SPEED AND SAFETY IN CIVIL AVIATION

The Third Daniel and Florence Guggenheim Memorial Lecture

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ABSTRACT

The lecture is divided into three main parts dealing with speed, safety, and speed versus safety.

The need for increased flight *speed* in civil aviation is discussed. A region is defined for the "Maximum Worthwhile Cutoff Speed," increasing with range, above which further speed increases would be senseless. The desirability—or sensibleness—of approaching this speed region depends, *inter alia*, upon the distance between airport and city center. The ground-time losses in hours are therefore studied as a function of airport distance. The total economical losses increase much more rapidly than in direct proportion to airport distance. A method is suggested for determination of "Equal Preference Speed Limits for Various Airport Distances" in relation to competing means of surface transportation.

On ranges below 1,000 miles, tremendous markets will be opened up for civil aviation by combination of V/STOL developments with cruising speeds approaching the speed of sound or, for ranges below about 300 miles, the lower "Worthwhile Cutoff Speed."

For ranges above about 1,000 miles the crucial question of today is whether or not supersonic transports (SST's) should be introduced. The time gain by SST's over near-sonic jets is appreciable on ranges above 2,000 miles. As, however, contemplated supersonic speeds fall close to the "worthwhile cutoff speed," the time gain will be of less value to the passengers than the gain in time obtained by jetliners over piston aircraft. Furthermore, the time gain by SST's would—in contrast to the jet/piston case—be counteracted by reduced comfort. Thus the net gain in combined time-comfort is likely to be questionable on ranges below 2,000 miles and marginal to moderate on ranges from 2,000 to 5,000 miles.

Nevertheless, the majority of passengers might prefer the SST to subsonic aircraft above 2,000 miles range at equal fares, airport distance, and availability of conveniently scheduled daytime flights. This is, however, an insufficient basis for conclusions about *overall* passenger preference for SST's, mainly because (a) subsonic aircraft will be increasingly able to use airports closer to city centers than the airports required for SST's, (b) the SST's will have greater difficulties than subsonic aircraft to achieve high passenger load factors on the inconveniently scheduled flights required for economic utilization, as the time gain is hardly worth encroachment upon normal sleeping hours, and (c) the "range flexibility" of subsonic aircraft will continue to provide a vast "intermediate-stop" market which will be inaccessible for SST's.

For equal average fares the operating cost of the SST's must be about as low as that of competing subsonic aircraft. The analysis of the operating costs is split up into a fictitious "static case," assuming stagnated aeronautical development after the introduction of the first SST, and the real "dynamic case," where conceivable aeronautical progress is taken into account. For the "static case" it is concluded that the operating costs of the SST's will be appreciably higher than for subsonic aircraft, mainly because (a) the annual utilization of the SST's can, for scheduling and other reasons, hardly amount to more than two-thirds of that of long-range subsonic aircraft, and (b) the maintenance and overhaul costs for the SST's will be higher due to design complexity and aerodynamic heating. On the other hand, the utilization and load factors of subsonic aircraft will benefit from their great "range flexibility." They have also better possibilities of increasing the revenues by supplementary cargo.

In the real "dynamic case" new subsonic types of aircraft (applying design principles that might be used by long-range subsonic aircraft competing with SST's) will be developed at an about 15 times higher rate than the one at which new types of SST's can be put on the market. Aeronautical improvements yielding, *inter alia*, lower operating costs will therefore be realized more rapidly and with less risks of failure for subsonic than for supersonic aircraft. This implies that the difference in operating costs between SST's and competing subsonic aircraft will continue to grow over and above the initial difference in the "static case."

After the first "supersonic sensation years" and as new types of subsonic airliners are developed, which are successively improved both in comfort and in the ability to use airports closer to the city centers, the passenger preference is likely more and more to favor subsonic flying.

The successively increasing difference in operating cost and in passenger preference gives the economy of the SST enterprise an unstable character. The "system" is likely to fall out of balance—implying increasing losses— if not earlier, then at least when lower fares are applied for subsonic than for supersonic aviation as a consequence of pressure both from subsonic operators and the general public.

To attain a status of profitable economic "equilibrium," the SST's must therefore from the very outset have a considerably lower operating cost than contemporary subsonic long-range aircraft in order to compensate for the anticipated more rapid developments in subsonic technology. This seems far from possible even according to the most optimistic estimates made by anyone.

Nevertheless, should supersonic aviation be introduced, it will inevitably hamper the promising prospects now in sight for subsonic aviation to become a really cheap means of mass transportation on all ranges. One reason for this is that it is hard to believe that SST-manufacturing countries, which will spend billions of dollars on development and production of SST's, will also spend very considerable efforts and money to produce low-fare, near-sonic aircraft and/or aircraft capable of using centrally located airports—i.e., the most efficient way conceivable to counteract the success of the SST's.

It has, however, repeatedly been stated that there are reasons other than consideration for the passengers for launching supersonic aviation, namely prestige and general economical aspects, in particular, to keep the aircraft industry occupied. These motives do undoubtedly bear considerable weight, but a failure of the supersonic enterprise would counteract rather than promote them.

The level of flight *safety* in civil scheduled aviation is today so high that the risks should be of little concern to the individual passenger. The statistical risk level is, however, not the significant aspect of flight safety. What really matters is that the absolute number of air accidents per year has become so high that public confidence has been seriously affected, and, above all, that if the accident rate is not greatly reduced, the number of accidents will in the future grow with the expansion of civil aviation to such an extent that it will become disastrous for public confidence in aviation and thus for its prosperity.

It is, therefore, imperative (*a*) to agree internationally on safety goals, the attainment of which would insure full public confidence regardless of the growth of aviation, and (*b*) to find new ways, over and above the methods hitherto used, of radically improving the safety level in order to meet the goals.

A long-term policy of stepwise improved goals is suggested. For the first safety goal, e.q., fixed to about 1980, a risk level corresponding to one passenger fatality in 10^9 passenger miles is proposed, an improvement over the present risk level by a factor of 10.

The present methods of improving safety are mainly based upon "accumulated experience." The efforts currently made are indeed impressive, but is even if greatly intensified, it will not be possible to improve the safety level, by this method alone, even nearly in pace with the expansion of aviation.

As a supplement a new approach is proposed, the "Allotment of Probability Shares"—or APS—method. The fundamental feature of this statistical approach is to divide the maximum total risk corresponding to the flight safety goal into "Probability Shares" allotted to various groups of accident risks and further subdivided into sub-shares and sub-divisions, etc., for preconceivable, statistically independent accident risks. The main function of this method is to identify (or make) as many as possible of the preconceivable risks as "statistically controllable." This implies that the risks can be treated by statistical mathematics and be reduced, wholly or partly, *at will* to exceedingly small values.

In contrast to the present situation, where innumerable risks are added to each other, yielding an unknown, and largely uncontrollable, total risk level, the APS method thus aims at a limitation of the total accident rate to a maximum value by means of statistical considerations and treatments.

The difficulties and costs involved in implementing intensified efforts according to the present is methods together with the APS method will be very great indeed. However, in the long run no other investment will bring greater dividends for a prosperous future of civil aviation than devoting a very substantial portion of available resources to improvement of flight safety. As any actions to improve safety have slow effects, radical international measures to increase safety are a matter of utmost urgency. It is beyond comparison the greatest challenge to the aeronautical sciences right now as well as in the future.

Safety in aviation should also comprise the avoidance of other detrimental effects of aviation upon the occupants of the aircraft and people on the ground, in particular airport noise. This constitutes one of the most serious hindrances to the healthy growth of civil aviation, in particular with regard to reducing ground-time losses by construction of airports closer to the city centers.

A proposal recently made about "International Long-term Planning Aiming to Limit Airport Noise" is reviewed. Its main advantages would be (a) that the manufacturers and operators would have a direct interest in developing quieter aircraft, and (b) that, in the planning of new airports, noise could be taken into account on a quantitative basis to enable the community to weigh the great advantage of a nearby airport against the predictable maximum noise disturbance around the airport.

With regard to *speed versus safety*, there seems to be little direct causal connection between these two facets of aviation; in principle, substantial speed increases can be made without endangering safety, provided that the higher speeds are accompanied by adequate requirements and progress in the branches of technology relevant to safety. This seems possible to achieve in subsonic aviation.

In contrast, it does not seem possible to introduce supersonic aviation without adversely affecting safety in civil aviation. In the first place, to achieve the same airworthiness of the SST itself as that of subsonic aircraft seems hardly possible, for the main reasons (a) that the SST incorporates a great number of simultaneously introduced radically new features, implying many unforeseeable risks, and (b) that the aerodynamic heating is likely to cause unpredictable troubles that might endanger safety. Secondly, the almost "ballistic" operation of the SST's poses extremely difficult safety problems both for the SST's and for subsonic aircraft operating in the vicinity of destination airports of the SST's. Thirdly, the great efforts and money that would be required for the SST enterprise will detract from the efforts that could otherwise be concentrated on the urgent task of improving safety in subsonic aviation.

Over and above this, supersonic aviation will affect safety in the wider sense by the sonic boom and by cosmic radiation. Considering, in particular, the great deviations from the mean values of boom overpressure, including "super-bangs" due to focusing effects, it is most unlikely that the general public will accept supersonic aviation. The physiological and genetic hazards due to cosmic radiation are at present largely unknown. A necessary condition for successful supersonic aviation is that it should be proved in advance that the adverse effects of cosmic radiation are negligible.

For the reasons indicated supersonic aviation, as it is at present conceived,

seems incompatible not only with an economically prosperous development of civil aviation but also with flight and public safety. It is then important to observe that the *need* for supersonic speed is rather limited; the adverse effects seem to be out of all proportion to the moderate net gain in time-comfort that the SST's might at best offer a small portion of the air passengers.

Aviation has come to a crossroads in its development: One direction is concentration of efforts towards improving safety, reduction in fares and noise, development of V/STOL aircraft, and improvement in reliability, comfort, and availability.

The other way is detraction from such efforts by launching supersonic aviation before its basic problems of economy, sonic boom, cosmic radiation, and safety, are solved.

Aviation should take the lead in proving that spectacular technological advances could and should be balanced against the harms and hazards they might inflict. The balance should be guided by ethical rules and standards.

FOREWORD

To be asked to present the Daniel and Florence Guggenheim Memorial Lecture is indeed a great honor both for the Aeronautical Research Institute of Sweden and for me personally. It is, however, also quite a demanding task to undertake, as such a very high level has been set for these opening lectures of the ICAS congresses by the first and second Memorial Lectures presented by Theodore von Kármán in Madrid 1958 and by Jakob Ackeret in Zurich in 1960.

The science of aeronautics is very fortunate to have enjoyed the patronage of the Guggenheim family from as early as 1925. Several institutes and laboratories owe their existence to the Daniel and Florence Guggenheim Fund. In particular, the name of Guggenheim is connected with safety in aviation. Thus the Daniel and Florence Guggenheim Aviation Safety Center at Cornell University was founded in 1950 with the objectives:

> to achieve safety in aviation as effectively as we have achieved speed and efficiency. Speed is now assured beyond the most enthusiastic expectations. Safety has likewise made great progress, but fresh emphasis is due.

For this reason it seemed particularly appropriate when the subject "Speed and Safety in Civil Aviation" was suggested to me by Mr. E. T. Jones, one of the founder members of the International Council of the Aeronautical Sciences.

INTRODUCTION

Speed and safety are, perhaps, the two most significant concepts characterizing civil aviation (Fig. 1).

High *speed* is the spectacular signature of aviation that makes it superior to other means of transportation; it has often been stated that the Number One commodity that aviation "sells" is speed.

Safety is also spectacular although in a negative way, inasmuch as lack of safety—that is, accidents—is sensational and causes uneasiness among those who fly and increases the possible fear of flying among those who have not yet flown.

The title of my paper gives me freedom to deal with speed, as such, and with safety, as such, and also to try to explore the relationships between speed and safety. This leads to the division of the paper into three main parts, *speed*, *safety*, and *speed versus safety*.

Obviously the subject of each of these parts has tremendous scope. This study will, therefore, by necessity be incomplete. In particular, I have confined myself to dealing with the subject of safety in a broad way and mainly in a long-term perspective, in order, among other things, to try to formulate the *goals* that should be set not only for flight safety as referring to the aircraft and its occupants but also for safety in aviation in the wider meaning of including "public safety"—i.e., the security and well-being of people on the ground.

Such a broad treatment of the safety problem is vital because civil aviation, which is still in its infancy, will undoubtedly develop into the most important means of all for commercial transportation of people and into a very commonly used means of private travel, eventually comparative in volume to traveling by private automobiles. We have thus to anticipate an endless future development, implying that an increasing number of people will spend more and more time in the air. In view of this, I think it is high time that safety in aviation should be considered in intimate relation to the goals visualized for the future security and welfare of mankind.

Fig. 1.

The paper deals primarily with commercial passenger aviation, in particular scheduled aviation. However, I believe that most of the views and conclusions are applicable also for all other types of aviation, such as executive and private flying and freight aviation.

I have also limited the study to aviation within the atmosphere of the earth. I will thus not deal with interplanetary aviation, for the main reason that I do not think that commercial aviation, in the sense of transportation of ticket-paying passengers in outer space, for any meaningful purpose, will come about on a significant scale within the next hundred years.

PURPOSE OF AVIATION

Neither speed nor safety is an end in itself. They can only be compared and weighed against each other in the perspective of a sensible purpose for aviation.

This, I think, should be to provide Air Transport Systems for complete door-to-door journeys for as many people as possible, which offer short *total* traveling time, safety, cheap fares, comfort, reliability, and extensive availability; and all this should be done with a minimum of harm to people on the ground —i.e., with a high degree of "public safety" (Table 1).

By this definition the two concepts dealt with in this study—flight speed and safety—are put in their proper relation to all the other elements of the purpose of aviation. It might be observed, however, that flight speed is only one of the two main factors governing short traveling times, the other being short ground times to and from the airports.

I think everyone would agree that high flight speed, although it is the spectacular signature of aviation, is not a significant measure of progress. If any one of the eight purpose factors is to be regarded as the specific goal of aviation or

Table 1. PURPOSE OF AVIATION

to provide air transport systems
for complete *door-to-door* journeys for

1. as many people as possible—i.e., big "*volume*"—with

2. short total *traveling times*, to be obtained by high *flight speed* and short ground times,		Subjected to optimum balancing to insure *economy* and create maximum "volume"
3. high *flight safety*	Passenger Appeal Factors	
4. cheap *fares*,		
5. good *comfort*,		
6. high *reliability*,		
7. extensive *availability*,		

with a minimum of harm to people on the ground, i.e., with
8. high *public safety*

the dominant yardstick of its progress, I think that it is to transport as many people as possible—i.e., to create a big *volume* of aviation, in passenger-miles.

Elements 2–7 could be called the "Passenger Appeal Factors." They are subjected to an internal balancing process within the aviation community, in particular the operators, with the object of insuring *economy*—earning a profit. The progress of aviation is greatly dependent upon how this balancing process is carried out. The mechanism of the process is very complicated with a great number of "feedback" factors. Increased volume, for instance, leads to bigger series of and thus cheaper aircraft and reduces the overhead costs for the operator, who then might be able to afford improvement of one or more of the Passenger Appeal Factors. Another example is that an increased volume usually results in an increased availability of air services by a greater choice of connections—that is, by a greater number of direct flights between city pairs and by establishment of new routes.

In this intricate interplay between all the first seven purpose factors and economy, flight speed and flight safety play very important roles, but these cannot fruitfully be evaluated without considering all the other factors, which govern the mechanism of progress in aviation.

Finally, the last factor, public safety, important as it is, falls outside the balancing process, because it will have little or no effect on the extent to which people fly, and it might largely be contradictory to the immediate interest of the operators.

PART I: SPEED

PAST DEVELOPMENT OF SPEED AND FUTURE POSSIBILITIES

In a way, the fascinating history of aviation is the history of dramatically increasing flight speed (Fig. 2). It is noteworthy that the civil development has shown an appreciable time lag in relation to the military speeds, as the civil aircraft have largely been developed from military ones.

The relative rate of speed increase for civil transports decreased from more than 5 percent per year around 1925 to about 4 percent around 1950, but this leveling off was drastically broken by the advent of jet propulsion. This was pioneered during World War II for interceptors and other military short-duration purposes, but it was immediately possible to envisage the superiority of the jet engine also for long-range transports and thus for civil airliners.[1,2]

With the first civil jet transport, Comet I, which went into service in 1952, an increase in speed of no less than 60 percent was taken in a single jump over propeller aircraft in service at that time. This development was, however, interrupted by the disastrous lack of structural fatigue safety resulting in the tragic accidents in 1954. Although this particular experience certainly cannot support any general conclusions, it must be recalled in any study of speed and safety.
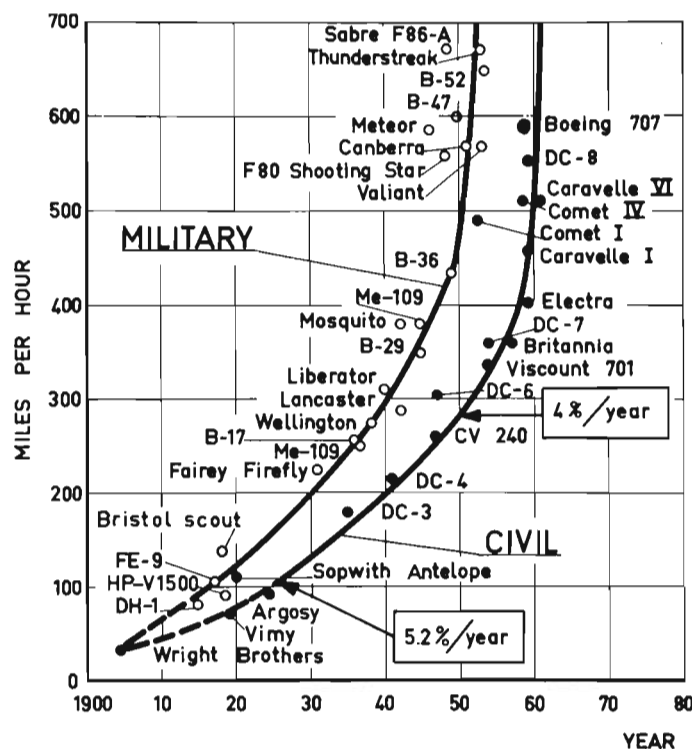

Fig. 2. The increase in aircraft speed.

