logical range for the future SST. For example, a range of about 7000 miles would permit traveling from New York nonstop to any point in Europe, South American, China, Japan, India, northern and western parts of Africa, and Central Asia. Also, it would permit direct flights from Los Angeles to Australia, South America, the USSR, and all of northern Europe. At the same time, flights of 6 hours, including one-hour stopovers for

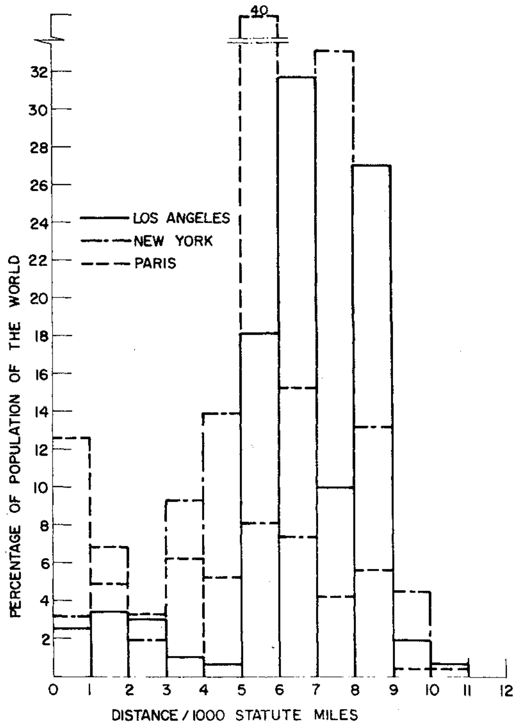

Fig. 1 World population distribution.

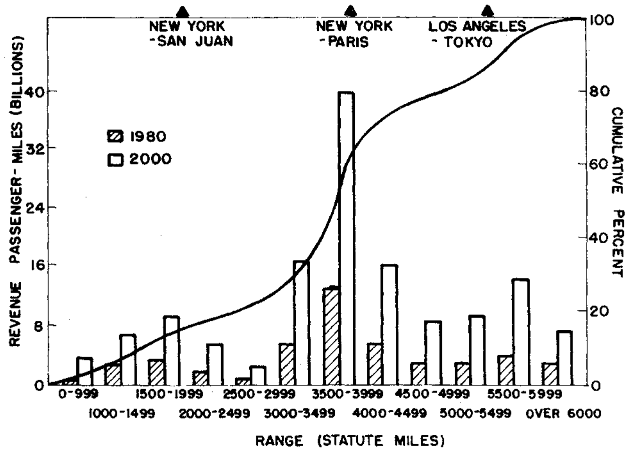

Fig. 2 Predicted revenue passenger miles distribution by range.

refueling could cover a 9000-mile range for an SST flying at $M=2.70$. A 6-hr flight is a well-accepted time from the point of view of human fatigue.

The point should be discussed immediately if flights having these distances can produce sufficiently large traffic to justify a regular route with a large airplane. I have analyzed projections made by experts on this matter and must say that some of their projections are not encouraging. A typical projection for a distribution of traffic in 1980 and 2000 is indicated in Fig. 2 taken from Ref. 1. However, this type of projection is short-range. The data of the figure have been generated by assuming a fairly uniform increase of present traffic requirements; therefore, it does not take into account fully the fact that the present situation could and will change rapidly. Far away regions will become more and more important to us because the standard of living of the densely populated area of Asia will increase rapidly while the regions of Africa and South Anerica will become more important to the world. In addition, such a projection does not take into account changes generated by the introduction of a new system of rapid transportation.

An indirect indication of the manner in which the improvement of transportation affects communication can be

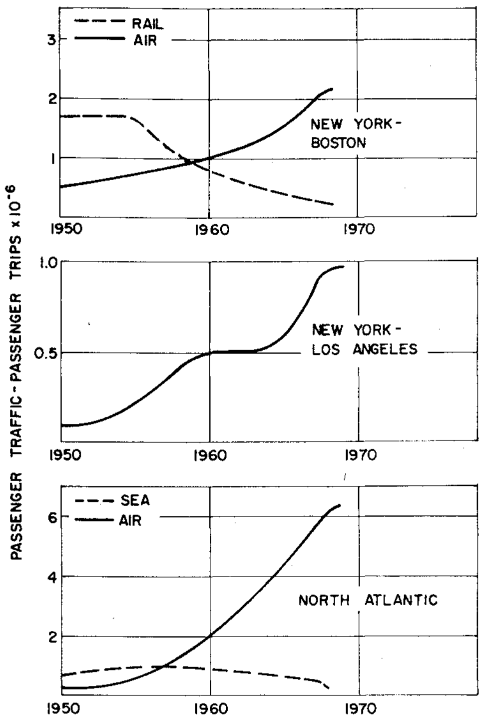

Fig. 3 Growth of air travel for three typical travel markets.

obtained by analyzing the effect of the introduction of jets on the traffic between the East and West coasts of the U.S. and across the Atlantic. The data on the traffic as a function of years are shown in Fig. 3 taken from Ref. 2. The figure shows clearly the rapid increase in utilization of air transportation produced by the introduction of the jet. Projections which attempt to take into account such effects and possible future predictable changes tend to indicate that the long range travel will increase rapidly, especially if the travel is made more comfortable.

While the development of an SST capable of spanning distances on the order of 7000 miles appears to be a much more ambitious but more easily justifiable goal than the 4000-mile design of the first generation, several fundamental questions require an answer: 1) Is this an important goal for the nation? 2) Is the goal achievable? 3) What are the economical aspects and what is the energy utilization of such a vehicle? and 4) What are the ecological impacts on such a project? While the last three questions can be discussed on the basis of technical imputs, the first question is less amenable to a clear answer. I believe that many different aspects tend to indicate that this is the case. It is clear that the aeronautical industry is a very important element of the economy of the nation. Such industry needs for economic and military reasons to maintain a strong competitive position with respect to the industries of other nations. The competitive position of the U.S.A. in the commercial market is gradually declining. The immediate future of the first generation of supersonic airplanes developed in Europe is not easily predictable. However it must be clearly understood here that both the Concorde and the Tupolev 144 represent major technical achievements and demonstrate a technical capability that cannot easily be overtaken by our technology. Their selection of airplane design performance is old, and as happens to any new revolutionary project that requires a long time to be completed, such a selection could possibly penalize the economical success of the project. However, this conclusion should not be reached prematurely, as often is done in the U.S.A. The conclusion has already been reached by many that this first generation of airplanes that competes with existing subsonic jets is too expensive and economically unsound to operate for a commercial airline. I am not so sure that this point has been proven. While the conclusion appears to be logical when we

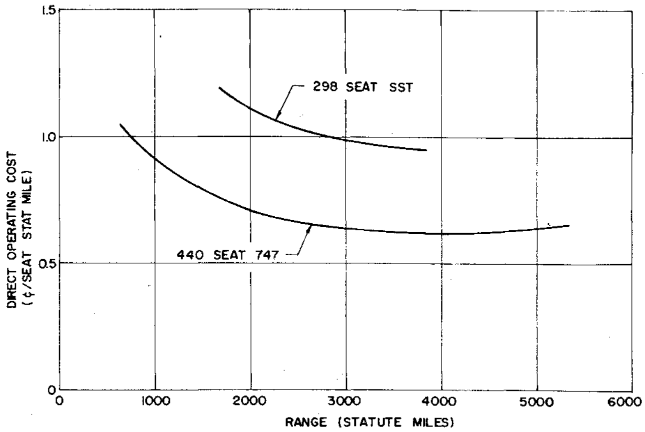

Fig. 4 Comparison of direct operating costs for the Boeing SST and 747 airplanes.

compare direct operating costs among subsonic and supersonic airplanes as shown in Fig. 4 (taken from Ref. 3), this type of curve permits a different conclusion, i.e., the SST needs twice the load factor of the 747 and some supercharge in order to have the same operating cost. This, in my opinion, can be a real possibility when the Concorde and Tupolev enter operation; then many of the negative conclusions could change.