The next and definite speed jump was taken in 1958, when the Comet IV and then the Boeing 707 went into service, the latter achieving a speed increase of 230 mph, or 65 percent compared with long-range propeller airliners such as the DC-7.

Looking into the future, the important question is whether or not civil aviation will go to still higher maximum cruising speeds, and, in particular, if and how soon a second big speed jump will be taken by introducing supersonic transports (SST's).

Reference 3 contains a prediction of flight speeds by Eugen Sänger, which is probably the boldest and most far-reaching ever made (Fig. 3). For manned high-speed vehicles, he foresaw orbital speed about 1971, a prediction that was beaten by a decade by the first manned satellite in 1961. This makes the prediction look rather conservative and might even, among space enthusiasts, support a belief in this forecast that man will fly as fast as the speed of light— or even somewhat faster, as he has actually extended the curve above this point —before the turn of the century.

For long-range transport aircraft, Sänger's curve passes through Mach 2 about 1969, through Mach 3 around 1972 and runs into and through the hypersonic regime—Mach numbers above 5—by the end of the seventies. The two first predictions agree fairly well with current plans for the development of supersonic transports, whereas most forecasts regarding transportation of passengers in hypersonic vehicles do not foresee this development until during
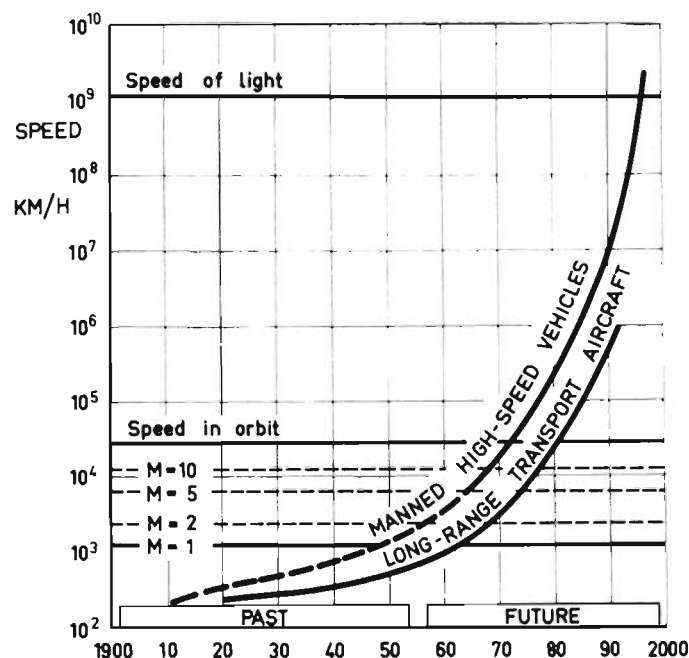

Fig. 3. Eugen Sänger's forecast (1955) of the speeds of long-range transport aircraft and manned high-speed vehicles (Ref. 3).

the eighties. Sänger furthermore predicts orbital speeds for civil transports around 1980 and about 30 times higher speeds 10 years later, a development which must assume interplanetary transportation of passengers.

Considering here only suborbital speeds, in view of the present rapid advances in science and technology, there can be little doubt about the *possibility* of building supersonic and even hypersonic vehicles with a big enough useful load capacity to carry an appreciable number of passengers over long distances.

To make a prediction of the future speed development in civil aviation, we have, however, to consider not only what is possible to achieve, but also what is *desirable* to attain in terms of further speed increase. Obviously, this makes a prediction exceedingly difficult, as it would require a foreknowledge of the extent to which civil aeronautical developments will be governed primarily by sound commercial considerations or by prestige and other intangibles.
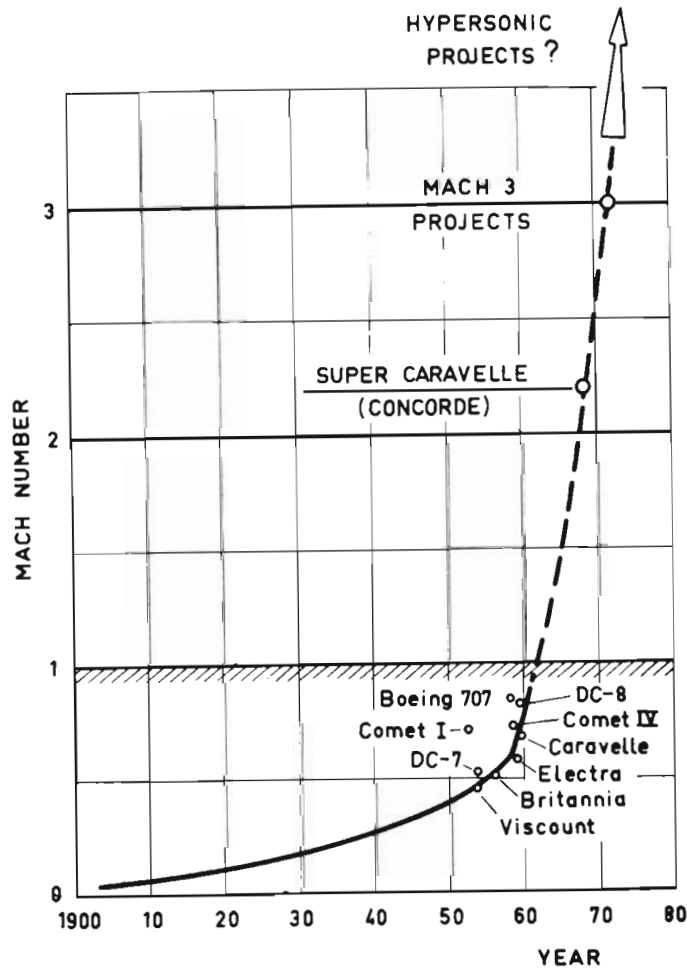
Fig. 4.   Mach number development of transport aircraft.

As I do not have that foreknowledge, I will refrain from making any predictions. Instead I will try to analyze in some detail the *need* of the passengers for further increase of speed, as well as the commercial soundness of supersonic and hypersonic speeds in *civil* aviation.

Figure 4 illustrates what supersonic speeds would mean in terms of a second big speed jump. This would be approximately 860 mph for a Mach 2.2 SST and some 1,400 mph for a Mach 3 SST—i.e., about 3.5 and 6 times greater jumps in miles per hour than the "propeller-to-jet" speed leap.

Startling and, indeed, impressive as these leaps in speed would be, they do not by any means give an adequate picture of the technical difficulties involved, mainly because the jump into supersonic speeds means penetration of the sonic barrier and then sustained flight in a new aerodynamic and atmospheric environment, and also because there is, for the first time, practically no relevant military background experience as a basis for the design of civil SST's.

THE NEED FOR FURTHER INCREASE OF
SPEED AND ITS ECONOMICAL IMPLICATIONS

In considering the desirability of further increases in flight speed, one must obviously distinguish between two questions: one is the need for higher speed than the near sonic speeds that have been obtained by modern jetliners, and the other is the need for higher speeds of such types of aircraft—from helicopters to turboprop aircraft—mainly for short-haul ranges, which today have much lower cruising speeds. For both these questions, the need for speed increase in the various range brackets depends on three main factors:

● the relative size of the potential markets,
● the value to the passenger of gains in traveling time as a function of range, and,
● the absolute and relative gain in traveling time that can be obtained on different ranges by increased flight speed.

Furthermore, the desirability of speed increase is, of course, also dependent on the cost at which it can be attained.

THE RELATIVE SIZE OF POTENTIAL "RANGE MARKETS"

There appears to be a "Distribution Law of Transportation," implying that the total volume in passenger-miles or ton-miles rapidly falls off as the range increases.[4] This is an important law to observe for judging the potentialities of various "aviation range brackets."

It is then interesting to note that the encroachment by aviation upon surface transportation is greatest for the long-range market—in the United States it is almost 100 percent—and smallest for the short-range market. This means that aviation can expand, by encroachment, much more on the vast short and medium range markets than on long ranges. The potential air markets for different ranges will, however, never be directly proportional to the total trans-

port markets, because the encroachment by aviation will always be greatest for long ranges and smallest for the shortest ranges.

However, aviation does not grow only by encroachment upon surface transportation; it has continuously created new traffic and will continue to do so in the future. At first sight it appears that this increase will be greatest, relatively, for the long-range market, but there are many factors that speak for the opposite development.[4]

The relative size of the potential markets in the distant future is obviously dependent upon how optimistic one is regarding the possibilities of developing vertical and short-takeoff-and-landing aircraft, so-called V/STOL aircraft, and utilizing them profitably on short distances.

For this study it is suitable to deal separately with the air markets below and above 1,000 miles, for the main reason that this appears to be the dividing line above which supersonic aviation has been contemplated, whereas no one seems to have seriously proposed such aviation below this distance. Ranges below 1,000 miles thus comprise short-haul plus the lower half of the medium range, according to commonly used definitions, and ranges above 1,000 miles comprise the upper half of the medium range plus long ranges.

On the basis of available statistics[5-7] and with a reasonably optimistic belief in the V/STOL development, I have estimated the potential air markets to be approximately as shown in Table 2, which also indicates subdivisions for the two main range brackets considered.

Table 2. **RELATIVE AVIATION RANGE MARKETS**

Range bracket, miles	Distribution, about 1959, percent		Estimate for about 1980			
			Alt. *A*, percent		Alt. *B*, percent	
Below 1,000		42.5		47		50
0– 250	7.5		10		12	
250–1,000	35		37		38	
Above 1,000		57.5		53		50
1,000–2,000	24		22		21	
2,000–5,000	30		27		25	
Above 5,000	3.5		4		4	

TOTAL GROUND-TRAVEL TIMES AS A FUNCTION OF AIRPORT DISTANCE

Whereas railways, bus lines, and even steamers usually have their end stations or harbors close to the center of the cities, the flight portion of an air journey practically always terminates at an airport located at a considerable distance from the city center. This is the one serious fundamental disadvantage

of aviation, because the "ground-time loss" usually consumes a great portion of the gain in time obtained on the flight portion of a complete air journey, compared with traveling on the surface.

The extent to which this disadvantage can be reduced is one of the most important factors governing the public appeal of aviation and thus the extent to which its immense potential will be realized. The ground-time losses are also of great importance for the worthwhile increases in flight speed in the passengers' view, and must therefore be considered in this study.

The ground-time losses consist of travel and waiting times. The travel times depend in the first place upon the distance between the airport and the city center and also upon a great many other factors such as the size of the city, traffic congestion, and whether the passenger takes a taxi or car direct to the airport or whether he prefers to go to the bus terminal and then uses the airline bus for getting to the airport. The waiting times at the bus terminal and the airport also vary considerably due to many factors, as is well known.

It is thus very difficult to obtain a typical picture of the ground-time losses because of the widely different local conditions all over the world. Figures 5 and 6 illustrate, however, what is believed to represent average conditions for the cases when the passenger travels direct to the airport by taxi or private car, and via the bus terminals, respectively. The assumed waiting times and speeds of ground vehicles are specified in the figures.

For the case when the passenger travels direct to the airport, the total ground time varies from slightly more than an hour up to about $2\frac{1}{2}$ hours for distant
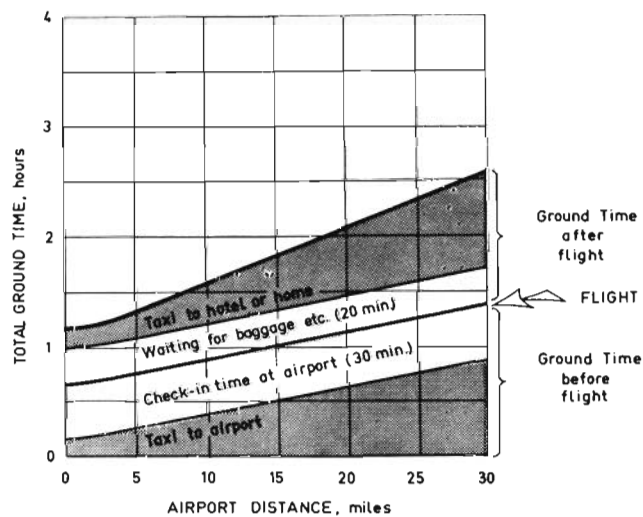

Fig. 5.   Ground time for passengers traveling direct to and from the airport by taxi or private car. The taxi times have been computed assuming that the distance from hotel or home to airport is, on the average, 1.5 miles further than the distance from the city center to the airport, and that the average speed of the taxi (or private car) is 25 mph for 5 miles within the city area and then 40 mph. The minimum time, when the airport is located in the city center, is taken to be 10 minutes.
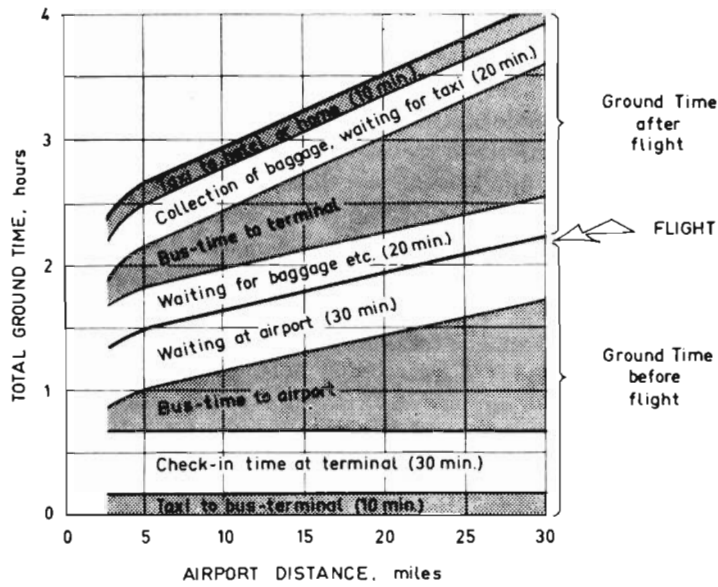
Fig. 6. Ground time for passengers traveling via bus terminal. The bus times have been computed assuming an average bus speed of 15 mph for 5 miles within the city area and then 35 mph.
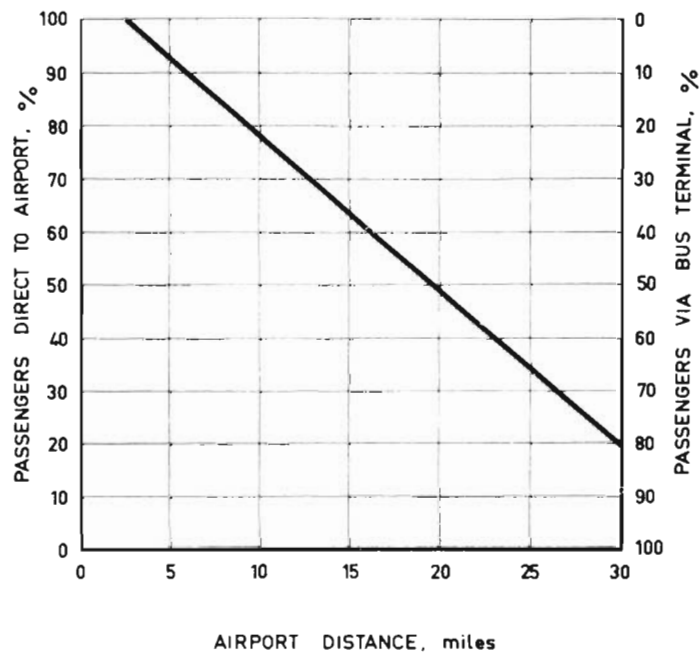

Fig. 7. Assumed proportion of passengers traveling direct to the airport as a function of airport distance.

airports. For traveling via the bus terminals, the ground time can approach some four hours.

In order to assess the ground-time loss as a simple function of airport distance, an assumption has to be made on the percentage of passengers who prefer direct travel to and from the airport, to travel via the bus terminal. This percentage depends, in the first place, upon the airport distance but also upon other factors.

For the following analyses, a straight-line relationship has been assumed from 100 percent "direct travelers" at an airport distance of 2.5 miles to 20 percent at an airport distance of 30 miles (Fig. 7). Using this assumption, a weighted average of the ground-time loss has been calculated as a function of airport distance (Fig. 8). As is shown, the total ground time appears to increase roughly in direct proportion to airport distance.

THE "POWER LAW FOR AIRPORT DISTANCE"

However, this relationship does not reflect correctly the value of short airport distance, for the main reasons that the value to the passenger of savings in
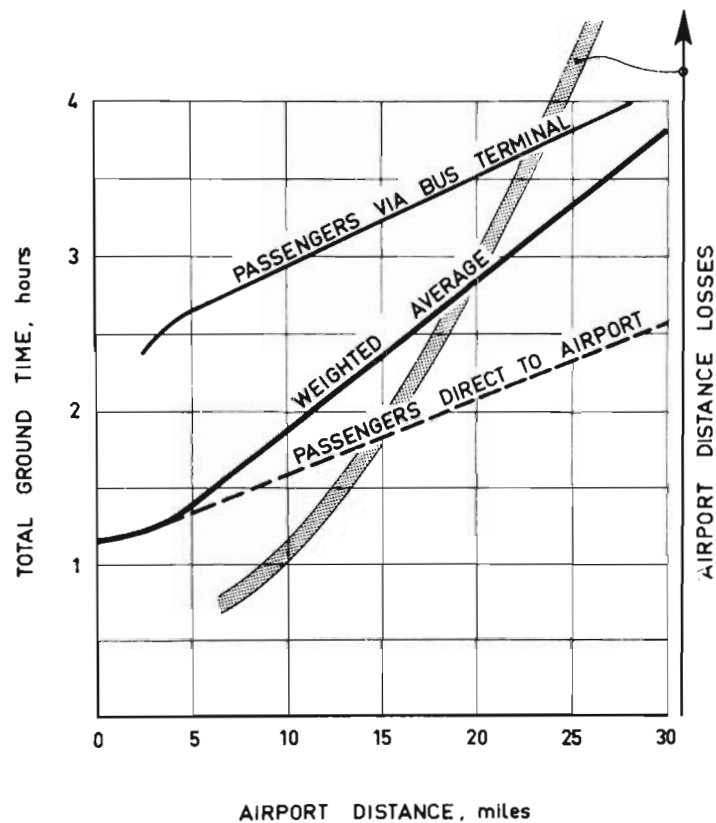

AIRPORT DISTANCE, miles

Fig. 8. Weighted average ground-time loss based upon Figs. 5–7. Shaded curve illustrates that the losses due to airport distance from city center increases much more rapidly than in direct proportion—the "Power Law of Airport Distance."

ground time varies greatly during the 24 hours of the day: As is well known, a great proportion of air passengers prefer morning flights, or must use such flights, but most of them find it rather unappealing to arise much earlier in the morning than usual. A flight departure at 8.30 a.m. might, for instance, be ideally suitable for the passenger in order to utilize the day as efficiently as possible, e.g., for a long journey or, in cases of shorter flights, for reaching his destination in time for a meeting. If, now, the airport distance is merely some five to eight miles, yielding a ground time of about 45 minutes (using taxi, Fig. 5) and the passenger allows himself an hour and a quarter for dressing, breakfast, and last-minute packing, he would have to arise around 6.30 a.m., which might be acceptable. If, on the other hand, the airport is located some 20 to 25 miles from the city center, then the ground time would amount to about two hours, assuming that the passenger for cost reasons travels via the bus terminal. To catch the 8.30 a.m. flight, the passenger would have to arise at 5.15 a.m.—i.e., an hour and a quarter earlier than in the previous case. This addition in ground time is highly important, regardless of whether it merely annoys the passenger or whether it induces him to use surface transportation or take a later flight (if available). The time loss he would suffer in the latter alternative might be much greater than the difference in ground time because he might have to fly the previous day in order to arrive in time for a meeting.