An airplane as just postulated that can transport 1500 people roundtrip to Europe without refueling or transport 600 people and dense cargo 7000 miles in 25 hours surely has important military applications. Other similar technical or economical arguments in favor of the SST can be raised on this point. However, my inclination is to justify the importance of the airplane for our nation, not on the basis of economics or military importance alone, but on the basis of the impact on our relations with far away people is Asia, Europe, Africa, South America, and Australia. If we analyze the distribution of expenses of our national budget or more generally the functions that we consider important for the nation and we are willing to support, we find that very few of these functions can be justified on the basis of a return measurable in dollars of justifiable on the basis of economics.

All scientific, and military activities, and all activities related to supporting the sick, the elderly, and the underpriviledged, are surely justified only on the basis of human sensitivity, human interest, or human ability to survive. I feel that an efficient SST can perform the mission to improve understanding, knowledge, and appreciation of characteristics, problems, and interests of distant people, which in my opinion, is a mission as important as other humanitarian or educational missions, and is a fundamental step toward improving stability in the world. I am especially sensitive to the importance of this mission because I had the chance to have a first-hand evaluation of the basic consequences of the lack of understanding among people that led to the last World War. I would hope that some experts in political and social sciences, who often become involved in technical or economical discussions like this one, would develop fully this argument and prove that the development of an efficient SST is a justifiable cost for the nation. I will discuss now the technical aspects of the problem and attempt to define possibilities and required research and development to meet the goal.

II. Airplane Requirements and Corresponding Technology Improvement

Several different technologies influence strongly the airplane characteristics, with the most important being: 1) propulsion, 2) aerodynamics and aerodynamic design, and 3) structures and materials. In addition, the selection of the mode of utilization and operation of the airplane influences substantially the actual utilization of airplane performance.

On the basis of present knowledge, substantial improvements can be predicted with confidence in all these fields in the near future. Such improvements can influence tremendously the overall airplane performance. In order to discuss the effect of possible improvements, it is useful to establish a base line SST using present technology.

Recently, several companies under NASA sponsorship have conducted investigations to determine possible airplane performance for an SST based on presently available technology. Several SST layouts have been evaluated. The differences among the configurations are important; however, the variations are not too significant for this discussion. Therefore, on the basis of these studies, a base-line configuration can be defined. I will use here as the base-line configuration the one defined by a NASA Langley internal study. This report, performed by the Advanced Supersonic Technology office of Langley Research Center, has been made available to me. Reference 4 summarizes some of the technical developments presented in this report and in the technical studies performed by the companies. The study has been of great help to me in reaching many of the conclusions presented here. This study tends to indicate that an airplane having a takeoff gross weight of the order of 760,000 lb could carry under present modes of operation about 300 passengers at a range of about 4600 miles. Such an airplane would use as engines advanced dry turbojets possibly with variable geometry turbines, having 800lb/sec air flow at takeoff. The installation meeting present noise specifications defined as FAR 36 T.O. would require a noise reduction with respect to the basic engine of 11.7 dB. Such a reduction must be produced by means of silencers. Such an airplane would have a wing of about 11,000 ft^2, a span of about 150 ft, and a length between 300 and 330 ft. The weight distribution of the airplane is approximately as shown in Table 1.

Such airplane performance represents a substantial improvement with respect to the present SST and assumes the use of high-temperature turbines and very efficient component performance. The L/D of the airplane configuration is assumed to be 8.57, and the installed SFC at cruise is assumed to be 1.39. Such an airplane could cruise subsonically for 4000 miles, if required, The airplane can deliver 5.0 passenger miles/lb of fuel which is somewhat lower than present subsonic airplanes (the DC 10-30 delivers about 7.5 passenger mile/lb fuel); however, it is a big improvement with respect to the Concorde (which delivers only on the order of 2.8 passenger mile/lb of fuel).

The approximate distribution of weight shown in Table 1 indicates that in this airplane configuration about 50% of the takeoff weight is the fuel to be used in the mission; therefore, improvement in propulsion and in operational procedures that can increase fuel utilization can benefit substantially the performance of the airplanes. Typical engine performance for a dry turbojet having 800 lb/sec air flow compression ratio of 5 and 2600°R maximum turbine temperatures is shown in Fig. 5, taken from Ref. 1. (This performance is the installed value.)

The data shown in Fig. 5 correspond to dry turbojets having fixed geometry turbines defined as turbines in which the corrected flow cannot be changed for a given set of con-

Table 1 Airplane weight distribution

Aircraft component	Total weight
Total weight	760,000 lb
Empty weight	325,000 lb
Structural weight	195,000 lb
Propulsion	70,000 lb
Equipment (system weight)	60,000 lb
Operating empty weight	345,000
Fuel	355,000 lb
Passengers and baggage	61,000 lb
Time of Flight for 4000 n.mi	3hr 20 min

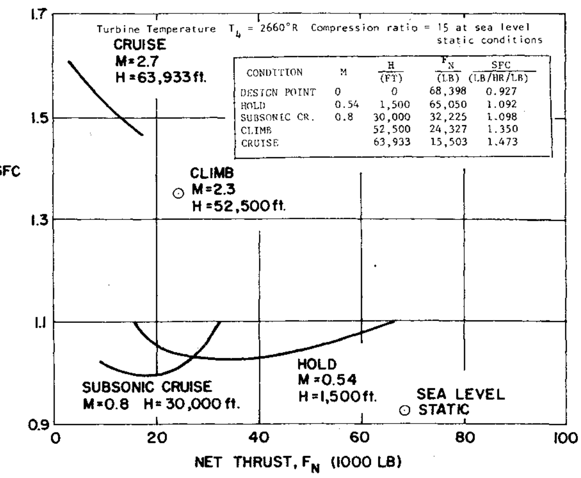

Fig. 5 Dry turbojet, single spool.

ditions. If this type of engine is used, then the range of the airplane for the weight described before is about 4000 miles. An increase of turbine temperature from 2600°R to values of the order of 3200°R decreases the SFC at supersonic cruise from values of the order of 1.49 to values of approximately 1.39.