This example might suffice to indicate that the morning hours are of immense importance for a great percentage of air travelers; as little as possible of this precious time should be spent on ground traveling and waiting in terminals, etc.

The conditions are similar, but not quite as pronounced, at the end of the day, it being important for the passengers to avoid arriving too late at home or at the hotel.

The losses to the airline operators due to a long airport distance are probably even greater. In the first place they will lose many passengers. Secondly, for given average passenger demands with regard to avoiding too early rising in the morning or too late retiring in the night, the ground time encroaches, in both ends, upon the daytime part of the 24-hour day, which is the most used period for takeoffs and landings. One effect of this is that the usual concentration of flight departures in the morning will be still more pronounced with the result that, when the number of aircraft movements per hour has reached the maximum capacity for the airport and traffic continues to expand, an increasing number of flight departures must be distributed over later hours, implying undesirably late departure times for many passengers.

Another implication of long ground times is that the reduction of the efficient daytime period either reduces the maximum feasible daily utilization of the aircraft or affects adversely the passenger load factors on early morning and late evening flights. This is particularly serious for aircraft with short flight times per flight, thus for short-haul subsonic and for supersonic aircraft, as they for productivity have to make as many flights as possible between two subsequent nights.

It should follow from the above brief observations (a) that the total losses, to the operators and to the passengers, of long airport distance are very great

indeed, and (b) that the losses increase much more rapidly than in direct proportion to the ground time. This does not seem to have been fully appreciated by all planners of airport locations. It is, therefore, a research topic of great urgency to try to determine quantitatively all the costs and indirect losses of far-off airports as a function of distance to the city center and other significant parameters, such as the size of the city, its growth potentials, etc. It would then be possible to balance these costs against the real estate costs of airport sites, which normally increase as the distance to the city center decreases.

Pending thorough research in this field, I do think it is safe to state that the losses due to far-off airports are roughly proportional to a rather high power of the airport distance. This observation might be called the "Power Law of Airport Distance" is illustrated by the shaded curve in Fig. 8, for which a power of 2 has been applied.

THE VALUE OF REDUCTIONS IN TRAVEL TIME FOR DIFFERENT RANGES

The introduction of faster and longer-range transport aircraft has brought about most spectacular reductions in traveling time on long and medium distances in comparison with surface transportation. Instead of spending many days and nights on, for instance, transcontinental railways, the passenger can fly in a matter of hours.

These radical improvements over surface transportation made it justifiable to consider the advent of air transportation as a means, to quote Dr. T. P. Wright, not only "to decrease the effective size of the world" but also "to increase the effective span of life" of the passenger.[8] Thus the time spent on the surface vehicle was thought of as a *loss* from which the passenger was "saved" by flying.

This basic outlook was no doubt essentially correct when considering the enormous gain in time obtained by aircraft over trains and ships, but I do not think it is applicable when estimating the value of further increases in flight speed. I really question the basic outlook of considering the *whole* time spent on board a transport aircraft as being a complete loss which shortens the life of the passenger.

Considering in particular the possible introduction of supersonic aviation it would be most regrettable, to put it mildly, if billions of dollars were to be spent on this development due to a false picture of the real needs of the passengers.

To avoid this, we have to get to the core of the problem: What is essential for the traveler and what is not?

In the first place, I believe it to be most important for the traveler, both the business man and the holiday maker, to have his daily sleeping and eating rhythm as little disturbed as possible, so as to arrive at his destination fit to work or fit to enjoy his vacation fully from the very beginning. This condition will in the future be more and more important as travelers become more particular.

The by now classical story of the gentleman who upon landing after a jet flight across Europe refused to leave the aircraft until he had had time to finish

his dinner, is not only true; it is, perhaps, a most important lesson for all planners of aviation.

I do not wish to imply that short journey time is not often important, but I maintain that there is, usually, *a certain part of the travel time* that is both comfortable and even to some extent valuable and thus *cannot be regarded as a loss to the passenger*. It can be really enjoyable and relaxing, particularly for holiday makers, but it might even give the business man and the executive an opportunity to rest or to do some work.

This portion of the travel time, which could be called *the "enjoyable time," can, in principle, equally well be spent in the air as on the ground*. It might vary from zero to the whole flight time depending primarily on:

- the frequency, i.e., how often the passenger repeats the same flight,
- the range,
- the comfort level, including the passenger's confidence in safety, and,
- the purpose of the journey.

If a journey is made very often, for instance daily commuting to and from work, I think it is right to say that the whole travel time, be it on the surface or in the air, is a loss and that every minute that can be saved is a gain. Considering less frequent journeys over longer distances than commuting, the "enjoyable time" usually tends to become longer as the distance increases and is, of course, also longer, the higher the comfort level.

Finally, the "enjoyable time" is in most cases shorter for the business man than for the tourist. Within these categories, the length of the "enjoyable time" varies, of course, also with the individual, and there is obviously no sharp limit between this time and the "wasted," or uncomfortable, portion of the flight.

It should follow from these observations that, although reduction in flight time to the extent that the average "enjoyable time" is encroached upon might not be valueless, such reductions are of only marginal value.

THE MAXIMUM WORTHWHILE SPEED ON DIFFERENT RANGES

We are now in a position to discuss more closely the need for speed increases as a function of range. Figure 9 shows how the reductions in block flight time obtainable on various ranges become smaller and smaller as the speed increases. Considering in particular the fact that the "enjoyable" portion of the flight cannot be regarded as a loss, there must, obviously, be some upper speed limit for each range above which it just does not make sense to strive for still further time reductions, as that would call for a speed increase out of all proportion in relation to the possible gain in time. It is suggested that the "worthwhile cutoff speed" is determined as the upper limit of the relative speed increase R that yielded the "last" worthwhile time reduction in minutes, the increment ΔT.

A basic or reference combination of these two parameters can be obtained from the current discussion of the relative merits of Mach 2.2 or Mach 3 SST, as it has been questioned whether or not the time reduction of about half an hour on a range of 3,000 miles is worth the speed increase of some 35 percent.

Then it seems reasonable to say, in view of the observations made above, that a time saving of five minutes on a range of 100 miles is at least as valuable as a time saving of half an hour on 3,000 miles. A straight line in double-log plot seems to yield a sensible relationship between ΔT and range for other ranges as well (Fig. 10). It seems suitable to define two values of R in order to indicate a band rather than a definite limit for the cutoff speed, and the values of 25 and 50 percent are suggested.

With these assumptions, the range for the worthwhile cutoff speed is obtained in Figs. 11 and 12. As indicated above, many air passengers, when considering savings in travel time on a given distance by increases in flight speed, do not merely look at the absolute time gain in minutes; the time gain is valued also in relation to the ground time: the longer and more annoying the ground time is the less sensible it seems to gain the "last" few minutes (ΔT) in the flight portion of the journey by a further increase in speed. (See Figs. 13, 16, and 17.) Thus, the upper speed limit ($R = 50$ percent) may be thought of as representing approximately the maximum worthwhile speeds for very short airport distances, say below five miles, and the lower limit as corresponding to the maximum worthwhile speeds for very long airport distances, say above 20 miles.
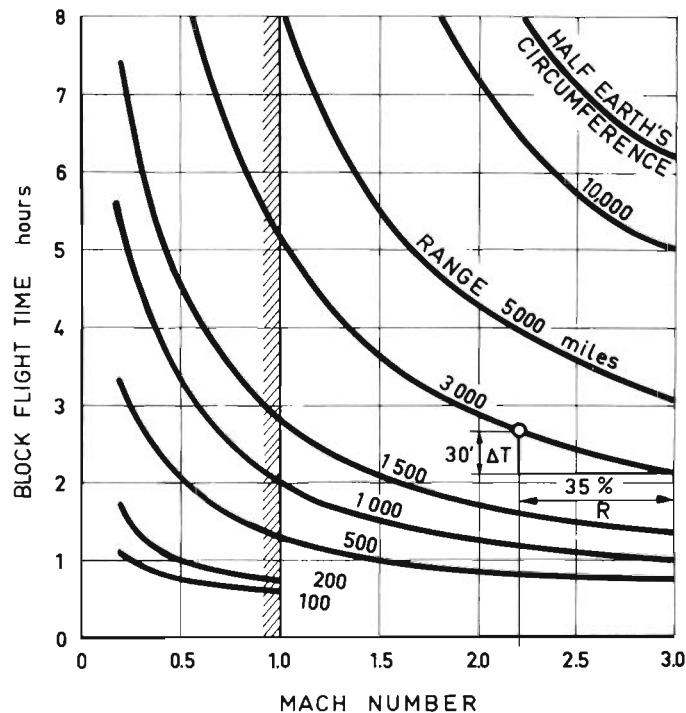

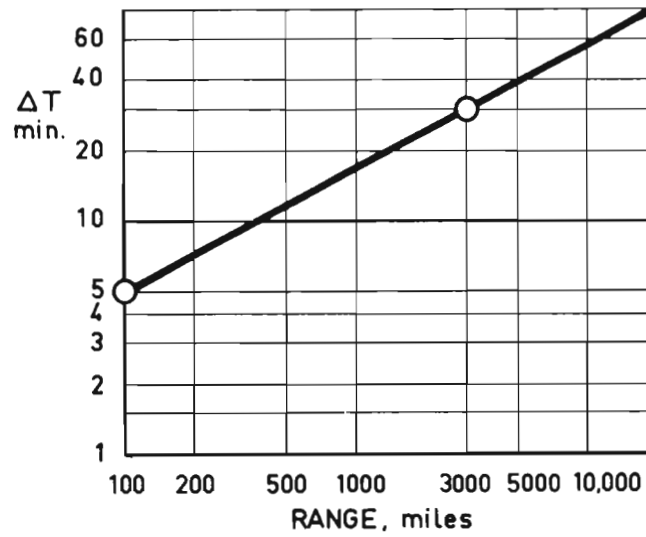Fig. 9.   Block flight time as a function of Mach number and range.

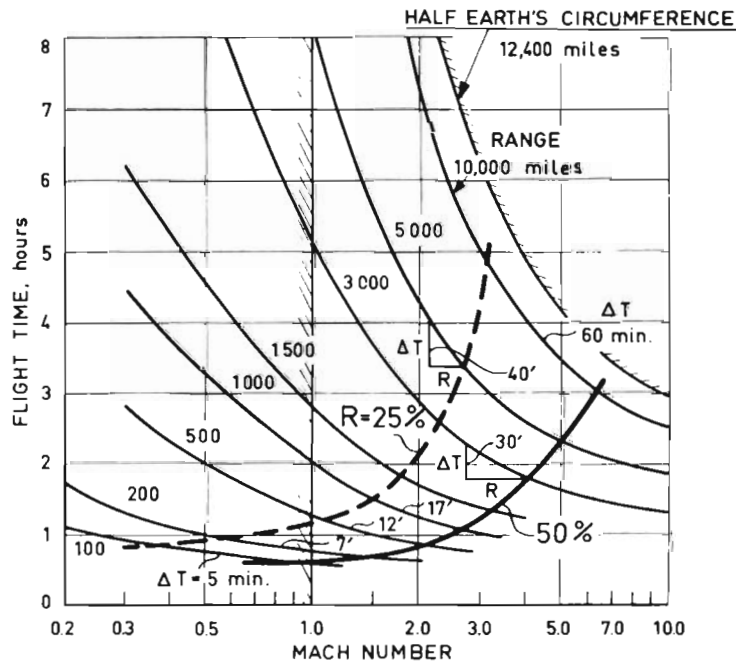Fig. 10. Assumed values for the "last" worthwhile time reduction as a function of range.

Fig. 11. "Worthwhile cutoff speed" for 25 and 50 percent speed increase, R, to attain the "last" worthwhile time reduction, ΔT.

If we consider about the middle of the speed band, Figs. 11 and 12 indicate roughly that it might just be worthwhile to fly with a speed of

● Mach 1, or just above Mach 1, above some 300 to 400 miles range
● Mach 2 above about 1,200 miles
● Mach 3 above about 3,000 miles, and
● Mach 4 to 5 on ranges of about 10,000 miles

I wish to emphasize that these cutoff speeds should be regarded as the extreme maxima that might be worth attaining on the basis mainly of time reduction and the general assumption that the technical difficulties in obtaining a relative or percentage speed increase were approximately the same regardless of the absolute value of the speed. In practice, other considerations—in particular the special difficulties and the costs connected with supersonic speeds—might impose limitations to appreciably lower worthwhile maximum speeds than this rough background estimate would indicate.
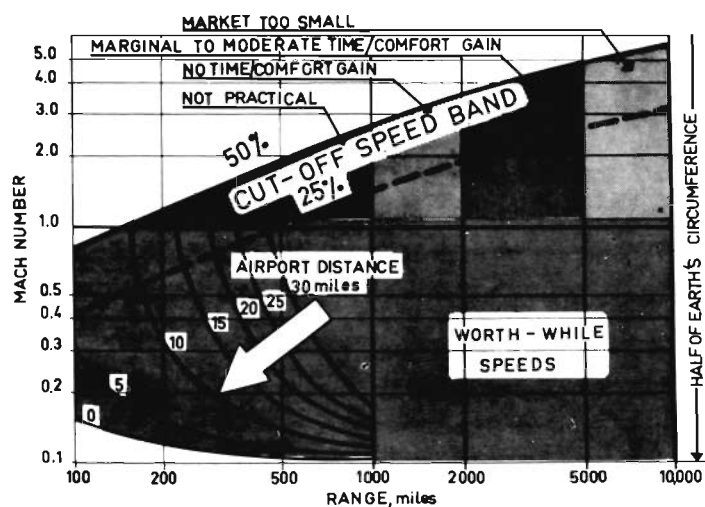
Fig. 12. Mach number/range areas significant with regard to improvements in speed. The "cutoff speed band" indicates the region in which little is to be gained by further speed increases. In the area bounded by Mach 1.0 and range 1,000 miles, increase in subsonic speed up to the cutoff speed band or $M = 1.0$ is important, but reductions in airport distances, and thus V/STOL developments and noise suppression, are even more efficient. The curves in this section, which are explained in Fig. 15 ($P = 100\%$) indicate roughly the gain, in terms of speed, that can be won by shortening the airport distance. The area beyond 1,000 miles range is subdivided into three range-brackets for which the feasibility of supersonic speeds is indicated.

THE NEED FOR INCREASE IN FLIGHT SPEEDS AND V/STOL DE-VELOPMENTS ON RANGES BELOW 1,000 MILES

Considering next in more detail the need for high subsonic flight speeds below 1,000 miles, it should be observed that on this range bracket, passenger aviation has to compete with surface transportation and this competition is, of course, increasingly severe as the range decreases.

Figure 13, showing total journey time versus Mach number for a range of 200 miles, indicates rather strikingly how *the ground-time loss dominates over flight time, in particular as the speed increases.* The great importance of short airport distance is exemplified by the arrows which indicate that a decrease of the airport distance from 15 to 7.5 miles is equivalent to an increase of the cruising speed from about 150 to 350 mph.

To study the ability of aviation to compete with surface transportation, such as trains, comparison is made with mean train speeds of 75 and 100 mph, assuming a total "extra" time loss, for taxi and waiting times at both ends, of an hour and ten minutes, the same as was assumed for a very centrally located airport. Equal journey times by air and train are marked in the figure.
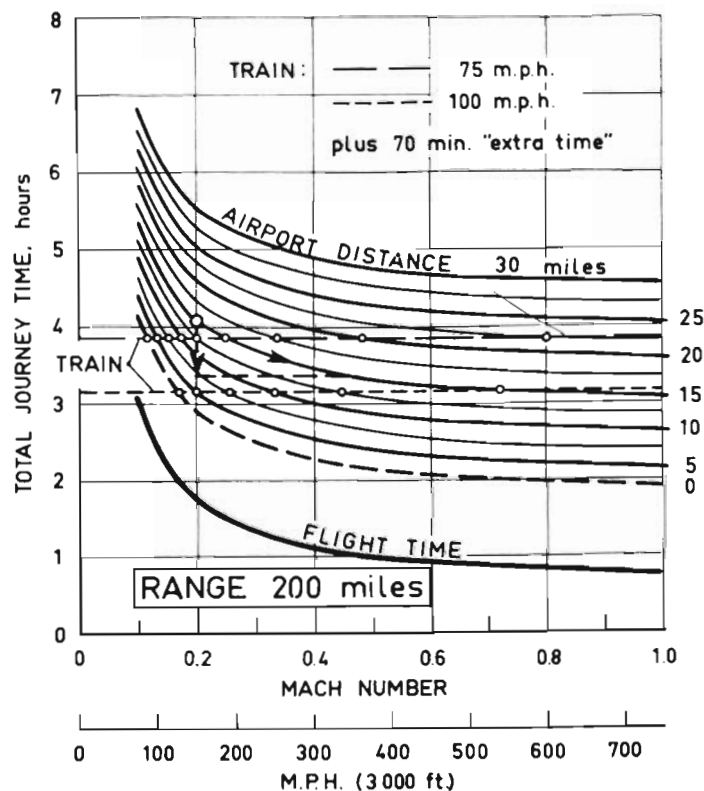

Fig. 13. Total journey time as a function of speed and airport distance for a range of 200 miles. The times for a fast train journey are shown for comparison.

The total journey time is, however, not the only thing that matters. In order to rationalize the comparison between air and surface travel, it is assumed first that the fares are equal and also that the two means of transportation offer the same reliability and passenger confidence with regard to safety. Then the two significant factors for the comparison are *comfort* and total *journey time*.

In Fig. 14 a comparison is made, for the range of 200 miles and an airport distance of 7.5 miles, between a 75-mph fast train and two aircraft having cruising speeds of Mach 0.16 (120 mph) and 0.22 (165 mph) respectively. Assuming modern trains and aircraft, the time on board can, for the short durations in question, usually be regarded as mainly comfortable and enjoyable, whereas the ground and "extra" times are increasingly annoying the longer they are. This is illustrated [in the original] by green and red colors respectively, and the intensities of the colors are intended to indicate roughly the degree of comfort and inconvenience. The "fastened time," when the passenger is fastened

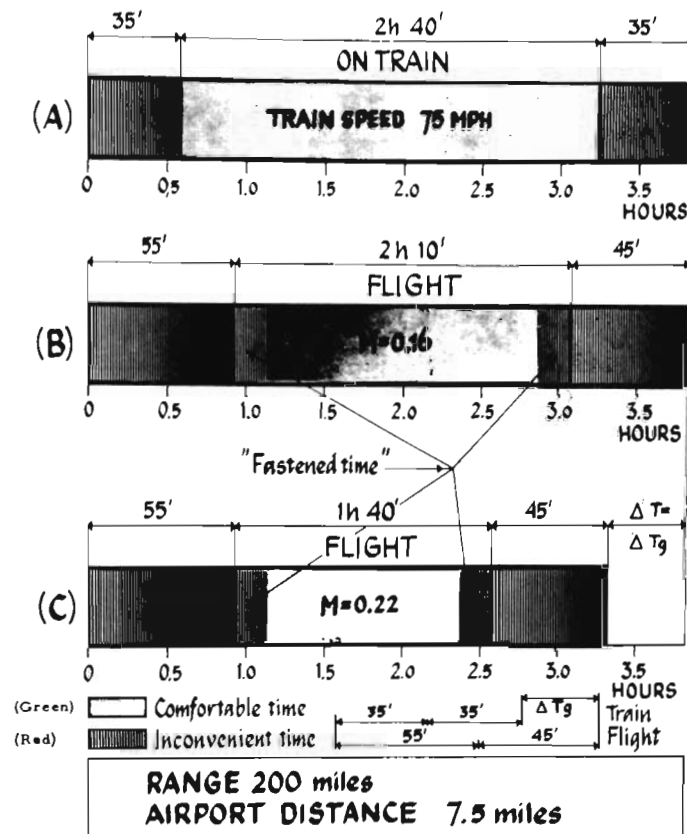Fig. 14. Comparison of comfort and total journey time between a 75 mph train and two aircraft. One has a speed which together with the ground times to and from the airport yields the same total journey time as the train. The other has an increased speed so as to yield a time gain, ΔT, equivalent to the difference, ΔTg, between the ground times for the flight journey and the "extra" times for the train journey.

with seat belts, is considered slightly inconvenient, mainly because the corresponding first and last parts of climb and descent often are somewhat bumpy.

As Fig. 14(B) indicates, a speed of $M = 0.16$ yields the same total journey time as that of the train. As, however, the inconvenient ground times are much longer for the flight journey than the inconvenient extra times for the train journey, few people, if any, will prefer flying in this case, unless the comfort in the air, for instance with regard to vibration and noise, is very much higher than on the train. Thus, for a given journey, passenger preference on a journey-time-plus-comfort basis is likely, in most cases, to be greatly dependent not only upon the magnitude of the time gain, ΔT, that is obtained by flying, but also upon how big this time gain is in relation to the difference, ΔTg, between the inconvenient ground times for air and surface traveling. Fig. 14c illustrates the case where the time gain, ΔT, equals this difference, ΔTg, this calling for a cruising speed of Mach 0.22.

The passenger preference will obviously increase with the ratio $P = \Delta T/\Delta Tg$ until a value of P (which might be below or above 100 percent) is reached where there is an equilibrium of preference and above which the preference is increasingly in favor of flying. The value of P, for this equilibrium, will vary with range and many intangible factors, such as the comfort level of the competing means of surface transportation. Figures 14(B) and 14(C) represent the cases $P = 0$ and $P = 100$ percent, respectively. It is believed that preference equilibrium will usually occur somewhere between $P = 0$ and $P = 100$ percent.

On the basis of graphs of the type represented by Fig. 13, it is possible to establish the Mach numbers required for obtaining specific values of the quantity P for various ranges, airport distances, and mean speeds of the competing surface vehicle. Such curves for "Equal Preference Speed Limits for Various Airport Distances" are computed in Fig. 15 for the two cases of $P = 0$ and $P = 100$ percent and for a 75-mph train.

The "Equal Preference Speed Limits" are the counterpart to the "Maximum Worthwhile Speeds," as inability to attain cruise speeds above these "Minimum Cutoff Speed Limits" would, for given airport distances, lead to rapidly increasing preference for surface traveling the more the cruise speeds fall below the limit.

Figure 15 illustrates rather strikingly that short airport distance is of paramount importance for the encroachment of commercial aviation upon commercial surface transportation; the importance of nearby airports is even greater than the figure indicates because of the "Power Law for Airport Distance" and the fact that the total transport market increases very rapidly with decreasing range.

In order fully to grasp the implications of the Equal Preference Limits, attention is drawn to the "Incentive Law" of preference for the faster means of transportation indicated in Ref. 4. For the case where fares, safety, and reliability are equal, this law implies that there will be an overwhelming demand for the faster means of transportation once equilibrium, with regard to comfort plus journey time, is appreciably exceeded, simply because there is then, in most cases, no reason whatever to choose the slower alternative of traveling.

The instability of this process is accentuated by the resulting increase in the volume of aviation which tends to decrease the cost—both the purchase price of the aircraft and the operating cost—and thus the fares. This will further increase public preference for flying, which, in turn, will stimulate the manufacturers to create faster and still more comfortable aircraft, thus reducing the value of P for equilibrium in preference, which will again increase the market, etc.

I am convinced that, once started, this process will lead to a most spectacular encroachment by aviation upon surface traveling on shorter and shorter ranges, as well as the creation of new markets in particular for short-haul flying. There are, however, three main conditions necessary for this process to come into full action:

- that the flight safety is improved roughly in proportion to the growth of aviation, as will be discussed later,
- that efficient V/STOL aircraft are developed with cruising speeds approaching the "maximum cutoff speed limit" and with low noise-level powerplants,
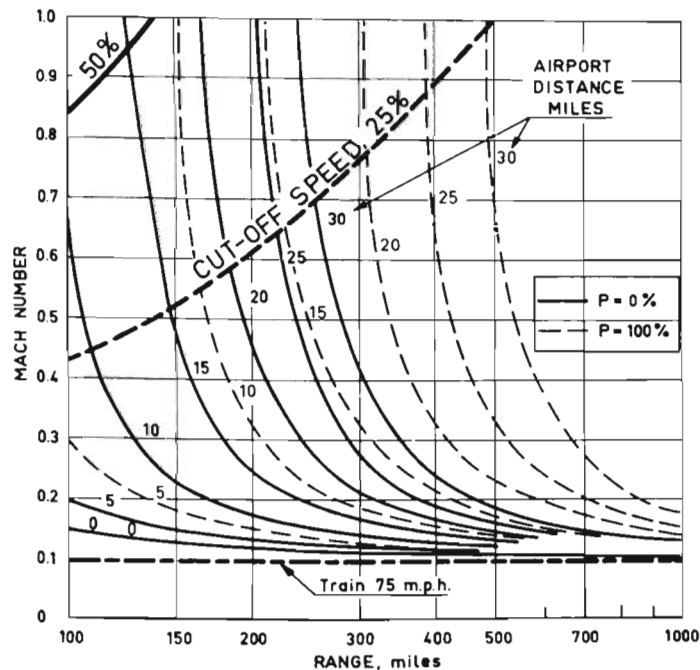
Fig. 15.   On short ranges the difference, ΔTg, between the inconvenient ground times for the flight and "extra" times for surface transportation is of great importance for the choice of method of traveling. The preference of flying is believed to depend greatly upon the percentage P of this difference that can be gained by flying. The figure, which is calculated for a 75 mph fast train, indicates that, for a given range, a certain value of P (for instance, 100%) can be obtained by short airport distance and/or by high flight speed. In particular for very short ranges, short airport distance is a much more efficient means of achieving a certain P than is high flight speed.

so that they are allowed to operate from centrally located V/STOL airports, and

- that such V/STOL airports are built on a large scale, this being a key question, as early construction of V/STOL airports will greatly promote the demand for V/STOL aircraft and thus stimulate the aircraft manufacturing industry to build such aircraft.[4]

The importance of V/STOL development, in its broadest sense, is greatly magnified by the Power Law for Airport Distance. For all ranges below about 1,000 miles, the V/STOL development is at least as important as high subsonic speeds, and for the enormous transport markets below some 200 to 300 miles range, mastering of the low-speed problems is, in fact, much more important. This is illustrated by the arrow in the lower-left sector of Fig. 12.

To sum up, on ranges below 1,000 miles, tremendous markets for aviation will be opened up

- by increasing subsonic speeds up to the "worthwhile cutoff limits" (or to about Mach 1, whatever is the lower limit), and, even more important,
- by decreasing the minimum speed by introduction of efficient and low noise-level V/STOL aircraft, provided that reliability and, above all, passenger confidence in safety are about the same as for surface transportation.

PUBLIC APPEAL, ECONOMY, AND NEED OF SUPERSONIC AVIATION ON RANGES FROM 1,000 TO 5,000 MILES

GENERAL. THE NATURE OF THE PROBLEM

In considering the *need* for increases in speed above 1,000 miles range, this is obviously a question of whether or not there is a demand for supersonic aviation, as near-sonic speeds have already been attained. As distinct from speed increases on shorter ranges, which are largely a matter of competition with surface transportation, the introduction of SST's has mainly the character of competition within aviation itself. This is because subsonic aviation will undoubtedly continue to exist also in the range bracket suitable for supersonic aviation, as it is conceivable today.

The *public appeal* of supersonic aviation cannot be discussed fruitfully without considering the fares that the passengers would have to pay, and this calls for an analysis of the main factors that govern the economy of supersonic aviation in its competition with subsonic aviation.

For *economy*, the SST fares must, of course, cover the direct and indirect operating costs with a sufficiently large profit margin. If a profit is not obtained at the initial fare, chosen when the service is first offered, the SST operators will naturally try to improve the situation and reach the optimum fare level either by increases in fares with the hope of increasing total income in spite of reduced passenger appeal, or by reductions in fares to attract more passengers. This is, of course, the natural procedure also for subsonic aviation, but there is an important difference: The economy of subsonic aviation can, in principle,

attain equilibrium between supply and demand at a fare level that yields a profit. For a newcomer, such as supersonic aviation, there is, however, much less freedom in choosing the fare level, as this must be closely related to that of the existing subsonic aviation even if the advantages offered by SST's were substantial.

This means that, *if* at the optimized SST fare level—assessed by market research and/or successive trials—the operating costs exceed the income, the total loss to all the SST operators will then be greater the more the supersonic services are expanded, also because the passenger load factors are likely to decline with the greater supply available.

Thus the situation possesses features of an "instability problem," and the reason for this would, of course, entirely be due to the coexistence of competitive subsonic services.

In this section an attempt will be made to clarify the main phases of this instability problem. The analysis will in particular deal with speeds around Mach 2 and Mach 3 and mainly be confined to the first generation SST's as they are conceived at present according to published reports.[9–30] It will thus be assumed that they will be "long takeoff and landing" aircraft, will not apply laminar flow control for drag reduction, and will not be able to fly nonstop on ranges longer than 5,000 miles.

PUBLIC APPEAL OF SUPERSONIC AND SUBSONIC AVIATION ON THE BASIS OF EQUAL FARES AND AIRPORT DISTANCE, DISREGARDING SCHEDULING ASPECTS

Assuming equal fares, as well as equal reliability, availability, and confidence in safety, the extent to which passengers will prefer the SST to the subsonic transport will depend exclusively on *time gain* and *comfort*.

With respect to *time gain*, Figs. 16 and 17 indicate total journey time for the ranges 1,500 and 3,500 miles as a function of Mach number and airport distance. It is evident that airport distance becomes increasingly dominant as the speed increases, implying that the relative time gain is lesser the longer the airport distance. Furthermore, both the absolute and relative gain in time becomes lesser and lesser with increased flight speed. For instance, for an airport distance of 20 miles and a range of 1,500 miles, an increase in cruising speed from Mach 0.85 to 2—i.e., by about 125 percent, gives only a reduction in total travel time from 6.1 to 4.6 hours—i.e., 25 percent. A further increase in speed by 50 percent— i.e., to Mach 3—would only yield about 25 minutes' time gain, or a mere 9 percent.

The illustrations also permit comparison between the time gains obtainable by decreasing the airport distance and those obtainable by increasing flight speed. For a range of 1,500 miles, a decrease in airport distance from 20 to 5 miles yields, for instance, the same time gain, 1½ hours, as does an increase in speed from Mach 0.85 to about Mach 2.0. Thus a STOL aircraft capable of landing at small airfields at five miles distance from city centers would give the same time gain as a Mach 2 SST. The STOL service would, however, be much better as it would cut down on the inconvenient and annoying ground times, whereas
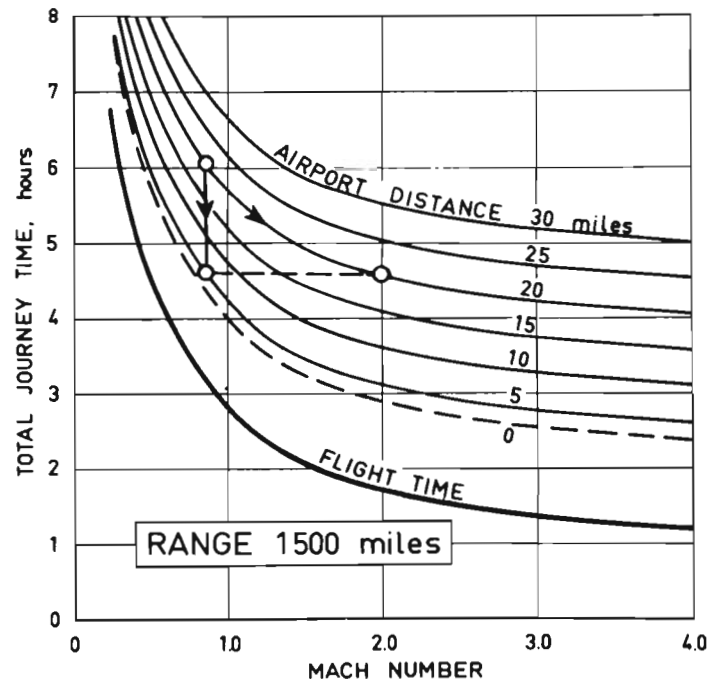
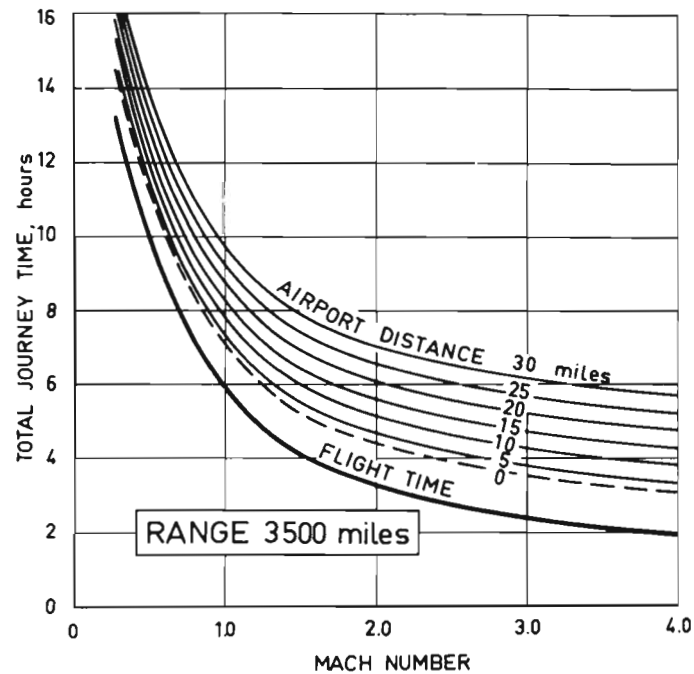Fig. 16. Total journey time as a function of speed and airport distance for a range of 1,500 miles.

Fig. 17. Total journey time as a function of speed and airport distance for a range of 3,500 miles.

the SST merely reduces the flight time, most of which is rather enjoyable for the majority of passengers on such short ranges.

For clarity, the following comparisons will, however, to begin with be made under the assumption that competing supersonic and subsonic aircraft will use the same airports or airports at equal distances to the city centers.

With regard to *comfort*, the SST's will be inferior to competing subsonic jetliners in the following respects:

1. The *"fastened time,"* when the passengers are fastened by seat belts, will be considerably longer; a total of about one hour instead of 15 to 20 minutes.

2. These periods will also be appreciably more uncomfortable due to the *steep floor angle* during climb and descent; no less than some 20 degrees "apparent" uphill angle in climb, including the effect of acceleration, and also a certain downhill angle during descent, which, together with the effect of deceleration, will cause the passengers to "hang" in the seat belts.