In addition, new engine concepts called variable cycle engines recently have been investigated. In some of the schemes, a variable area turbine has been introduced. Variable area turbines improve performance especially during subsonic and acceleration segments of the flight. The gains obtained at these lower speeds permit decreasing the fuel consumption during acceleration, descent, and the reverse. The amount of fuel used in this part of the operation is substantial as shown in Table 2.

The improvement of low-speed SFC resulting from the use of variable cycle decreases the reserve requirement and the fuel used for takeoff, climb, descent, and taxiing from a total value of 148,000 lb as shown in Table 2 to a value of 100,000 lb. The improvement obtainable by using high temperature and variable turbines is assumed in the numbers used for the base line airplane previously described which has a range of 4600 miles. However, additional gains can be obtained by developing new advanced propulsion technology.

The performance of an engine at supersonic flight depends on the cycle considered. Presently, the bypass engine has been considered efficient for subsonic flight. However, substantial gains can be obtained also at supersonic speed provided that the losses in inlet pressure recovery for the fan are minimized.

Typical curves of specific fuel consumption as a function of bypass ratio for different turbine temperatures are shown in Fig. 6.† These curves have been obtained by assuming high

Table 2 Acceleration, descent and the reverse fuel consumption

Fuel usage	
Takeoff	10,000 lb
Climb to $M=0$ to 2.7	60,000 lb
Cruise (4600 miles)	205,000 lb
Descent	6,000 lb
Taxi	2,000 lb
Reserve	70,000 lb
Fuel not recoverable	2,000 lb
Total fuel	355,000 lb
The reserve is determined on the basis of the following requirements:	
7% of fuel used	19,600 lb
Missed approach	10,400 lb
260 n.mi to alternate airport	24,500 lb
30 min holding at 15,000 ft	15,000 lb
	69,500 lb

†These results have been obtained in an investigation performed by the Advanced Technology Laboratory under NASA Lewis sponsorship. The project engineer at Lewis is L.C. Franciscus.

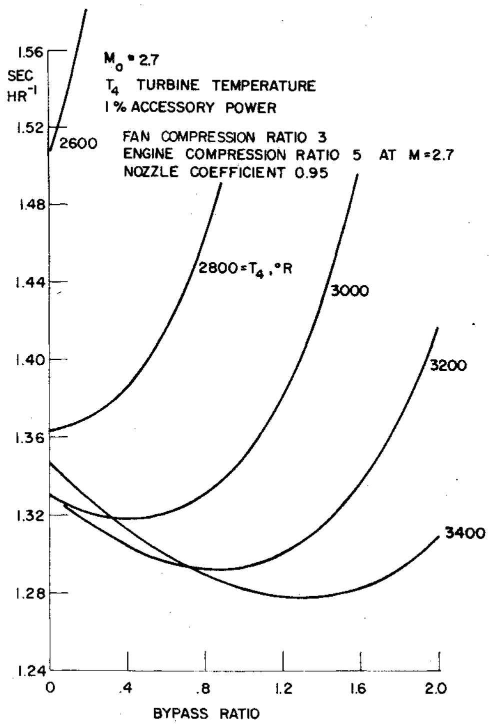

Fig. 6 Variable bypass turbine temperature.

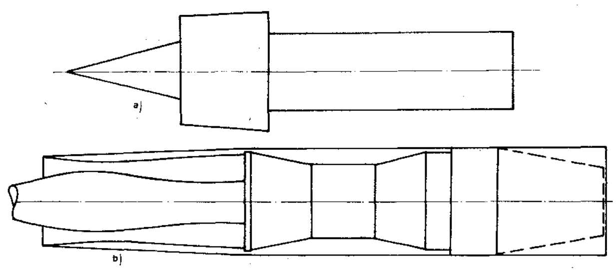

Fig. 7 Installed size comparison of a) variable bypass turbofan and b) conventional turbojet.

inlet fan pressure recovery and lower pressure recovery for the main flow. These figures show that SFC on the order of 1.28 is possible at temperatures of the order of 3200-3400°R. The performance has been obtained by using a supersonic fan. The investigation showed that a very compact engine can be developed that has attractive performance at cruise and acceleration even if designed for large mass flow at takeoff in order to decrease noise. A comparison of dimensions between a dry turbojet installation using 1000 lb/sec of air at takeoff is shown in Fig. 7. The installed specific fuel consumption for such an engine is approximately 0.62 at takeoff and 1.31 at cruise. The development and introduction of such types of engines could improve substantially engine performance, weight, and cost.

Other major gains can be obtained by changing some of our regulatory requirements and modes of operation which take into account use of more advanced methods of control of flight operation. It has been shown that the reserve fuel required for the airplane is larger than the payload. The possibility exists of reducing the requirement for reserve fuel by changing the mode of operation. For example, it can be expected in the near future that a large part of the fuel devoted to redirection to an alternate airport or to a holding at 15,000 ft for 30 min will not be required because of better planning that utilizes advance information obtained before departing or during flight and automated airport control. In addition, it can be expected that in future years it will be possible to predict airport traffic 3 hours in advance. Then, at least the 30 min wait at 15,000 ft could be eliminated in an SST operation.

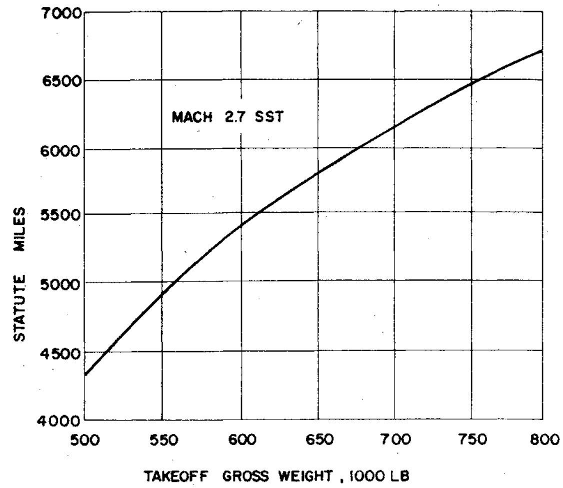

Fig. 8 Range as a function of takeoff weight.

This modification will reduce the reserve fuel required by 15,000 lb.

It must be also noted here, incidentally, that large improvements should be expected in the future in the time spent by international passengers on the ground. This makes the reduction in flight time more valuable. For example, simple obvious improvements could be the introduction of checking the passport in flight by flight attendants or a single control at departure that includes security and import controls which would eliminate the long delay on arrival.

Possible Performances Obtainable with New Engines and Reduced Fuel Reserve

An analysis has been performed where the fuel reserve has been reduced by eliminating the 30-min holding at 15,000 ft when redirection is required and by assuming the performance and weight predicted for the new engines described before. The results of the analyses are shown in Fig. 8. The payload is maintained constant at 61,000 lb for the curve that gives range vs takeoff weight. The figure shows that a range of 4600 miles could be achieved with a takeoff weight of 520,000 lb while a 760,000 lb airplane using present aerodynamic design and present structural weight would have a range of 6500 miles. These gains are obtained by improving engine performance only. However, other substantial gains can be expected because of the introduction of new material and new structural designs.