3. The *interior noise level* in cruise is likely to be higher than for subsonic jetliners because of the higher boundary layer noise.[10] During takeoff and acceleration through the transonic speed regime, the cabin sound pressure level will probably be still higher.[31]

4. The comfort standard with respect to width of seats and leg room— *the seat comfort*—will probably be lower for the SST's, if not when entering service, at least during the course of competition with successively improved jetliners. The reason for this is that, as the fuselage volume is a much more critical factor for the operating cost of an SST, the volume per passenger can be improved for a subsonic aircraft with less sacrifice in payload.[32]

5. For the same reason, and also because of the shorter flight times, the standard with regard to *meal services* will undoubtedly be inferior for the SST's.

6. The SST passengers are likely to be subjected to a greater number of severe "bumps" due to gusts, because of the higher speed with which turbulent regions are encountered and because it will be less possible to avoid them.

7. Finally, some passengers may *feel more insecure* in an SST than in subsonic aircraft and thus be subjected to a mental strain, even if it could be proved that the safety level were the same: The steep floor angles, the high accelerations and decelerations, the high cabin noise level during acceleration periods, etc., will—apart from decreasing the physical comfort—induce feelings, in particular with elderly passengers, that they are more or less at the mercy of a highly sophisticated piece of machinery, which might "go out of the hands" of the crew and that the crew will have less possibilities to cope with unforeseen difficult situations.

Over and above this, the "psychological comfort" for many SST passengers will be adversely affected, should there be any concrete reason to suspect— for instance, unexplained accidents—that the flight *safety* of SST's might not be the same as for comparable subsonic aircraft, or that the more intense *cosmic radiation* at supersonic flight altitudes might cause hazards that are not negligible. For reasons of clarity, these two safety aspects will, however, not be included in the concept of comfort; they will be dealt with separately.

The obvious conclusion from the inferior comfort in the 7 respects listed above is the following: Whereas *all* passengers prefer the modern jet to the piston aircraft at equal fares—because of appreciable improvements both in flight time and comfort—the public appeal of the SST's in comparison with subsonic jets and at the same fare is an open question; it will entirely depend upon the *balance*, in the subjective view of the passengers, *between the value of the gain in flight time and the disadvantage of less comfort*. It might be argued that "time gain means increase in comfort." This is correct for one interpretation of "comfort," but, to avoid confusion, the term comfort is used here in the sense of "average comfort per hour of flight."

As the time/comfort balance is, obviously, dependent upon flight duration, the further analysis will be made for the following main range brackets and corresponding typical ranges:

Main Range Brackets	Typical Range
1,000–2,000 miles	1,500 miles
2,000–3,000 miles	2,500 miles
3,000–5,000 miles	3,500 miles

Figure 18 shows a comparison of travel time and comfort for Mach 0.85 and 2.0 over a range of 1,500 miles, such as London–Athens, and for an airport
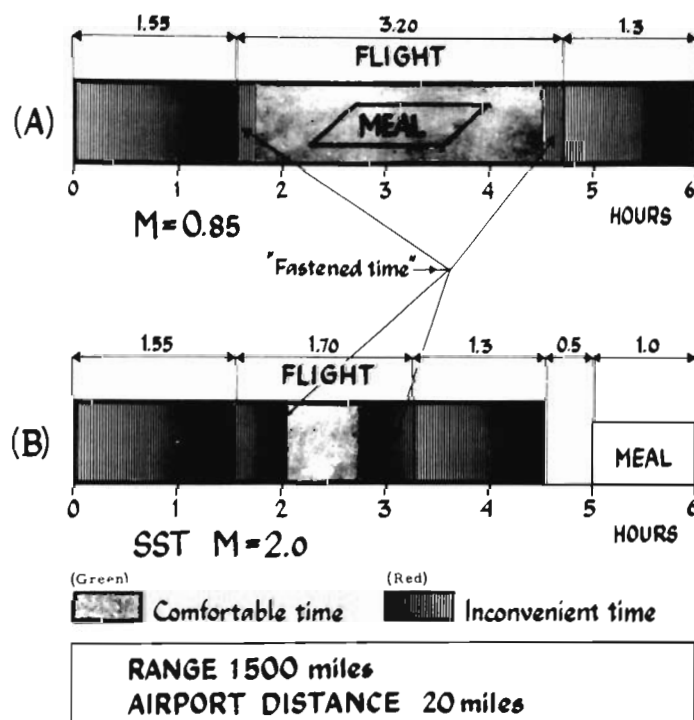

Fig. 18. Comparison of comfort and total journey time between a subsonic ($M = 0.85$) and a supersonic ($M = 2.0$) aircraft for a distance of 1,500 miles.

distance of 20 miles. The convenient portion of the flight time—i.e., between the "fastened times"—has been reduced by the SST by about two hours, whereas the uncomfortable parts of the complete journey have been increased by the longer "fastened times." It seems, therefore, rather unlikely that the average passenger would prefer to expose himself to the greater inconveniences of the SST than to fly subsonic to gain merely 1½ hours. In particular, if a meal is not served on the SST flight (the operator might prefer to make savings by avoiding the quick meal that can possibly be served during the 40 minutes of "unfastened time") the passenger will be hungry after a total journey time of 4½ hours and will thus have to eat soon after arrival at his destination. If we allow him half an hour before the meal and one hour for the meal, the time gain has been completely eliminated and there is, for most passengers, a definite "net balance" of merely greater inconveniences by flying supersonic.

It is concluded that, at equal fares and airport distances as for subsonic flights, only a minority of the passengers will fly supersonic on direct and conveniently scheduled flights in the range bracket 1,000 to 2,000 miles, and that even a quite small fare surcharge would reduce the number of SST passengers to practically zero.

For the distance of 2,500 miles, which is typical for U.S. transcontinental routes, the time/comfort competitiveness of SST's will also be greatly dependent on whether or not meals can or will be served (Fig. 19). This seems doubtful for a Mach 3 SST, but possible for a Mach 2, although the longer time available for the meal served on the subsonic airliner will no doubt make the major portion of the flight more enjoyable and restful. In view of this and the higher comfort level also in the other respects listed above, it seems uncertain that the SST passengers would be in a better shape some eight hours after the commencement of the journey than the subsonic passengers.

In spite of all this it is quite possible that the balance of time/comfort considerations for direct flights on ranges from 2,000 to 3,000 miles will favor the SST's, at equal fares, airport distances, and availability of conveniently scheduled services. The preference of flying supersonic will, however, hardly be strong enough to withstand any noticeable fare differential.

Regarding, finally, the range bracket 3,000 to 5,000 miles, the chosen typical distance of about 3,500 miles represents the transatlantic routes considered to be the backbone of supersonic aviation. Anyone who has crossed the Atlantic, even by modern jets, would certainly agree that the flight duration of some seven hours is tiring (Fig. 20). This, however, is not by itself conclusive proof that saving some 3 to 4½ hours by SST's will cause most of the passengers to prefer supersonic flight.

For a long flight, for which the flight time by means of jet airliners has already been reduced to a minor portion of the 24-hour day, it is believed that the passenger preference is mainly governed by his tiredness after the completed journey. This is particularly important for westbound or eastbound journeys, for which there is an appreciable difference in local time; for instance six hours over the Atlantic. To quote Dr. H. Strughold of the USAF School of Aviation Medicine:[33]

the newcomer's physiologic cycle, or "metabolic clock" behaves as though he were still in the area he just left, and it will take several days or more before he adapts himself physiologically to the local time of the new place. There is no question that the majority of people are sensitive to a phase shift in the day-night cycle.*

Naturally, the passengers will recover sooner the less they have been tired out by the flight journey as such or by encroachment upon sleep by too early departure or too late arrival times. Thus, it is important to assess the extent

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* This is confirmed by Dr. D. H. Stuhring, who in a paper, "Medical Problems Related to the Development and Operation of Supersonic Transports" (Aero-Space Division, The Boeing Company, Seattle, Nov. 1962) states: "It will take at least a full week before our metabolic clock and the local clock are again in phase," and "For the businessman, statesman, or competitor, such imbalance may be a distinct disadvantage in regard to overall physical and mental efficiency. Important meetings or events should not be scheduled until at least partial adaptation has been acquired." Dr. Stuhring also indicates that the problem will be more severe for supersonic flight: "Effects of the phase shift resulting from subsonic travel have already become apparent and will be intensified as speed increases."

Fig. 19. Comparison of comfort and total journey time between a subsonic ($M = 0.85$) and two supersonic ($M = 2$ and 3) aircraft for a distance of 2,500 miles, typical for U. S. transcontinental routes.

to which SST night flights and other inconveniently scheduled SST flights will have to be used for economic utilization of the aircraft, but this question will be discussed later.

Considering conveniently scheduled flights, the importance of the time gained by an SST lies mainly in the fact that the passenger can begin to rest earlier; only in exceptional cases will he utilize the time gain by starting to work or go sightseeing earlier than after a subsonic flight. If, however, the SST flight is found to be more tiring than a subsonic flight (this is very difficult to judge today), the SST passenger might not be in better shape after some 9 to 10 hours, the total time for the subsonic journey (Fig. 20).

In this connection it should be observed that in particular the long-range subsonic airlines will no doubt take advantage of the fact mentioned above that the "volume factor" is less critical by offering comfort levels—with regard to
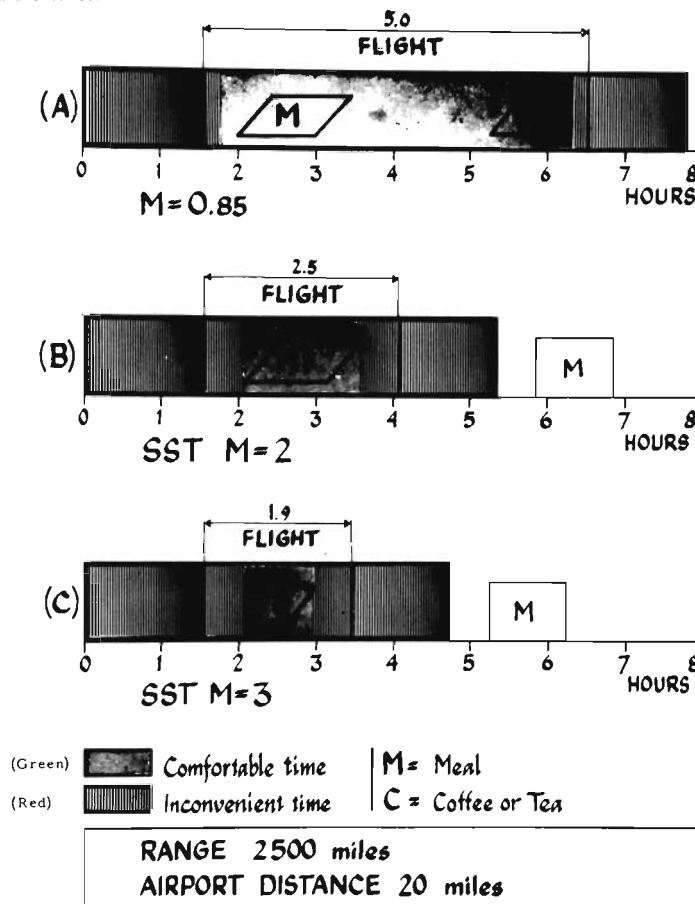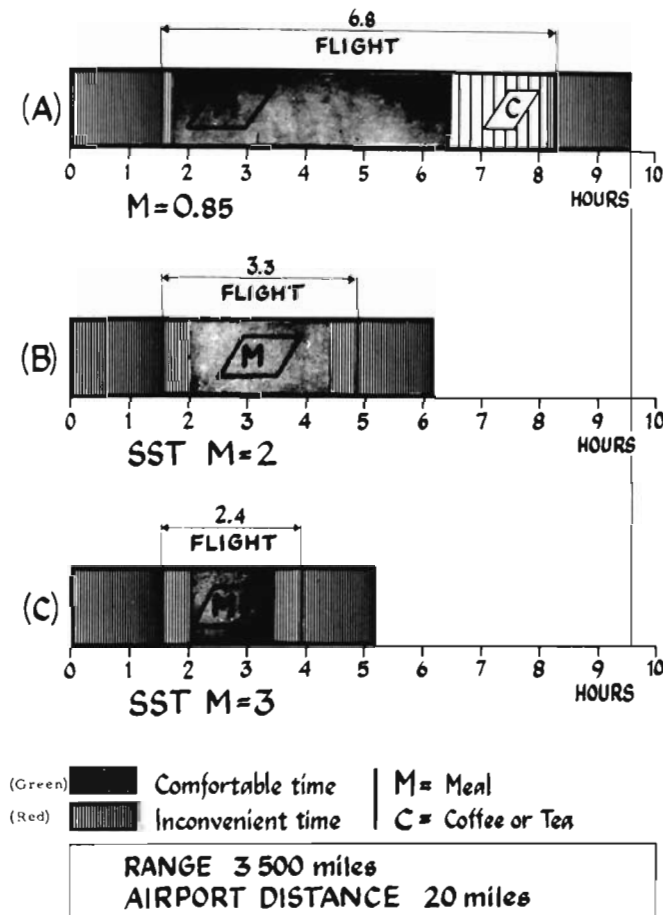

Fig. 20. Comparison of comfort and total journey time between a subsonic ($M = 0.85$) and two supersonic ($M = 2$ and 3) aircraft for a distance of 3,500 miles, representative for transatlantic routes.

perfect service and "seat comfort," etc.—so much superior to that of the SST's as to offset the longer subsonic travel time as much as possible.

Nevertheless, it seems probable, although by no means certain, that in the choice between flying supersonic or subsonic on direct, conveniently scheduled daytime flights, most passengers would prefer flying supersonic on the Atlantic and similar routes if the fare, airport distance, availability, reliability, and confidence in safety are the same. However, this preference is still likely to be marginal; for the majority of passengers it will hardly justify more than a moderate fare surcharge.

The above conclusions regarding public appeal of the SST's and acceptable fare surcharges on long ranges appear to be supported by the study recently carried out by the Federal Air Office of Switzerland.[34] This seems to be the only market research on this subject that has been conducted up to now and it was obviously limited to the case of conveniently scheduled daytime flights. According to this investigation:

- 48 percent of about 830 passengers interrogated were against any SST fare increase,
- 35 percent would accept a maximum SST fare surcharge of 10 percent, and only
- 8 percent would accept a higher fare surcharge than 10 percent.

It is also of interest to note that 47 percent consider shorter ground times more important than shorter air times and that 19 percent consider additional connections (improved availability) more important.

To sum up, the following conclusions can be drawn for the cases where there is a choice between supersonic and subsonic services at equal airport distance and on conveniently scheduled direct daytime flights:

1. On ranges from 1,000–2,000 miles only a minority—probably a small one— of the passengers would prefer the SST at equal fares.

2. On ranges from 2,000–5,000 miles a majority of the passengers might prefer the SST provided that no or at the most a moderate surcharge is applied.

The ranges 2,000–5,000 miles may, therefore, be referred to as the typical "supersonic range bracket."

Scheduling Aspects and Their Influence on Passenger Appeal and Fares

One prerequisite for equal fares is that the seat-mile costs and thus the direct operating costs (DOC) are about the same for SST's as for competing subsonic jets. According to most of such studies that claim that the DOC can be about the same for the SST's, a fundamental condition for this conclusion is that the productivity of the SST's, in terms of aircraft miles flown per year, is increased over that of subsonic aircraft in at least nearly the same proportion as the speed, which means roughly the same annual utilization in flight hours. This "Productivity Demand" implies that, for instance, a Mach 2 SST would have to make about twice and a Mach 3 SST about three times as many trips on a particular route or route system as a near-sonic aircraft.

Let us first consider *the maximum possible utilization during limited periods* and the associated scheduling problems in *the 3,000–5,000 miles range bracket.* Figure 21 shows that on *the Atlantic route,* for which the scheduling problems are particularly important, a near-sonic aircraft can make two single flights in a 24-hour day, and that it is physically possible for a Mach 3 SST to make six single flights, assuming a turnaround time of 1½ hours. As, however, such a schedule does not leave any time for maintenance, it has to be modified, for instance so that every second day the number of single flights is reduced to four—i.e., an average of five flights per day, implying a maximum of ⅚ of the utilization required to comply with the productivity demand. The reason for this is, of course, that each flight is burdened with a turnaround time, which means a greater "time expenditure" the more flights that have to be made.

The Mach 2 SST can fully comply with the productivity demand for limited periods, as it can make four single trips, allowing a daily maintenance period of about four hours.

Obviously, neither supersonic nor subsonic operation can be carried out to the extent indicated by Fig. 21 every day all the year round; there must be lengthy overhaul periods and a certain total amount of maintenance and reserve time, etc. It is, however, desirable for profitability that the maximum productivity of the aircraft can be extracted during peak-season periods and therefore a study of scheduling for maximum daily utilization is important.
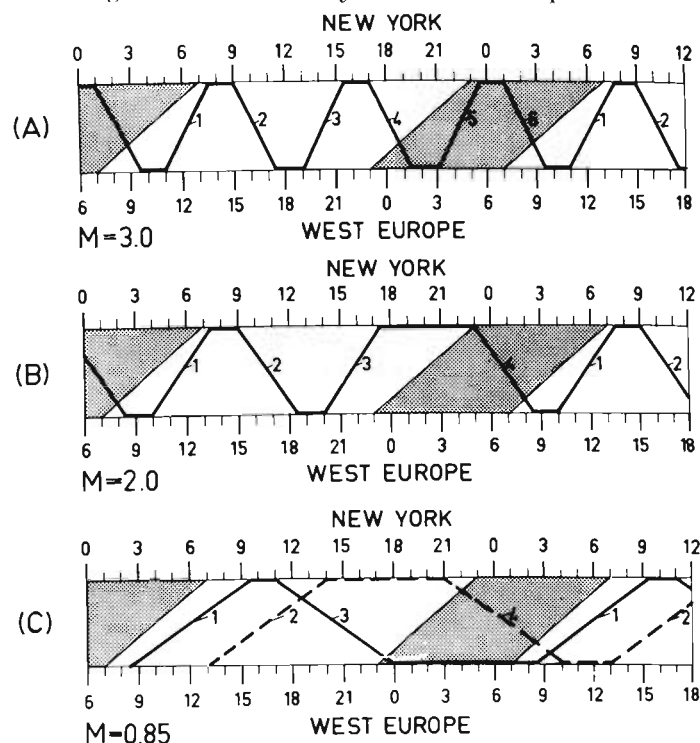

Fig. 21. Possible scheduling on the Atlantic route. Night (11 p.m. to 7 a.m.) is shown shaded.

A closer study of Fig. 21(A) for a Mach 3 SST, as well as of possible modifications of this schedule, reveals that of the maximum of six flights per 24-hour day over the Atlantic, only four can have reasonably convenient departure and arrival times, whereas of the two others; one must be a night flight and the other have a pronouncedly inconvenient departure or arrival time. If these two flights are canceled every second day, there will be an average of 20 percent inconvenient flights. The Mach 2 SST will suffer one night flight, or otherwise highly inconvenient flight—i.e., 25 percent inconvenient flights.

Regarding the *night flights*, it will be virtually impossible for the passenger to sleep at all during the supersonic flight of $2\frac{1}{2}$ to 3 hours, whereas he can normally sleep quite a few hours during a subsonic night flight of seven hours or more. The complete loss of sleep for one night will make supersonic night flights very unpopular, considering also that it would hamper the subsequent recovery from the time-difference nuisance.

With regard to the SST Atlantic *daytime flights with inconvenient departure or arrival times*, most people will certainly find it rather pointless to gain a few hours on such a long journey if they are compelled to get up much earlier in the morning than usual or are prevented from going to bed until much later than usual. Such inconveniences are about the same for subsonic flights, but the great difference lies in the fact that it is not possible to avoid such flights over the Atlantic for Mach 3 SST's, for reasons of utilization, whereas the subsonic jetliners can more easily be scheduled with fairly popular departure and arrival times.

It is, in other words, important to observe that whereas many Atlantic passengers might prefer a conveniently scheduled daytime SST flight to a subsonic flight, they will in most cases prefer a subsonic—day or night—flight to an inconveniently scheduled SST flight; but these latter flights must also be filled with passengers. The inevitable conclusion seems to be that *for SST night flights, and for the inconveniently scheduled daytime SST flights required for utilization, to be attractive, the fares will have to be set appreciably lower than for the competing subsonic, conveniently scheduled daytime flights or for subsonic night flights.*

With regard to *the range bracket 2,000–3,000 miles*, it seems difficult for an SST to attain the same maximum daily utilization as a subsonic airliner. As Fig. 22 shows, a subsonic jet can on the average make three flights per day over the U.S. continent, considering a two-day cycle. To comply with the productivity demand, a Mach 3 SST would thus have to make nine single flights per day and a Mach 2 SST six single flights, which is impossible. The Mach 3 SST can at the most make six single flights and the Mach 2 SST four (Alt. A), or possibly five (Alt. B), if extremely short daily maintenance periods can be accepted. The maximum utilization for the SST's would thus be only about $\frac{2}{3}$ (for the Mach 2 case at the very most $\frac{5}{6}$) of that of near-sonic aircraft.

If we consider the proportion of inconveniently scheduled flights, Fig. 22 reveals that no less than $\frac{1}{3}$ of the subsonic flights are of this type, whereas only $\frac{1}{6}$ of the Mach 3 SST flights must spoil the night more or less completely. For the case of four single flights per day with a Mach 2 SST, all the flights can

be conveniently scheduled, whereas if an average of five single flights per day is achieved, $\frac{1}{5}$ must be inconveniently scheduled.

At first sight, the superiority of the subsonic aircraft with regard to utilization thus appears to be counteracted by a higher proportion—$\frac{1}{3}$—of inconveniently scheduled flights: this conclusion would be correct if this $\frac{1}{3}$ of the subsonic flights would have to be flown at a loss due to insufficient load factors with or without fare reductions. In reality, however, the subsonic operators are able to compensate poor passenger load factors by supplementary loads of cargo, and thereby attain profitable total payload factors (see below). This possibility— which, of course, also applies to Atlantic flights—will undoubtedly be still more improved in the future by special cabin designs for so-called "mixed freight"
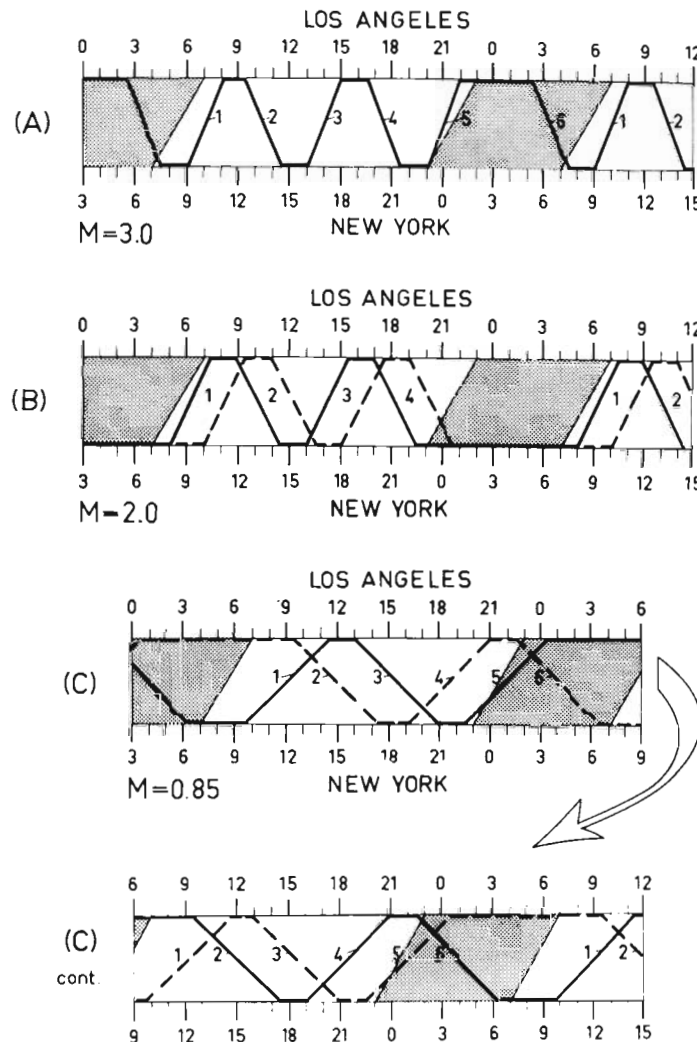
Fig. 22.   Possible scheduling on the New York-Los Angeles route.

versatility (one or more pallets for cargo in a section of the cabin). The possibilities to use SST's for mixed freight appear questionable and, anyhow, less efficient.

In comparison with the subsonic services, supersonic flights over the U.S. continent would, however, have one definite advantage in that it would be possible for an SST passenger to take a morning flight from the East Coast to the West Coast, do some business there during the major portion of normal office hours and then return the same day to the East Coast, thus avoiding the expense of spending the night at an hotel. This will probably be quite popular for some busy executives and business men, and they might therefore be willing to pay a certain surcharge. In the opposite direction, daytime return flights would, however, be less attractive, as they would only allow one or two hours work during office hours. The average proportion of daytime return passengers in relation to the whole transcontinental market would not be very great, also because such passengers will only be a minor part of the "expense account" passengers (most of them will probably spend one or more days at the destination), and there would be no point in rushed return trips for tourists.

Thus only a part of the passengers on the early morning flights and the late afternoon flights that are usable for daytime return flights will avail themselves of this advantage. Consequently, it appears unfeasible to apply a higher ticket price for such flights or for this particular part of the passengers; the advantage of daytime return flights will only result in improved load factors on some of the early morning and late afternoon flights.

Summing up, Table 3 is believed to give a fairly correct overall picture of the scheduling limitations for the SST's in comparison with subsonic aircraft on ranges from 2,000 to about 5,000 miles.

Table 3

Mach No.	Typical range, miles	Utilization of SST's in relation to subsonic aircraft	
		Maximum during limited periods*	Considering only conveniently scheduled SST flights
3	2,500	$\frac{2}{3}$	$\frac{5}{9}$
	3,500	$\frac{5}{6}$	$\frac{2}{3}$
	Average	75%	~60%
2	2,500, Alt. A	$\frac{2}{3}$	$\frac{2}{3}$
	2,500, Alt. B	$\frac{5}{6}$	$\frac{2}{3}$
	3,500	1.0	$\frac{3}{4}$
	Average, Alt. A	~85%	~70%
	Average, Alt. B	~90%	~70%
2	1,500	$\frac{3}{4}$	$\frac{1}{2}$

* Figures 21 and 22 show that the time available for maintenance is longer for the subsonic than for SST schedules.

In judging the implications of these limitations, it is seemingly rather immaterial, whether one assumes that only the conveniently scheduled SST flights will be flown resulting in a very low utilization or that also the inconveniently scheduled flights will be offered, implying either entirely insufficient load factors on these flights if the fares are kept the same, or unsatisfactory income from such flights also if reduced fares are applied to attain better load factors. Evidently, whichever of these three possible alternatives is chosen, the fact that the SST's cannot be utilized for conveniently scheduled flights to more than about 60 to 70 percent of the utilization of subsonic aircraft constitutes an appreciable economic burden. This must detract from, and it possibly more than outbalances, the extra income that can be derived from the moderate fare surcharge that SST operations might possibly be able to withstand on conveniently scheduled daytime flights on ranges above about 2,000 miles.

As it is probable that the SST operators will try to extract the maximum utilization of the SST's, thus some 75 to 85 percent of that of subsonic aircraft, it seems evident, considering the required fare reductions on night and similar flights, that the *average* SST fare level can at best be equally as high as the subsonic fares.

Considering, finally, *the range bracket 1,000 to 2,000 miles*, the subsonic aircraft on a range of 1,500 miles can make four single flights per day with $1\frac{1}{2}$ hours for turnarounds and five hours margin for maintenance. One of these flights must be a night flight. A Mach 2 SST cannot on the same basis make more than six single flights, two of which will encroach upon the night. The relative utilization of the SST will thus be about $\frac{3}{4}$ on the basis of all flights and $\frac{2}{3}$ on the basis of conveniently scheduled flights.

It must, however, be remembered also in this case that a subsonic night flight can usually achieve an above-break-even total payload factor by supplementary cargo even if the fares for the passengers would have to be somewhat reduced for attaining also a fairly good passenger load factor. The relative utilization on the basis of only conveniently scheduled SST flights and all subsonic flights is thus as low as $\frac{1}{2}$ (Table 3).

THE EFFECT ON PASSENGER APPEAL OF LONGER AVERAGE AIRPORT DISTANCE
FOR SST's THAN FOR COMPETING SUBSONIC AIRCRAFT

Up to now the analysis has been based on the assumption of equal airport distance for SST's and competing subsonic aircraft. It is, however, important to realize that subsonic aircraft competing with SST's will to a steadily increasing extent use airports at shorter distances to the city centers than the airports that can be used by SST's of the first and probably also the second generation. The main reason for this is that an increasing proportion of cities, big enough to justify SST operations, will have more than one major airport. This will be an inevitable consequence of the growing traffic saturating, sooner or later, the first major airport of the city. For many of the biggest cities such as New York, London, and Paris and for some medium cities such as Washington and Stockholm, this development has already taken place.

If a city has two or more major airports, their distance to the city center will usually be longer the bigger the airport. Both because of the long takeoff and landing distances and for noise considerations the SST's will, with few exceptions, only use the furthest-away airports. In contrast to this, subsonic aircraft will be able to use smaller airports closer to the cities as a consequence of aeronautical developments that have already begun, i.e., even without taking into account ture STOL aircraft expected at a later stage.

The combination of aeronautical development in this direction during the next 10–20 years and the increasing number of cities having more than one major airport will greatly favor subsonic aircraft in competition with SST's and, of course, more so the shorter the range. To mention only one example, the difference in airport distance between the Dulles and the National airports of Washington, D.C., is about 22 miles. The difference in total ground time for the average passenger can be estimated to at least an hour, assuming flights to or from one and the same airport at another city. For a range of 1,500 miles—for which only a minority of the passengers is likely to prefer the SST at equal airport distance—there would be no point whatsoever for the passenger to fly supersonic; he would at best gain a few minutes in total travel time and he would suffer from the much longer and more annoying ground time at one end of the flight as well as from the inconveniences of the SST flight as such.

Considering average and weighted conditions (many cities will for a long time only have one major airport or two or more airports at about the same distance from the city) in the middle of the seventies, it seems reasonable to count with about five miles longer airport distance for SST's than for competing subsonic aircraft. This would correspond to about half an hour longer total ground time (Fig. 8). For *the range bracket 1,000–2,000 miles*, I am convinced that an average difference in ground time of this order will reduce the number of people who prefer SST's practically to zero. In view of this, the operators are likely to be very reluctant indeed to introduce SST services in this range bracket; in their long-term planning they must also take into account continued development towards subsonic aircraft being able to use airports closer to city centers, to a steadily increasing extent as a consequence also of STOL aircraft being introduced at a later stage.

For *ranges above about 2,000 miles*, the gain in ground time of the order of half an hour, due to shorter average airport distance for subsonic aircraft, appears, at first sight, to have little significance as compared with a time reduction of anything between 2½–5 hours by flying supersonic. It must, however, be remembered that the saving of half an hour of the annoying ground time will, in the view of most passengers, be regarded as equivalent to a two or three times longer reduction of the more pleasant flight portion of the journey. The shorter average airport distance for long-range subsonic aircraft will, therefore, undoubtedly affect the public appeal of SST's rather seriously—in particular on ranges from 2,000 to 3,000 miles—bearing in mind that the preference is likely to be marginal even at equal airport distance.

Summing up, the combined effects of scheduling difficulties and the difference in average airport distance appear to justify the following conclusions, assuming

equal fares and that there is a choice between supersonic and subsonic connections:

1. On ranges from 1,000–2,000 miles, very few passengers will prefer the SST excepting perhaps one or two services per day with particularly popular departure times, such as an early morning flight.

2. On ranges from 2,000–5,000 miles, at the most half of the passengers are likely to prefer the SST, considering the whole market open for competition between supersonic and subsonic services, thus including both conveniently and inconveniently scheduled flights.

These judgments are significantly modified in comparison with the conclusions that can be drawn for the case of equal airport distance and considering only conveniently scheduled daytime flights.

The above discussions are believed to show that there is a great danger in drawing generalized conclusions about overall passenger preference for SST's, and about the economic feasibility of SST operation, merely on the ground of estimated passenger preference for conveniently scheduled SST flights using the same airports as competing subsonic airliners.

OTHER FACTORS AFFECTING THE ECONOMY OF SST's IN COMPARISON WITH
COMPETING SUBSONIC AIRCRAFT ASSUMING EQUAL FARES AND NO RADICAL
SUBSONIC IMPROVEMENTS

With the basic demand of equal fares, the profitability of supersonic aviation is essentially dependent on load factors and the question whether or not its actual direct operating cost can be the same as for competing subsonic aircraft, it being little reason to assume that the indirect operating cost will differ appreciably. It is obviously very difficult to answer this question in a general way, i.e., without referring to a particular SST project for which the manufacturer has stated the purchase price, fuel consumption, maintenance time, etc. Furthermore, even for a specific SST project, a fair comparison of the DOC of SST's and subsonic jets is difficult to make, because the development costs of the SST are expected to be covered by government funds and the dividing line between development and production costs can hardly be determined without a certain arbitrariness. Nevertheless it seems possible to analyze in considerable detail some factors that influence the "relative" economy of the SST's in comparison with competing long-range subsonic jets.

The following analysis is based on the assumption—apparently made by many SST proponents—that the DOC of the SST's would not be higher than for most competing subsonic jets in service at the time of introduction of the SST's, provided

- that the rate of amortization of the purchase cost is the same, for instance 10 percent per year, and
- that the annual utilization of the SST's does not have to be reduced, compared with subsonic aircraft operating on the same long routes, to a greater extent—usually some 10 to 15 percent—than experience has shown is normal for short-haul subsonic aircraft (with one or a few hours flying

time per flight) in relation to long-range subsonic aircraft (with flight times of some 5-8 hours).

According to the terminology of ATA (Ref. 35, which includes a curve for utilization versus flight time), this assumption can be said to imply that the SST would have the same "standard operating cost" as subsonic aircraft.

This basic assumption must be regarded as rather optimistic for the SST; according to some studies, the operating costs of the SST's are estimated to be appreciably higher than for *present* jets[36,37] and the subsonic DOC is likely to be continuously reduced during the time remaining until the anticipated introduction of the first SST.

Before analyzing the various factors significant for the comparative economy of the SST's, a few words will be said about the *aerodynamic or kinetic heating* that the SST's will be subjected to during each flight, because this will influence several of the most important economical factors, in particular annual utilization, amortization rate and the costs for maintenance, overhaul, and repairs.

The main implication of the kinetic heating is that the primary structure of the SST's, operating above about Mach 2.0 (possibly 1.8), will be subjected to extremely complex fatigue effects due to cycles of elevated temperatures being superimposed on the usual fluctuating load and stress cycles. Many of the mechanical, electronic, and hydraulic, etc., systems will also be subjected to severe and unusual environmental conditions due to the temperature cycles, unless they are enclosed in cooled portions of the aircraft, which might add to design complexity. Furthermore, the adverse effects of the heating during supersonic cruise might be magnified by its being preceded and succeeded by quite low temperatures in the subsonic climb and in the descent.

With regard in particular to the structure of the SST, the kinetic heating will have two adverse effects, which to some extent are interrelated. One is that it will be much more difficult to *predict* the structural reliability and safety than for subsonic aircraft and the other that the *scatter* in fatigue properties will be much greater.

As the main reasons for these two effects will be discussed in Part III of the paper, only a few observations will be made here. The difficulty to predict the long-term properties of SST structures is essentially caused by the fact that fatigue testing of structural parts and assemblies, which are heated up and cooled down for each simulated flight, will inevitably take much longer time than for the case of "subsonic" or "cold" structures. To obtain the same knowledge about the fatigue properties of the SST structures as is required for subsonic aircraft would—if at all possible—be likely to take something like a decade and the costs would be staggering.

The reason why the scatter in fatigue properties of aerodynamically heated structures will be greater than for subsonic aircraft is mainly due to the complexity of the superimposed or intermixed temperature-load cycles, and to the fact that there will be less similarity between the operation of individual SST's with regard to the temperature-load conditions that are experienced in service. The implication of the great scatter is, of course, that the differences between nominally identical SST structures will be much greater than for subsonic

structures with regard to how soon fatigue cracks will appear and to the subsequent "defect rate".