Structural Weight Improvement

Structural weight can be reduced by simplifying airplane design, improving structural design, and using new materials. Presently, the technology of airplane control design, structural design, and advanced materials is improving very rapidly. The introduction of the concept of active controls is a very important step because it permits us to decrease substantially the size, weight, and drag of the controls required for the airplane. For example, the introduction of advanced flight control systems that can stabilize the airplane electronically permits us to reduce substantially the aerodynamic stability required for the airplane. As a consequence, the control surface required in the design are smaller, and at the same time the airplane can be balanced with the center of gravity further aft than before. Such improvement reduces control surface weight and in addition substantially decreases induced and wave drag. Furthermore, it has other beneficial effects because of the acceptable changes for the center of gravity location. The wing moves upstream with respect to the fuselage with an increase of longitudinal stability, a reduction of vertical tail size, and an additional decrease of weight and drag. The same concepts can be extended to the longitudinal stability requirements, which are dictated by the control of the airplane during propulsion failure in high-speed flight. Again, the introduction of augmented lateral directional stability will permit a reduction of inherent aerodynamic stability.

Other improvements in structural weight can be obtained by introducing new techniques recently developed related to manuever and gust load alleviation. The alleviation of maneuver loads can be achieved by active use of onboard flaps electronically controlled. Similarly, the decrease of gust loads can be obtained in an airplane having an approximate length of 350 ft by dynamically controlling the angle-of-attack variation. Dynamic controls can be used to prevent flutter. The introduction of such new concepts alone will permit substantial reduction of the weight and drag of the airplane.

Weight reduction resulting from the introduction of active controls has been estimated, by industries in studies performed for NASA. Improvements of about 8000 lb have been considered possible for a 760,000 lb airplane. Even if this total weight saving cannot be fully realized, reductions of approximately 4000 lb are considered to be presently obtainable with minimum development risk.

Substantial reduction in weight can be obtained by the extensive introduction of composite materials. Presently, the use of composite materials in primary structural components is under intensive investigation. Composite materials, are being used today in secondary structures. Substantial reductions on the order of 15-20% of airplane weight have been predicted by industry with the respect to the structural weight estimated in Table 1 by either the improvement of metal properties or using a large amount of composite material.

Figure 9 obtained from Ref. 1 gives a typical projection of weight saving as a function of design Mach number. Other weight saving results from systematic improvements in auxiliary equipment which presently contributes substantially to the total weight and cost. For example, in a present large airplane there are approximately 750,000 ft of electrical wire for a total weight (with connectors) of about 6000 lb. Such wires are independently located. More advanced methods of construction and installation are being developed presently that could reduce the weight by 15%. Similar improvement can probably be obtained in other types of onboard equipment if a concentrated effort is performed.

Considering all reductions described, a decrease of the structural weight of 15-20% can be achieved in an advanced SST that is designed and constructed in the near future. A 10% reduction, which corresponds to a weight saving of 19,000 lb, includes 4000 lb resulting from the introduction of advanced control techniques, 2000 lb on the equipment weight, and 6.5% in structural weight. The value of 20% would include a reduction of 16% structural weight and a slightly higher reduction in control and system weight.

Aerodynamic Drag

A typical drag polar of a supersonic configuration of present generation is shown in Fig. 10. Such polar diagrams do not include the external drag of the propulsion system. The L/D of such a configuration is approximately 9.1 which becomes on the order of 8.87 when the engine drag is added.

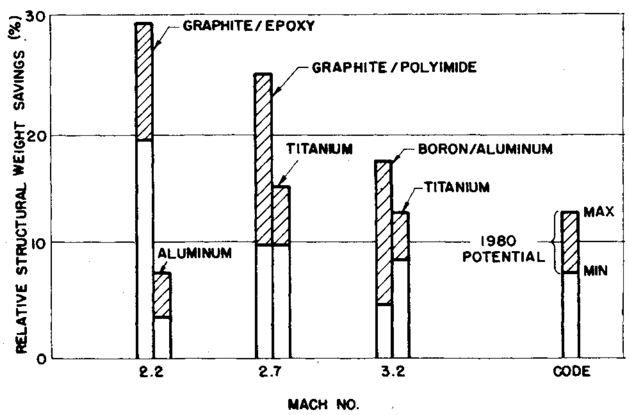

Fig. 9 Potential weight savings for composites and metals, 1980-1970 metal baseline.

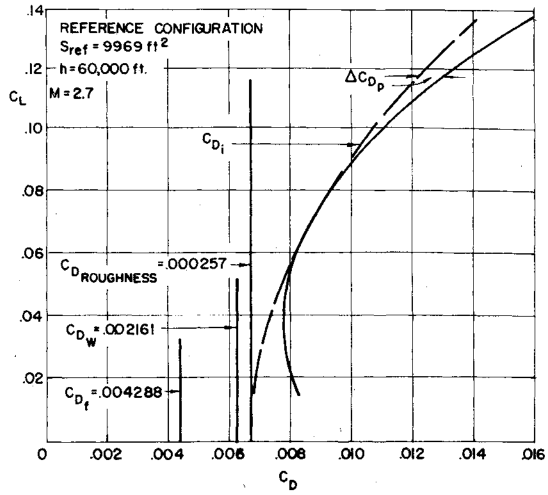

Fig. 10 Cruise drag polar breakdown—reference configuration.

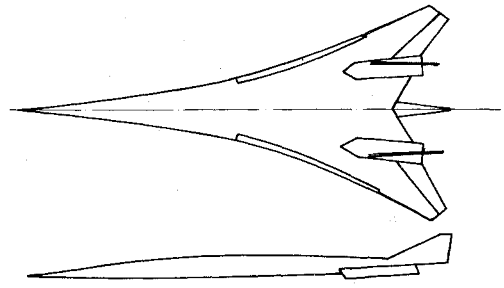

Fig. 11 Arrow wing concept tailless.

The figure indicates total value of the drag coefficient at best L/D is 0.011 of which 0.043 is skin friction, 0.0022 is wave drag, and the rest is induced drag. The value of L/D of 9.1 at $M=2.7$ is much higher than the L/D of present configurations flying at $M=2.2$. The use of augumented controls, the use of a blended fuselage and integrated configuration and smaller nacelle installation could present a decrease of skin friction drag of about 10% and a decrease of wave drag of nearly 5%. An integrated configuration when the fuselage is combined with the wing could reduce further skin friction and wave drag. A configuration of this type proposed by industry is shown in Fig. 11 from Ref. 5.

A similar configuration with highly sweptback wing and blended fuselage has been investigated in a preliminary way by NASA. One difficulty in the development of such a configuration is the fact that highly sweptback leading edges cannot be investigated fully in present available supersonic and subsonic facilities because of the low Reynolds number normal to the leading edge available in such facilities. However, such configurations are of great interest because of the large possiblility of reduction of skin friction and sonic boom.

Schemes have been proposed where injection of low velocity air and suction of the boundary layer have been considered for skin friction reduction. In principle, boundary-layer control can maintain the boundary-layer laminar in a large region of the wing at supersonic speed.[6] However, the problem is related to the efficient use of the mass of air removed in order to stabilize the boundary layer. A different concept has been developed[7-8] where the low velocity air is injected tangentially to the surface. Such injection reduces substantially the boundary-layer skin friction. A combination of the two schemes that utilizes local pressure differences to minimize losses of kinetic energy indicates a direction to be investigated for skin friction reduction at supersonic speed. For example, boundary-layer air can be sucked from the bottom surface of the wing and discharged in other regions of the

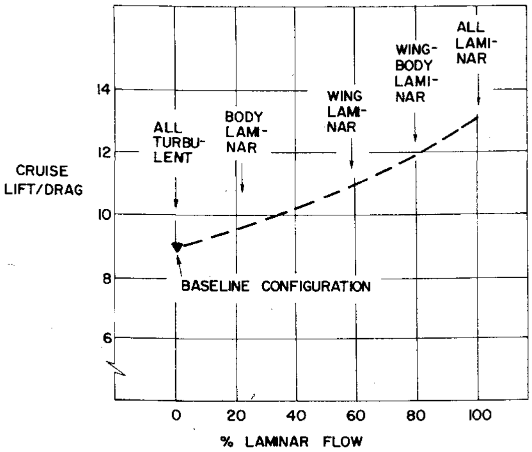

Fig. 12 **Effect of laminar flow on cruise L/D of baseline concept.**

wings where the static pressure is such that the air can be injected at low velocity. Preliminary analyses of the effect of injection of low velocity air in the boundary layer combined with suction to extend the region of laminar boundary layer tend to indicate that substantial skin friction reduction is possible. Then, it can be expected that in the future the L/D obtainable at $M=2.7$ will increase because of the development of new advanced configurations, while the introduction of boundary-layer controls could further increase the obtainable L/D. Figure 12 gives an indication of possible gains in L/D when skin friction is reduced in the base line airplane configuration.

Possible Performances

The combination of several of the technological improvements described previously can improve substantially the performance of the SST. Figure 13 gives the change in range of the airplane having 760,000 lb takeoff weight described in Table 1 as a function of the L/D for different levels of improvements in propulsion and structural weight. The first line corresponds to present design, structural weight, and engines and gives range as a function of L/D of the airplane. The second line indicates the effect of improvement of subsonic engine performance; the third line, the effect of reduction of reserve of 15,000 lb; and the fourth, the effect of supersonic engine performance improvement. The fifth and sixth lines indicate the improvement of structural weight (10% and 20%). The chart shows that ranges of about 7500 miles can be reached with moderate increase of L/D provided that structural weight and engine performance are improved. Conversely, an improvement of L/D could reduce the improvements required in the other technologies or decrease the weight of the airplane.

If an airplane capable of flying 300 passengers at 7500 miles can be developed, then the fuel consumption per passenger will be 0.160 lb/passenger mile which is the same as a 747 going the same distance. Therefore, the airplane becomes competitive from the point of view of energy utilization with subsonic airplanes.

III. Environmental Problems

Air Pollution

One of the major objections raised against the introduction of a large fleet of SST's has been based on the fact that the continuous discharge of large quantities of exhaust gases in the stratosphere can produce significant changes because of the large residence time of pollutants in the stratosphere. The possibility was raised initially by a group of interested scientists under the auspices of MIT.[9] They analyzed the problem and reached some preliminary conclusions which were based on the knowledge at that time and were in many aspects incorrect. Other investigations that followed emphasized initially the possibility of interaction between the ozone in the stratosphere and the water vapor added by the exhaust gases.

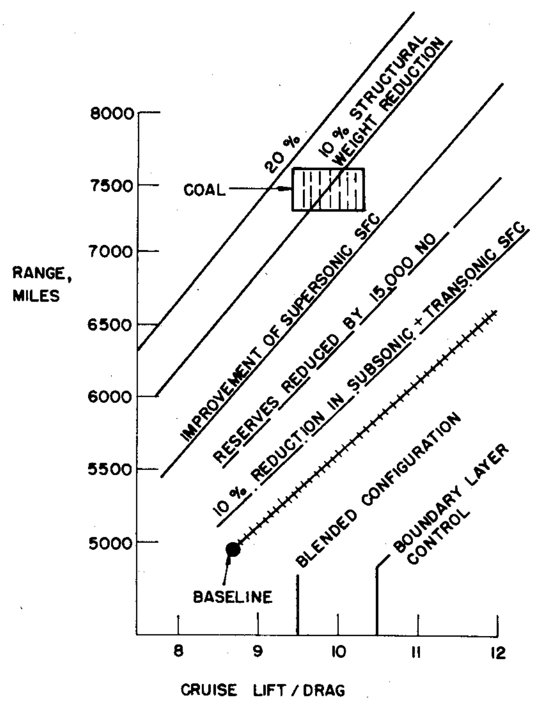

Fig. 13 **Effect of advanced technology on range performance.**

In the last few years, a substantial amount of scientific work has been performed on the subject that has clarified substantially the situation. Many researchers were involved.

Recently, the Department of Transportation, under Dr. A. J. Grobecker, has concluded a major effort directed toward the detailed investigation of this problem. The results obtained until now indicate that the problem exists but, as I pointed out early in 1972, can be solved because the water formation, which was considered as one of the chemical components that would reduce the ozone in the upper atmosphere, is not a dangerous pollutant; the arguments used at the time of the discussion in Congress against the SST not only are invalid but in fact wrong in sign. It has been proven that on the basis of better knowledge of the chemical reactions involved, the water content of the exhaust gases at 65,000 ft of altitude reduces the nitric oxide existing in the upper atmosphere. The nitric oxide is a catalyst for the ozone reaction and tends to reduce the concentration of ozone in the stratosphere; therefore, if the exhaust gas would contain only water vapor and carbon dioxide the net effect would be that an increase of ozone would take place. However, the engine exhaust contains substantial amounts of NO and SO_2. The NO of the exhaust gases, unless controlled, could have deleterious effects on the atmosphere because the NO produced in present engines is much higher that the NO destroyed by the water. In addition the SO_2 could effect the weather. Fortunately, the amount of NO produced in turbojet engines can be reduced substantially if required[10-14] while the sulphur can be reduced in the fuels; therefore, the problem of stratospheric pollution can be solved at the engineering level.

The question of the actual importance of the stratospheric pollution is far from being defined quantitatively. I have followed closely recent developments, and I have participated in the review of such efforts organized by the Academies of Science and Engineering. All the scientific work performed until now has convined me that a good possibility exists for the exhaust gases of a large fleet of airplanes, using present engines and flying in the stratosphere, to shift the equilibrium of the upper atmosphere. In fact, I believe that such possibilities exist for both long-range subsonic and supersonic airplanes.

A study of the possibility that this effect can actually be important is extremely complex and today cannot and, therefore, should not reach precise conclusions. In addition, other activities or phenomena outside the SST operation can produce similar effects and modify the ozone content in the stratosphere.