For the reasons indicated, it appears that the SST design can hardly be proven to be equally reliable as subsonic structures. Thus, surprises in service must be expected, and the SST operators will have to reconcile themselves with some rather unaccustomed prospects: Usually the "defect rate" for a new type of subsonic aircraft decreases as flight experience is gained on a number of service aircraft; there is a continuous "debugging" of the aircraft. However. whenever, appreciable temperature effects are involved, *experience by accumulating flight time will mean much less with regard to preventing future troubles.*

Somewhat schematically it can be stated that, whereas subsonic aircraft of a certain type, in the course of many years of service, usually tend to be more and more reliable—with successively decreasing defect and repair rates, as modifications are made—*the SST is likely to be less and less reliable as service time accumulates.* It also follows *that lead time on SST test aircraft* (flying without passengers), even if quite appreciable, say, some 10,000 hours—*will be much less of a safeguard,* compared with much shorter lead time on subsonic test aircraft, because damage and malfunctions due to creep, "heat fatigue," and other temperature effects might not appear until after a still longer service time.

In order to rationalize the following comparison, it is first assumed that no appreciable aeronautical improvements are made, either in subsonic or supersonic technology, after the introduction of the first SST. Furthermore, the SST's are in the first place compared only with "first-line" subsonic aircraft modern at the time when the first SST is introduced.

1. The *reduction in annual utilization* of the SST's, in relation to long-range subsonic aircraft operating on the same routes, is likely to be much greater than the reduction that short-haul subsonic aircraft are usually subjected to compared with long-range subsonic aircraft, for the following reasons:

(a) The minimum *average time for turn-arounds will be longer for SST's* than for short-haul subsonic aircraft with the same flying time per flight, mainly because for the latter, intermediate stops are often made without refueling, whereas refueling will be a normal procedure for each turn-around of an SST (as with long-range subsonic aircraft).

(b) Delays in departure time will be more objectionable for SST than for subsonic short-haul operation, for many reasons: the latter are often characterized by a high frequency service, the idea of gaining time by flying supersonic is incompatible with a delay at the very beginning of the flight, and, if one flight with an SST is delayed, this will have repercussions on the subsequent flights, as they will also be delayed until there is a longer stop for maintenance or scheduling reasons. *The SST turn-around time must, therefore, include a longer "schedule protection time"* than equal-duration subsonic flights.

On the other hand, the SST operator will probably devote greater efforts—and expenditures—to reducing the turn-around times by automatic checkouts, etc., than the subsonic competitor. Because of the greater "repercussion effect" on subsequent flights, it is, however, doubt-

ful whether the SST operator can base his schedule on shorter turn-arounds than the subsonic operator serving the same long routes.

(c) The reduction, according to experience, in annual utilization for short-haul aircraft, as compared with long-range subsonic jets, is also due to the fact that *the total maintenance and overhaul time per year increases appreciably with the number of flights per year.* The reason for this is that for many items of the aircraft—such as the landing gear, the high-lift devices, the pressure cabin, the wing and the control surfaces—*the wear and tear, as well as structural fatigue, is wholly or partly proportional to number of flights rather than to flying time.* This "number-of-flights dependency" in relation to flight-time dependency, will probably be more pronounced for SST's than for subsonic aircraft.

This will increase the total time per year for maintenance and over-haul of SST's as compared with short-haul subsonic aircraft even if one could neglect the peculiar environmental and loading conditions of the SST's and their design complexity.

(d) However, whereas the subsonic jet is a comparatively robust and simple vehicle, *the SST will be the most complicated and sophisticated flying machine ever produced,* with a great many systems of new designs. Over and above this, the SST's will be subjected to *kinetic heating* during their entire service life as described above. There can be no doubt that these two factors will still more increase the maintenance and overhaul time over that of equal-range subsonic aircraft.

(e) Even if the effects on maintenance time of the kinetic heating, etc., can be minimized by sophisticated designs, *the number of, and time for, in-spections must, for equal demands on safety, inevitably be greater for SST's* than for subsonic, equal-duration as well as equal-range aircraft.

Rough estimates of the effects of the 5 factors indicated above point at some 30 to 40 percent reduction in maximum annual utilization for a Mach 2.2 and some 40 to 50 percent reduction for a Mach 3 SST, instead of the 10 to 15 per-cent reduction typical for subsonic short-haul compared with long-haul aircraft.

It thus appears that *speed itself, in particular supersonic speeds, contains some inevitable detrimental elements that to a great extent consume the increase in produc-tivity that would theoretically follow from higher speed.*

The reduction, discussed above, in the maximum possible annual utilization is, of course, not wholly additive to the limitations in utilization that are due to scheduling problems, because avoidance of night flights and flights with in-convenient departure and arrival times would provide some time for inspections and maintenance. The combined effect will, however, usually imply further reductions in utilization, for both supersonic and subsonic aircraft. Whether this further reduction will be greater for the SST's than for subsonic aircraft or vice versa depends on many rather intangible factors. If, for instance, night flights are avoided on a particular route for both categories, that would be a less disadvantage for the SST's because the nights can then be more efficiently utilized for the longer maintenance and inspection times required for the SST, whereas the less amount of work to be done on the subsonic aircraft could,

perhaps, be conducted in a few hours, leaving the aircraft idle during the rest of the night. If, on the other hand, subsonic night flights will be made—for instance on long ranges where they permit some sleep—but not supersonic night flights (for reasons of loss of sleep or sonic-boom considerations), that would favor the subsonic aircraft with regard to utilization.

Considering average conditions for ranges from 2,000–5,000 miles, I am inclined to believe

- that, if kinetic heating and design complexity do not appreciably affect maintenance and overhaul time, the effects of the factors (a), (b), and (c) in combination with the scheduling difficulties during limited periods will reduce the maximum annual utilization of the SST's in relation to that of competing long-range subsonic aircraft to about 75 percent for Mach 2 and about 70 percent for Mach 3 aircraft.
- that, if the effects of kinetic heating and design complexity are appreciable, the relative annual utilization of the SST's will be reduced further to about ⅔ for Mach 2 and to some 55 percent for Mach 3 SST's.

As we have so little knowledge in particular about the long-term effects of kinetic heating, I think it would be unsafe to count with higher relative utilization of the SST's, averaged over the entire service life of some 40,000 hours, than the last-mentioned figures.

2. This discussion was for SST's and subsonic aircraft operating on the same, direct long-range routes. However, the subsonic aircraft have a great advantage in that they can operate economically also on much shorter distances. This *"range flexibility"* has the following implications:

(a) The subsonic aircraft can make one or more *intermediate stops* on long routes, such as over the U.S. continent, and thus serve traffic demands on long, medium, and even short ranges at the same time. In order fully to grasp the importance of this, one has only to look at maps over the vast network of air routes covering the U.S., Europe and other continents. The intermediate-stop possibility tends obviously to improve *utilization* and *load factors*, as well as *availability*, i.e., the number of flights between city pairs among which passengers can choose.

The intermediate-stop market can be split up into two parts. One is intermediate-stop services between pairs of cities large enough to support direct SST flights, and the other is such services between pairs of cities, one or both of which are too small to support direct SST flights between them. For the former part, the number of intermediate-stop flights are likely to be somewhat reduced as a consequence of fast direct SST flights, but there will always remain a great amount of such services (by one or more operators) that some passengers will take advantage of, for instance because of suitable departure times.

The intermediate-stop market between city pairs too small to have supersonic connections is the most important part in this analysis, because it will remain inaccessible for SST's due to what could be called the *"straightest-way" principle*. This means that passengers living any-

where except in the vicinity of big cities with SST connections to (or close to) the destination, will in most cases prefer making two or more intermediate-stop flights rather than one "out-of-the-way," subsonic flight to the nearest city having SST connections to the destination. Just to mention one example, a person living in Louisville, Kentucky, who intends to fly to Los Angeles, would, unless Louisville has a direct supersonic service to L.A., prefer to fly to L.A. on subsonic aircraft, even if it involved one or two intermediate stops, rather than to fly to New York—i.e., in a "wrong" direction—and catch an SST there, which would cost more and probably not save any time.

It might be argued that there will be a continued trend towards more and more direct flights between large and even medium-size cities and that this will favor the supersonic services. This is undoubtedly true, but it should be observed that also the volume of intermediate-stop aviation will grow, although probably not equally fast. Another important aspect is the fact that in many cases the traffic demand between two cities might be sufficient to support one or at the most two direct services per day but no more. This is likely to be insufficient for economic operation of an SST, whereas it might well give a subsonic aircraft sufficient utilization, at least if the aircraft besides these few direct flights also make a number of other equally long or shorter flights to other communities, for instance in typical feeder-line service.

There is, obviously, a need for research to determine the total relative size of those portions of the "intermediate-stop", including the "straight-estway" markets, which are inaccessible for SST's. Pending such research, I would estimate that *at least 30 percent of the 2,000–5,000-mile market will be inaccessible for SST's.*

(b) Furthermore, the subsonic aircraft are superior also with regard to *feeder services with the same aircraft to and from the two ends of a long main route*, such as New York–Paris, for instance a route Chicago–New York–Paris–Frankfurt. This is attractive for the passengers flying the total distance, Chicago–Frankfurt, because they do not have to change aircraft. Contrary to this, if they fly supersonic on the main route, New York–Paris, they must use subsonic aircraft to N.Y. and from Paris and thus change aircraft twice, as the two "feeder legs" of the route are too short for supersonic flights. The overall load factor for all-subsonic operation will obviously benefit from passengers flying only on each of the three legs of the route.

It is true that the range flexibility of SST's can be improved by *variable sweep* of the wings, which would better their economy in subsonic flight. It should be remembered, however, ● that the productivity, the very basis also for the economy of such an SST, will be seriously impaired if it is to be used extensively on subsonic speeds, and ● that the operating cost for a variable-sweep SST flying on short ranges must anyhow be much higher than for subsonic aircraft because of the higher purchase cost of the SST as well as the excess weight being carried to resist the kinetic heating not existing at subsonic speeds.

3. Some types of *subsonic aircraft can fly nonstop on very long distances*, up to about 6,000 miles (and improvements well up to half of the circumference of the earth are in sight), whereas the first generation SST's will probably not be able to operate efficiently on longer routes than 4,000 miles. Besides their "range inflexibility" it must be regarded as one of the most serious drawbacks of the contemplated SST's that they are unable to operate efficiently on longer ranges where the time gain would indisputably be of appreciable value. Most passengers on routes such as Los Angles to Europe are likely to prefer one direct subsonic flight to two supersonic flights even if the latter alternative would yield a time gain of a few hours; such a small time gain would hardly compensate the tiring effect of being subjected twice, in a short period of time, to the inconveniences of supersonic flights.

On the other hand, the SST's are likely to be preferred, in most cases, on still longer routes, for instance England to Australia, where they would yield a more substantial gain in time over long-range subsonic jets, although usually at the expense of a greater number of flights. The market for such long ranges is, however, relatively small (Table 2).

4. Subsonic aircraft have inherently greater possibilities than SST's of obtaining high total payload factors by *supplementing passenger load with cargo* for the main reason that the "volume factor" is less critical than for the SST's. As pointed out above, this is beneficial for improving the payload, for instance by "mixed freight," whenever the passenger load factor is unsatisfactory. Over and above this, subsonic aircraft in intermediate-stop operation do not require full fuel load, which makes it possible to combine very high passenger load factors with a considerable amount of freight in the normal cargo compartment.

5. Because of the long-time effects of the kinetic heating—which are probably to a large extent unpredictable—it will be difficult, if at all possible, to foresee the economical and/or safe life of the structures and some of the systems of SST's. This means that, even if the manufacturer claims a service life about the same as for subsonic jetliners, for instance, 40,000 hours, *the SST operator will probably find it wise to amortize the purchase cost at an appreciably higher rate, say with some 15 percent per year instead of the about 10 percent* normal for subsonic aircraft. The difficulty or impossibility, also for reasons other than kinetic heating, to find purchasers of secondhand SST's would also support such a cautious amortization policy (see below).

6. Contrary to this, subsonic, first-line aircraft are often likely to enjoy a service life appreciably exceeding the life on which their "standard operating cost" is based, as has been the case with many piston aircraft (some DC-3's are reported to have attained service lives of about 80,000 hours). This might either justify a low amortization rate (i.e., below "standard") or enable the subsonic operator to make a profit when the aircraft are sold.

Furthermore, the SST's—as well as first-line subsonic aircraft—will be in *competition with a steadily increasing number of second-line aircraft.* Such aircraft are defined here as aircraft which have pronouncedly low operating costs either because they are of old types—such as piston aircraft, turboprops, and first

generation turbojets—which have been fully amortized by the first user, or because they have been purchased secondhand at a very low price in relation to the remaining service life. Even if the same fares are applied also for second-line subsonic aircraft, their low operating costs will be beneficial for their profitability.

Secondhand subsonic aircraft will also be used to an increasing extent for *low-fare charter operations*, in particular if a uniform fare level for scheduled operations is enforced. Such operations will, of course, decrease the portion of the long-range market available for direct competition between SST's and subsonic aircraft in scheduled services.

7. The effects of kinetic heating in combination with the complexity of the SST's will imply not only reduced utilization but also *increased cost for maintenance, overhaul, and inspections* as compared with subsonic aircraft.

8. Finally, it seem likely that the kinetic heating will result in *unforeseen major defects and repairs* on SST airframes more often than for subsonic jets. Besides high repair costs, the SST's might therefore have to be taken out of service more often, and probably for longer periods, than subsonic jets, which would lead to impaired utilization and a greater demand for reserve SST's. Compared with subsonic aircraft, the loss in revenue because of removal from service of an SST will be greater bacause of its higher productivity.

The Effects of Successive Introduction of Radically Improved Types of Subsonic Aircraft and SST's Assuming Equal Fares

The above analysis was for the unrealistic "static" case where neither the SST's nor the competing subsonic aircraft are improved compared with the level when the first SST was introduced. The real development will, however, be pronouncedly "dynamic" in that future types of both subsonic aircraft and SST's—if they are to survive—will display very substantial improvements. It is, therefore, most important to try to estimate, for several decades ahead, the relative possibilities of creating radically improved types of SST's and subsonic aircraft and the effect of the developments on economy.

It can be discussed indefinitely whether SST's or subsonic aircraft have the greatest theoretical potentialities with regard to future aeronautical improvements. The very fact that the SST represents a completely new category of flying machine might by itself give better hopes for spectacular future advances. It has also been stated that, if a certain percentage improvement in various parameters, such as fuel consumption and structure weight, can be achieved, that would yield a greater relative improvement in operating cost for the SST than for subsonic aircraft.[38] On the other hand, probably the most important progress conceivable, that of laminar flow control (LFC), is likely to give a greater reduction in drag and operating cost for subsonic than for supersonic aircraft, because the wave drag of the latter is not primarily affected by LFC.

Such comparisons are, however, of hardly more than academic interest, unless they are closely combined with estimations of the rate at which new types of SST's and subsonic airliners, respectively, can—or will—be developed.

In this respect the subsonic line of development is much superior, for the following main reasons:

● The total transport market in passenger-miles for subsonic aircraft, applying design principles that are used by long-range aircraft, competing with SST's, is much greater than the market that the SST's can possibly capture.

● The production in passenger-miles during the service life in flight hours of an SST is increased over that of subsonic aircraft in direct proportion to its higher block speed, assuming the same number of passengers per aircraft.

Regarding the size of the subsonic transport market that is relevant with regard to aeronautical improvements of significance in comparison with super-sonic developments, it is rather obvious that one should take into account not only the range market that is feasible for SST's—i.e., about 2,000–5,000 miles—but also the major portion of the market for all shorter ranges. The reason for this is that aeronautical improvements—for instance with respect to V/STOL, noise, LFC, new configurations or structural design principles—which are intro-duced on a new aircraft type, primarily intended for a portion of the whole range area under consideration, is in most cases also feasible for other ranges. Just to mention one example, the engine mounting à la Caravelle has been adopted both for medium- and long-range, as well as for short-haul aircraft.

It is believed that a range of about 150 or at the very most 250 miles is a repre-sentative lower limit for the relevant total "new-design-principle" subsonic transport market, because only below this approximate limit are design principles likely to be applied, which to some extent might not be applicable for longer-range aircraft. The subsonic-range market in this respect should, of course, also include charter and freight—mixed freight as well as all-cargo—transportation.

The ratio between the subsonic and supersonic transport markets in passenger miles for scheduled operation, considering the whole range area from 250 to 5,000 miles, can be obtained from Table 2 together with estimates about the encroachment of SST's in the two range brackets 1,000–2,000 and 2,000–5,000 miles. Assuming that the intermediate-stop and straightest-way factors make 30 percent of these two range brackets inaccessible for SST's, that the SST can encroach by 10 percent upon the remaining 70 percent on ranges from 1,000 to 2,000 miles and by 50 percent on ranges from 2,000 to 5,000 miles, it is found that the ratio between the relevant subsonic and supersonic markets is about 9 for alternative B in Table 2 and about 8 if the present range distribution will be retained also in the future, if it is furthermore assumed that subsonic charter and freight transportation will add to scheduled subsonic aviation by 20 percent. The market ratio will be decreased to about 5 and 6 for the present and Alt. B distributions, respectively, if it is assumed that 20 percent of the accessible market is taken by SST's on ranges from 1,000 to 2,000 miles and as much as $\frac{2}{3}$ on ranges from 2,000 to 5,000 miles. In view of the discussion above with regard to the questionable to moderate time/comfort gains by flying SST's together with longer average airport distances for such aircraft in the seventies and eighties, I do believe that the encroachment figures 10 and 50 percent are more realistic than the figures 20 percent and $\frac{2}{3}$. It thus appears that a market ratio of 6 is a rather conservative estimate.

The lower of the two SST encroachment alternatives would yield fleets of about 120 Mach 2 and 100 Mach 3 100 passenger SST's (with due consideration of the low annual utilization of SST's assumed in this paper), instead of the fleet sizes of about 250 and 200 SST's respectively, estimated for instance by Convair.[5]

With regard to the average weighted ratio between supersonic and subsonic block speeds, it must be taken into account that a great proportion of commercial subsonic aviation on ranges above about 250 miles will not have higher Mach numbers than about 0.5 even in the seventies and eighties. A conservative ratio between average weighted block speeds for Mach 2 SST's and subsonic aircraft is believed to be about 2.4.