In view of the important possible consequences predicted by the experts on all living organisms, produced by a large modification of the ozone content in the stratosphere, it appears logical to conclude that prudence should prevail and efforts should be made to minimize such effects. However, this does not imply that the only solution is a limitation of the SST operation as advocated by many. It does require the introduction of advanced combustor designs that are technologically feasible if we decide to do so. It is important to notice that if we accept present knowledge as valid, because of the opposite effects of water and nitric oxide it is possible to define a "zero impact airplane", as suggested by R.C. Oliver of IDA, which would produce zero effect on the ozone and on the weather. Such an airplane would require a strong reduction of NO_x emission with respect to present airplanes, which, however, is technically possible. The concept of a zero impact airplane is of great importance because it solves the problem of pollution independently of the number of airplanes and size that will be constructed in the future. The concept of a zero impact airplane can be extended also to the effect of sulphur oxide on the temperature of the Earth.

It has been suggested that changes in temperature are possible when substantial amounts of water vapor and sulphur dioxide are discharged in the stratosphere. The increase of water content in the stratosphere has several consequences: 1) It affects the infrared radiation flux; 2) It can change the energy balance at the surface of the Earth and, therefore, the temperature; and 3) It can affect the NO_x cycle because it reacts slowly with the ozone, producing destruction of the ozone. The effects of the water on temperature are the opposite of the effects produced by aerosols. The interaction of the water vapor with the ozone is small while the interaction of the water with NO_x tends to decrease the concentration of the NO_x already present. The zero impact airplane should not produce any changes in the local ozone concentration by producing only the amount of NO_x that balances the effect of the increased water content caused by the engine. The amount of water vapor produced per kg of fuel corresponds to 1.250 kg. Then, if we accept the present knowledge of the chemistry in the stratosphere, the emisiion index for NO_x (measured as NO_2) required for zero impact corresponds to an emission index of 0.3 g/kg fuel. The presence of water vapor affects the radiation process and has an opposite effect than the aerosols produced by the sulphur dioxide. The zero impact airplane would require 0.024% in weight of sulphur in the fuel. These values can be obtained in practical engines and fuels.

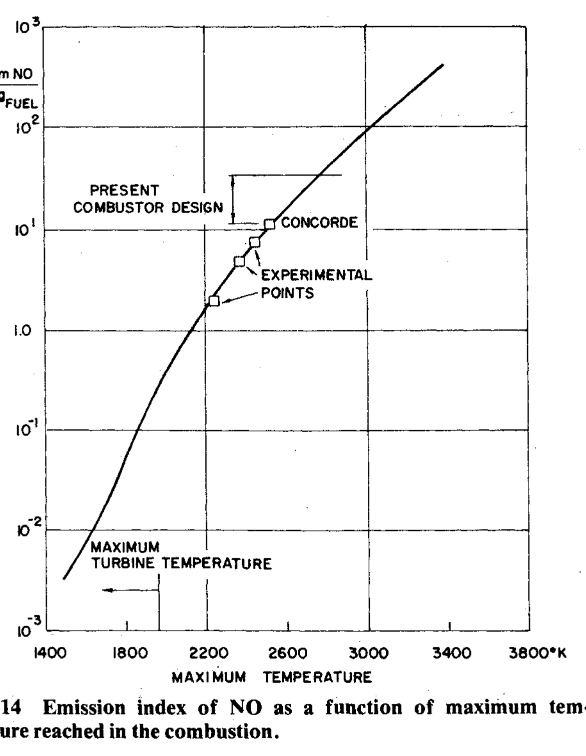

Fig. 14 Emission index of NO as a function of maximum temperature reached in the combustion.

The mechanism of the formation of NO_x in the present combustors has been described in Ref. 10. The formation of NO_x is due to the fact that in the present combustors liquid fuel is injected by a spray nozzle that atomizes the liquid in a combustion region where high turbulence is produced. The liquid fuel droplets vaporize and react locally with the surrounding air. The gaseous fuel produced by the evaporation diffuses rapidly into the air. Combustion takes place in the region where fuel and air ratio is close to stoichiometric; then, locally very high temperatures are reached which are a function of the initial air temperature.[11,13,14] The average temperature in the combustion region remains high until the combustion gases are cooled by mixing with additional air in order to produce gases having temperatures acceptable to the turbine.

A chemical kinetic analysis shows that NO formation occurs near the end of the carbon or hydrogen reaction with oxygen, and the delay time for the formation of large quantities of NO_x is very small. Then the NO formation gradually increases and slowly moves toward equilibrium values. Figure 14 gives the values predicted by the analysis as a function of the maximum temperature reached in the combustion region for practical combustor designs.

The final temperature required for the exhaust gases in engines required for an SST at cruise is on the order of and lower than 1800°K. Then, if we can limit the maximum temperature reached during combustion close to these limits, the amount of NO_x formed can be minimized. The scheme proposed in Ref. 10 for reaching low NO_x formation is to vaporize the fuel and premix the fuel with air in the correct proportion before combustion, then burn the mixture. In this type of combustion, the time required to reach equilibrium temperature is approximately the relaxation time for translation equilibrium which is much smaller than the delay time for NO formation. Then NO is not formed. Preliminary experiments described in Ref. 10 indicated that this scheme is efficient for NO reduction.

Other experiments performed under simulated conditions by NASA (Ref. 12) and under NASA sponsorship (Ref. 14) indicate that combustion of hydrocarbons where NO_2 indices on the order of 0.3 g/kg fuel can be produced with high combustion efficiency. The scheme described previously probably can be mechanized efficiently in an actual engine. Other schemes have been proposed and investigated successfully based on catalytic reactions. On the basis of these results, it can be predicted that the pollution problem of the SST can be solved satisfactorily provided that the work necessary to go from the laboratory experiments to the engine development is performed. The difficulties of such a step, and the cost and time involved should not be minimized. However, this first step already should be sufficient to eliminate the unqualified opposition raised against the SST on the basis of possible dangerous ecological effects.

Sonic Boom

When an airplane travels at supersonic speed or accelerates near sonic speed, shock waves form and all disturbances generated by the airplane remain localized in a region downstream of the front shock wave. The waves propagate through the atmosphere and strike the ground where they are reflected. Then, an observer on the ground senses a "sonic boom" that usually starts with a discontinuous pressure jump and terminates with a second sharp pressure jump.

A "standard" sonic boom signal propagating to the ground from a high altitude can be described as an *N*-wave with the

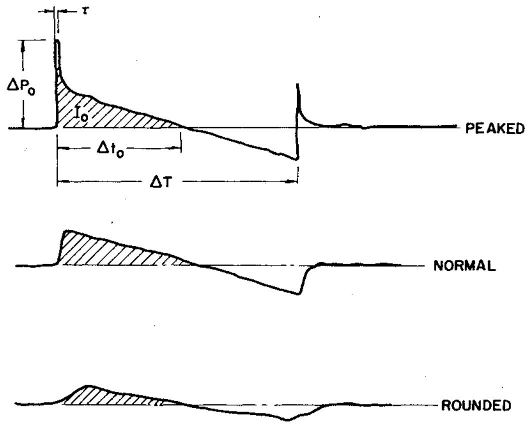

Fig. 15 Tracings of measured SR-71 sonic boom pressure-time histories along ground track showing some waveform categories and signature definitions.

head and tail shock following one another at a time interval that depends on the flight Mach number altitude of flight and airplane length. For an airplane 350 ft long flying at $M = 2.70$ at 65,000 ft, the time difference is about 300 msec.

The strength of the head and tail shocks for the first generation of SST is between 2 and 3 lb/ft^2 when the shocks are reflected by a flat rigid solid ground. Atmospheric turbulence and air temperature gradients affect the decay of the waves and modify the shape of the signal. Configurations of the ground influence also the strength and shape of the reflected waves; typical measured sonic boom signatures and possible modifications of wave shape are shown in Fig. 15 from Ref. 15.

The value of 2-3 lb/ft^2 overpressure is presently considered objectionable, especially at night and in regions of low noise. Therefore, present regulations bar supersonic flight over U.S.A. territory.

Figure 16 indicates a typical pattern of signature of sonic boom and levels during the different phases of flight trajectory. Known phenomena that produce startling effects of the same nature of the effects produced by sonic boom also are

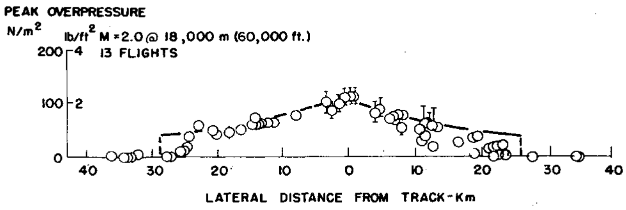

Fig. 17 Lateral distribution of peak overpressure for XB-70.

indicated in the figure together with corresponding overpressure values. The figure indicates that Δp on the order of 1 lb/ft^2 or lower is comparable to a distant thunder that is considered as a minor startling phenomenon and therefore probably could be accepted. Figure 17 from Ref. 16 indicates that the sonic boom decays laterally, and a lateral cut-off distance of the SST sonic boom exists. Experimental results tend to confirm the trend shown by the analysis. The sonic boom is felt as noise by people and animals and is objectionable mainly because it appears without warning. A boom which has a small initial shock wave will have a higher degree of acceptability because it will produce effects similar to noise already accepted in populated areas.

Acceptability criteria are difficult to establish. Experiments performed in 1960-1970 are probably not indicative for revealing long-range conclusions because of the publicity given to the experiments and because of the novelty of the phenomenon. However, they are indicative for establishing variations of annoyance produced by different levels of sonic boom. Some of the results obtained[17] are shown in Figs. 18-19 as a function of the peak overpressure of the first shock. The data presented assumed 10 to 15 flights a day; that is a very high level of supersonic flight over a given region. The data indicate that maximum overpressures on the order of 0.6 to 1 lb/ft^2 are probably acceptable for a few flights a day. It must be noted that this maximum overpressure value corresponds to a small region of the boom carpet and that the overpressure decreases rapidly, moving laterally away from the vertical plane of the flight. Then for a long range airplane, the possibility of flying overland, especially in the last part of the range, appears to have a practical possibility. It is assumed

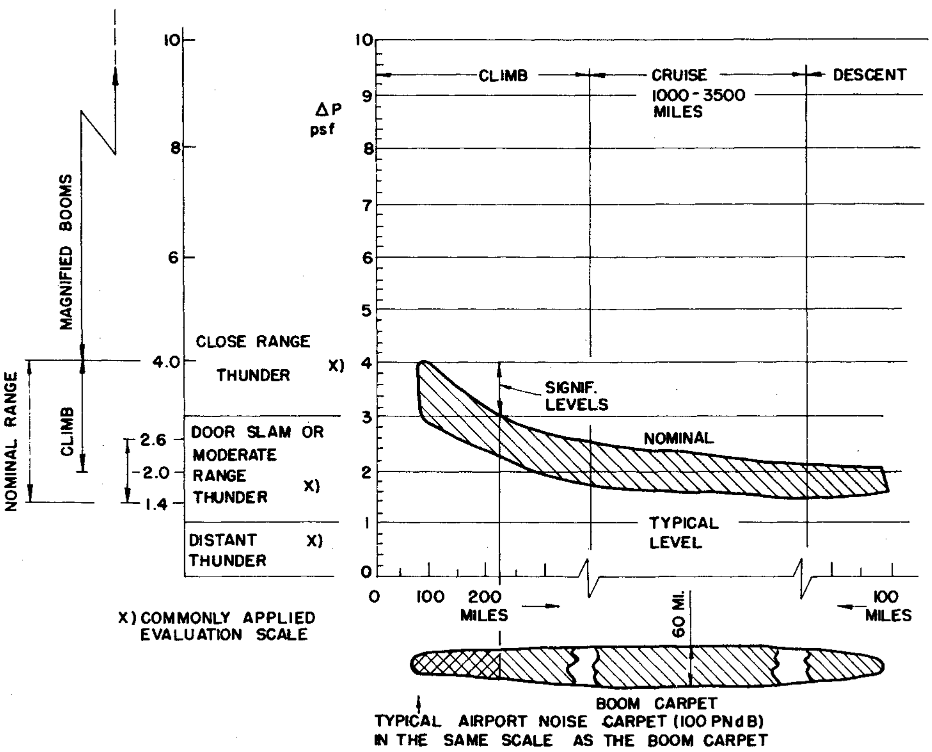

Fig. 16 Ranges of SST boom overpressures.

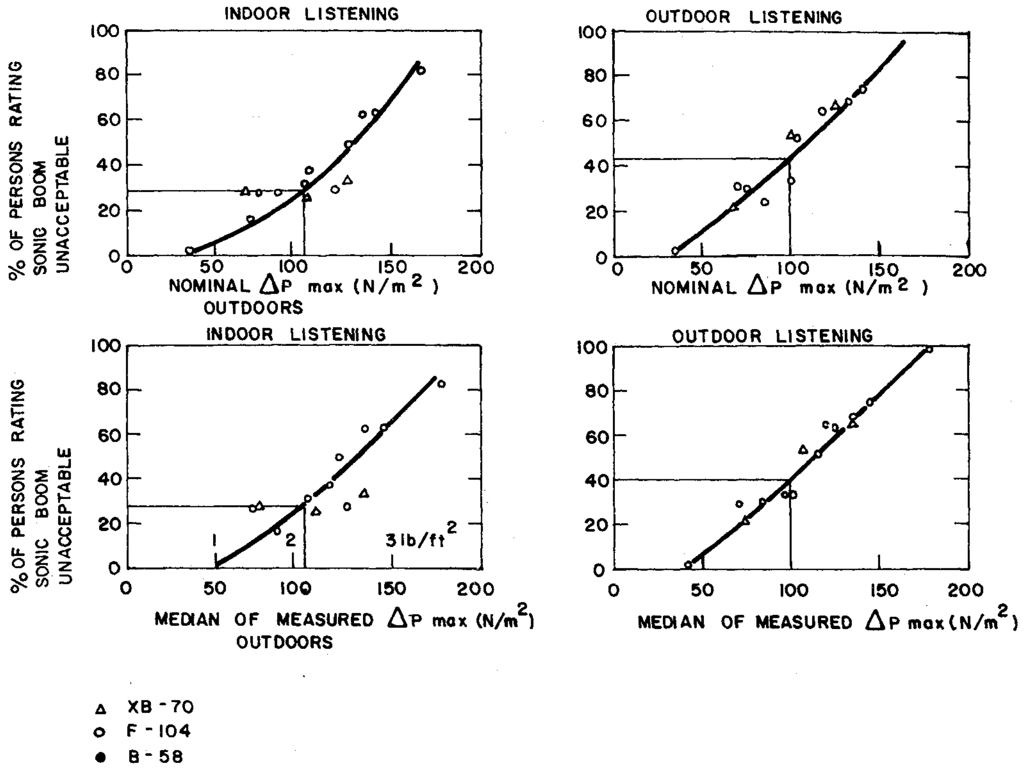

Fig. 18 Percentage of people who rate as unacceptable sonic booms from XB-70, F-104 and B-58 aircraft. (Listeners from Edwards Air Force Base.)

here that the deceleration from supersonic to subsonic flight will not be gradual and coupled with highly inclined descent trajectories. This assumption has been included in the data shown in Fig. 16.

Substantial understanding has been obtained recently on the selection of an airplane configuration that minimizes sonic boom.[18-22] Airplane configurations having highly sweptback wings starting near the nose of the fuselage permit us to obtain "near field signature" for the sonic boom which corresponds to signature shapes as shown in Figs. 20.

The signature depends on the length of the airplane and on the lift and, therefore, on the weight of the airplane and on the details of the aerodynamic configuration. The airplane discussed previously will have a weight of approximately 465,000 lbs near the end of the flight range and will have aerodynamic lengths of the order of 350 ft. The actual length of the airplane is smaller than the aerodynamic length quoted in Fig. 20a because the length of Fig. 20a is determined by taking into account the height of the airplane as shown in Fig. 20b. A difference of 20-30 ft exists between the aerodynamic length and actual length in practical configurations. Then, signatures as shown in Figs. 20 can be obtained for such airplanes. Lower signatures can be obtained if the weight near the end of the flight is decreased as shown by the curve in Fig. 21. These data indicate that the problem of sonic boon could be reduced to acceptable limits especially if the SST is used for global transportation. Then, only as few as two flights per day will be used on a given route, and low sonic boom airplanes can be developed because of the large ratio between takeoff and empty weight.

Additional work is required before changes on the present regulations can be discussed. Such work should be based on observation of public reaction to the sonic booms produced by future SST commercial flights and on studies of L/D best obtainable for low sonic boom configurations.

IV. Recommendations and Conclusions

A long range SST is a logical and important development for the U.S.A. An airplane capable of carrying 300 passengers for ranges on the order of 7000 miles appears to be within the capability of advanced technology. Only a few of the several

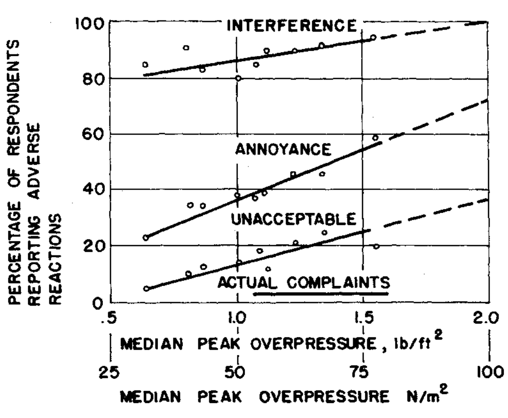

Fig. 19 Percentage reporting adverse reactions to sonic boom. (Community reactions to sonic booms in the Oklahoma City area.)

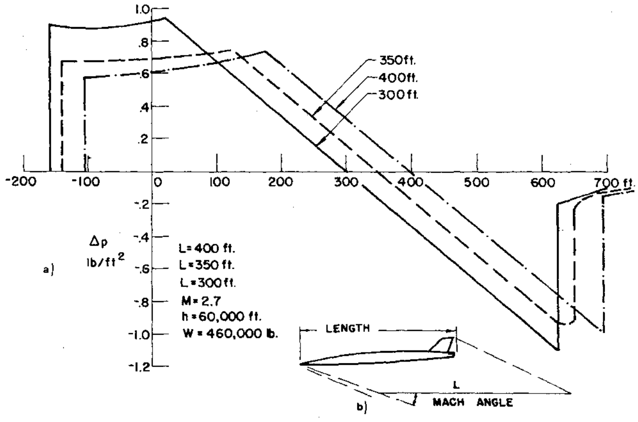

Fig. 20 a) Effect of length on sonic boom signature. b) Aerodynamic length of an airplane.

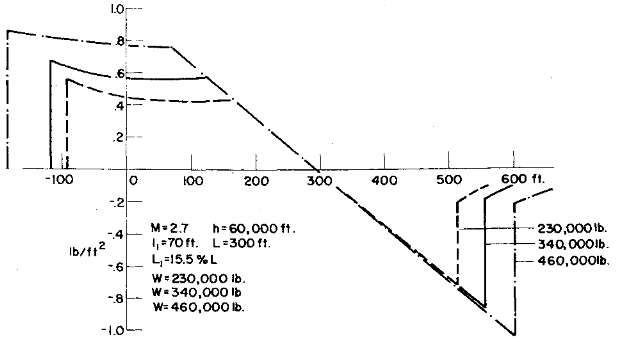

Fig. 21 Sonic boom signatures as a function of airplane weight.

predictable technological advancements are required to reach such a goal. Such advancements can be reached by means of a well-focused research and development program. The main fields to be investigated are:

a) Propulsion. Rapid development of variable cycle engines and variable bypass engines should be performed.

b) Structural and airplane design. The use of augumented control techniques must be investigated in flight, and the use of advanced materials for structural components and corresponding new structural designs should be investigated in flight.

c) New advanced aerodynamic configurations, boundary-layer controls, and low sonic boom airplanes. Field measurements on sonic boom response should be performed as soon as the Tupolev and Concorde initiate operation.

d) Advanced accessories and service equipment. The goal of the effort is to save cost and weight.

e) Operational changes. A program in operations should be directed at improving airplane performance. These should be defined and systems required by such changes developed.

This program can be expensive; therefore, we should ask if the research and development program can be afforded. I am not an economist; however, I have seen several studies of the SST performed by experts where economical analyses were presented. Such studies show that a substantially improved version of the SST, but still less advanced than the one suggested here, would be economically sound. In these studies, no government support for the development cost was assumed. Therefore, I am confident that a detailed economical analysis of the approach described will give a satisfactory answer. The comparison of fuel consumption per passenger mile, given between the advanced SST and the 747, and the comparison of structural weight are already indications of the economical aspects of the problem. Because of the long-range implications for our nation and the world, I believe that this program is more important than other aeronautical programs directed to retrofiting or to developing lower fuel consumption short-range airplanes. An advanced SST gives us new important possibilities that surely will be required in the near future. I hope that the Congress and the nation will proceed urgently with such a research and development program.

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