It thus appears that the "fleet ratio," i.e., the ratio between the number of subsonic and supersonic fleets of aircraft (a fleet being defined as a number of aircraft of one and the same basic design, thus excluding modifications), required for meeting the respective transport demands, will fall anywhere between 12 and 20, for the Mach 2 case, assuming the same total service life in hours for each aircraft, the same number of aircraft in each fleet, and the same average number of passengers per aircraft. For the Mach 3 case, the fleet ratio will fall between about 16 and 26.

In order to give a visual impression of the significance of the fleet ratio, Fig. 23 has been prepared, which also includes the simple relationship for this ratio.

In practice, all the subsonic fleets will not be composed of aircraft embodying widely different design principles; as has been the case up to now, rather similar basic types are still likely to be developed by competing manufacturers. This is, however, evidently a great advantage, as it reduces the risks connected with introduction of a radically new feature and also usually results in the best type being produced in the greatest number. These are "luxuries" which the SST development will be able to enjoy only at the expense of exceedingly small production series, far below the break-even level, at an acceptable purchase price.

Figure 24 illustrates a possible rate of development of new subsonic aircraft types, to which different design principles are applied, from 1970 and onwards. In this example it is assumed that the new design principles appear at a frequency of one every third year and that each time, on the average, three manufacturers apply the same fundamental design principle for the basic types.† Assuming, furthermore, that the subsonic aircraft will, on the average, have a service life some 20 percent longer than the SST's, mainly due to extended secondhand use, and that the number of aircraft in each subsonic fleet is the same as in a fleet of SST's, *new types of Mach 2 SST's can only be produced at a rate of, at the most, one in 10 years.*

This also presumes that the market for one SST type is just about big enough for attaining break-even production at an acceptable aircraft price, an assumption that is probably too optimistic at least for the first generation of SST's, even if only one type were built. If one European and one American type are

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† Thus one new aircraft type is, on the average, assumed to appear every year. After the war over 30 new types, intended for commercial operation on medium and long ranges, have been developed, an average rate of about 1⅔ per year.
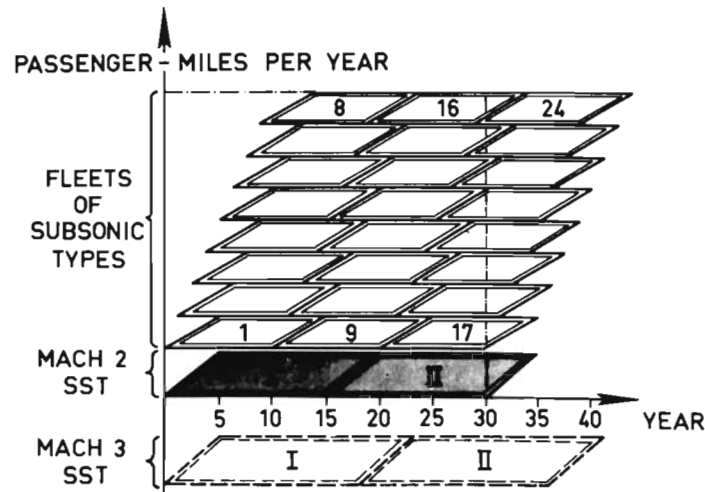
Fig. 23. The "fleet ratio"—i.e., the ratio between the number of subsonic (subscript u) and supersonic (subscript s) fleets of aircraft required for meeting the respective transport demands (a fleet being defined as a number of aircraft of one and the same basic design), is

$$\frac{N_u}{N_s} = \frac{M_u}{M_s} \cdot \frac{n_s}{n_u} \cdot \frac{T_s}{T_u} \cdot \frac{S_s}{S_u} \cdot \frac{L_s}{L_u} \cdot \frac{V_s}{V_u}$$

where M = size of the market in passenger-miles
n = average number of aircraft in each fleet
S = average number of seats per aircraft
L = average passenger load factor
T = average service life of each aircraft in hours
V = block speed

In the figure, each fleet is represented by a parallelogram assuming a five-year delivery schedule, and, for simplicity, the same rate of withdrawal from service.

As explained in the text, the subsonic market, for which new aircraft designs can be developed, is at least six times greater than the corresponding supersonic market. The figure illustrates that 24 fleets of different subsonic types are required, if two subsequent types of Mach 2 SST's are developed to meet the supersonic market, assuming a ratio V_s/V_u of 2.4 and that n, S, L, and T are the same. It is also assumed that, on the average, the annual utilization of the SST's is $\frac{2}{3}$ of that of subsonic aircraft, but this does not influence the ratio between the fleets.

The big Mach 3 SST parallelograms below the abscissa, representing two fleets of the same size, n, as the Mach 2 and subsonic fleets, indicate that the productive capacity of each Mach 3 fleet is about 35 percent higher than that of Mach 2 fleets. Thus, if the supersonic transport market is just big enough for one fleet of Mach 2 SST's sufficient for break-even production, the market would be too small for break-even production of Mach 3 SST's.

The figure is, of course, schematic. The successive expansion of the market is not taken into account, which, however, does not alter the basic relationships.
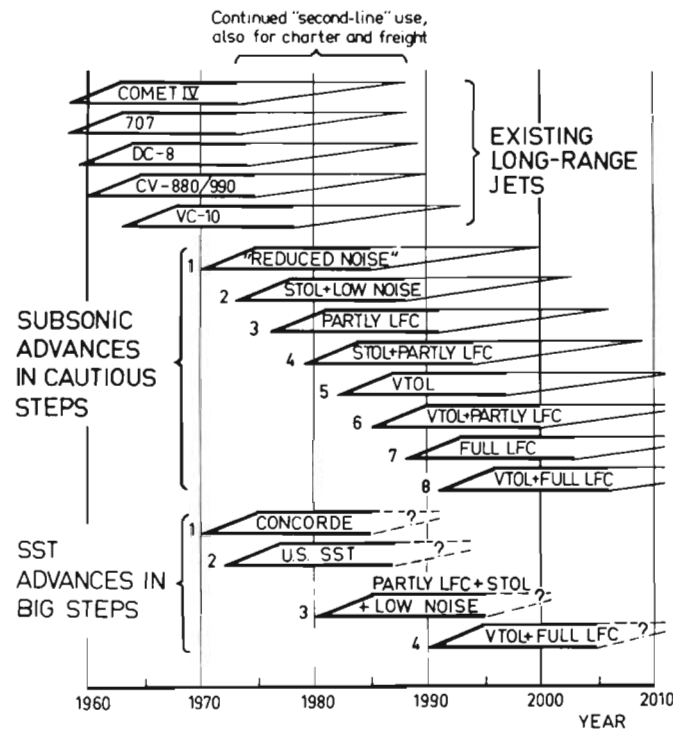
Fig. 24. Illustrates a possible rate of development of new subsonic aircraft types to which radically new design principles are applied. It is assumed that each design principle, Nos. 1, 2, 3, etc., for subsonic aircraft is, on the average, applied to three different basic types. On the basis of Fig. 23, and if it is assumed that the subsonic aircraft will, on the average, have 20 percent longer service life than SST's, new types of SST's can only be produced at an average rate of one in every 10 years. The figures for different design principles are, of course, schematic. The heavy-lined portions are intended to indicate the possibility of service times exceeding the normal amortization period of 10 years, and the fine-lined portions the possibility of continued "second-line" use for a decreasing part of the fleets (especially of the latest modifications of the original basic types). For the SST's, the question marks indicate the difficulties to use the aircraft for "second-line" purposes.

The specific aeronautical advances indicated in the design-principle figures are merely examples and should not be thought of as a forecast of the sequence or pace with which steps in development will take place. In particular, step 1 for "Reduced Noise" might be taken as a major advancement in engine design, resulting in both lower noise and fuel consumption; noise suppression will probably not come about as a sudden change.

The comparative figures for some existing long-range aircraft should rightly have been supplemented with all other subsonic aircraft types, employing design principles adaptable for long-range aircraft.

produced about simultaneously, they will have to share a market which would probably correspond to less than 150 SST's.

Anyhow, the third and the fourth types of SST's can hardly appear earlier than around 1980 and 1990, respectively, as indicated in Fig. 24.

For a realistic appraisal of the difficulties that the SST enterprise will encounter, it should also be observed that *the secondhand market for SST's will always be very poor*, for the following four reasons:

- SST's which are "outmoded" by a new type with lower operating cost or radically better performance will not be attractive, either for established SST operators or for newcomers in the field.
- Because of the fact that SST's require a high degree of specialized and qualified techniques, with regard to operation, maintenance, etc., airlines, which have previously decided to remain subsonic, will be particularly reluctant to change that decision by acquiring, even at low cost, SST's of an old type that does not represent the latest improvements in such techniques.
- Use of SST's for charter and pure freight operation does not seem feasible.
- Any airlines, supersonic or subsonic, will be hesitant to buy, even at low cost, SST's which have had an appreciable service time, say, some 10,000 to 20,000 hours, because there is reason to fear that—even if the SST's offered have so far displayed good repair-rate records—the kinetic heating might in continued service give rise to a steadily increasing amount of trouble.

In all these respects, the situation is entirely different from that when jets replaced—and are still replacing—piston aircraft or turboprops, first because such older subsonic aircraft are often attractive secondhand propositions, and secondly because subsonic jets do not pose any new operational or technical problems. This great difference between the secondhand markets for subsonic aircraft and SST's will also apply in the future.

On the basis of these observations, it seems evident that either any one or a combination of the following developments will occur:

(a) If, in spite of all, new SST types are developed at an appreciably higher rate than about one in 10 years, for instance a basically new SST about every fifth year, but the production series are limited, by foresightful planning, with due regard to the factual supersonic market, as well as to the normal demands of service lives for each aircraft of some 30,000 to 40,000 hours, the series will be very small indeed. Unless prohibitively high prices are to be applied, implying unacceptably high operating costs, the series will be far from break-even magnitude and the SST manufacturers will suffer great losses.

(b) If new SST types are developed at such a too high rate and the manufacturers succeed—as a result of skilled sales campaigns—in selling the aircraft, in quantities sufficient for break-even production, the SST operators will find themselves in a rather difficult dilemma:

- In the first place, they might try to sell their "old" SST's—thus long before they have been fully amortized—in order not to be outmoded by competi-

tors buying SST's of the newest type. Such sales will, however, hardly be possible without great losses, because of the poor secondhand SST market. The remaining alternative for an SST operator are about as gloomy:

● To scrap the old SST's, implying great losses.
● To fly both the old and new type of SST's. Having two basically different SST types would imply increased operating costs, and would if this policy is followed by most SST operators, result in an "oversaturation" of the supersonic transport market and, consequently, uneconomical average load factors.
● To refuse to buy the new SST and continue operation with the old ones until their initial costs have been fully amortized. Depending on the amortization policy applied, this would take some 8 to 12 years. During the latter part of this period, the old SST's will probably lose their passenger appeal because they will be in competition not only with the SST's of the much improved new type bought by other SST operators, but also with new and improved subsonic jets.

(c) If new SST types are not developed more often than at the most once in every 10 years—the most sensible policy also because it would give reasonable time for amortization—then *all* the operators using the first generation SST's will find themselves in increasingly severe competition with subsonic aircraft of a number of new types, many of which are likely to be radically improved with respect to operating cost and/or ability to use centrally located airports.

This should be clear from Fig. 24 and is illustrated by Fig. 25, which exemplifies the situation that *the first generation SST's* will confront more and more often in the seventies and in the eighties. The figure is a time/comfort comparison between a Mach 2.2 SST and a Mach 0.90 airliner operating on 2,500-mile ranges and using airports 20 and 7.5 miles from city centers, respectively. There can be little doubt that practically all passengers would prefer the subsonic service at equal fares, both because the net time gain of about an hour can hardly outweight 1.2 hours longer ground time, and because of the longer and more uncomfortable "fastened" times and the other inconveniences of the supersonic flight.

This example might suffice to indicate that the first generation SST's rather soon are likely to lose much of their initial passenger appeal in comparison with new, improved types of subsonic airliners.

The situation for new types of SST's appearing in the eighties and nineties might be even worse, as then extremely advanced subsonic airliners with low operating cost will probably offer still more intense competition (Fig. 24).

It should thus be evident that, whatever alternative, (a), (b), or (c) will be followed, the result will be an increasingly embarrassing economic situation for the SST operators and manufacturers even if a uniform fare structure can be upheld.

Besides these purely economic aspects, a premature introduction of SST's would also affect their *safety and reliability:* The fact that new basic types of SST's cannot—without disastrous economic consequences—be developed at

even nearly the same rate as new types of competing subsonic aircraft, means that, in order to reasonably well keep in pace with subsonic advances, *much bigger technical "development steps" must be taken for each new SST type*, for instance application of STOL or VTOL, LFC and efficient noise-suppression techniques at the same time (Fig. 24).

Contrary to this, the development of subsonic long-range aircraft can proceed with incorporating only one radically new design principle at a time, and each such development step can be more safely realized by several manufacturers making different basic designs according to each design principle.

As is rather evident (and discussed in detail in Parts II and III of this paper), it is inherently more difficult to ascertain a certain high level of safety for a new aircraft type the greater the number of radical and unproven features incorporated. This is pointed out here because, if new types of SST's have a lower level of safety—and reliability—than subsonic aircraft, and that results in fatal accidents and/or inferior regularity, that would have serious implications with regard to passenger appeal and thus for the economy of SST's.
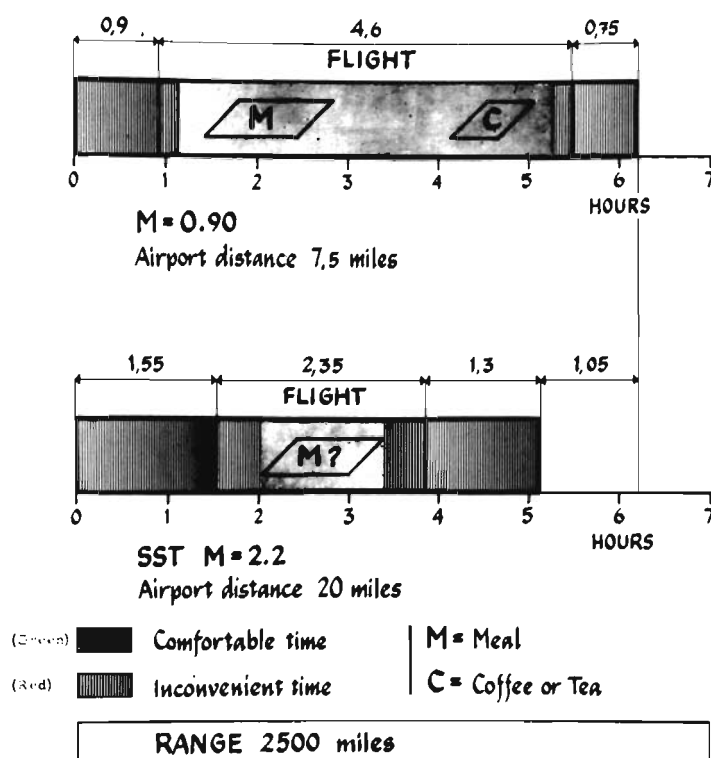

Fig. 25. Comparison of comfort and total journey time between a subsonic (M = 0.9) aircraft and a Mach 2.2 SST. It is assumed that the former by virtue of VTOL or STOL properties can use airports at distances of 7.5 miles from the city center, whereas the SST's might require long runways only available in airports 20 miles from city centers.

Summary of the Analysis of the Economy of SST's in Comparison with Competing Subsonic Aircraft Considering also Fare Differentials

It should be clear from the above survey that the factors affecting the economy and passenger appeal of SST's and competing subsonic aircraft are, indeed, legion; to base a judgment of the profitability of SST's merely on the assumption, however well-supported, that their "standard operating cost" will be about the same as for subsonic aircraft, would be hazardous and fallacious.

It is, therefore, difficult but important to simultaneously bear in mind all the many relevant factors and their implications to obtain a comprehensive appraisal of the situation. This might be facilitated by splitting up the comparison into four main phases, A–D, within which the statements made in the two previous sections are briefly summarized. The phases are schematically illustrated by Fig. 26, indicating the probable development of operating cost, income, and profit for supersonic and competing subsonic operations.

Phase A: The Starting Point for the Comparison. This is appropriately the assumptions:

- that the first generation SST's at the time of introduction have the same "standard operating cost" as contemporary competing subsonic aircraft, which is probably an optimistic assumption for the SST's, in particular if the manufacturers are not subsidized also with regard to production and thus have to charge the high price required to break even at the production volume corresponding to the possible demand,
- that the same fares are applied,
- that the passenger preference is about the same for SST's as for subsonic aircraft competing on the same routes,
- that there is no overcapacity (or equal overcapacity), and
- that, consequently, the load factors are about the same.

Phase B: "Static" Case—i.e., Stagnated Aeronautical Progress. Limiting then, the comparison in the first place to the fictitious, "static" case, where no improvements, either in subsonic or supersonic development, are made after the introduction of the first SST, it is concluded (the symbols $B1$, $B2$, etc., referring to Fig. 26):

($B1$) that the average annual utilization of the SST's can hardly amount to more than $3/4$ (or less for Mach 3 SST's) of that of subsonic aircraft, if the effects of kinetic heating can be disregarded, otherwise at the most about $2/3$;

($B2$) that the greater complexity and the, partly unpredictable, effects of kinetic heating will imply increased costs for maintenance, overhaul, inspections, and major repairs for the SST's;

($B3$) that the SST operators, for the same reasons, will be inclined to adopt a higher amortization rate than will be normal for competing "first-line" subsonic aircraft;

($B4$) that in particular for "second-line" subsonic aircraft the amortization cost will often be very low, which reduces the average level of operating costs for subsonic aircraft competing with SST's;

(*B*5) that the "range flexibility" of subsonic aircraft—in particular with regard to intermediate-stop services—will be beneficial for passenger load factors, and

(*B*6) that the subsonic aircraft have better possibilities of increasing the revenues by supplementary cargo, which contributes to better overall payload factors.

The conclusion from the phases A and B is that the profitability of SST's will be much less than for competing subsonic aircraft, even in the fictitious, "static" case of stagnated aeronautical progress.
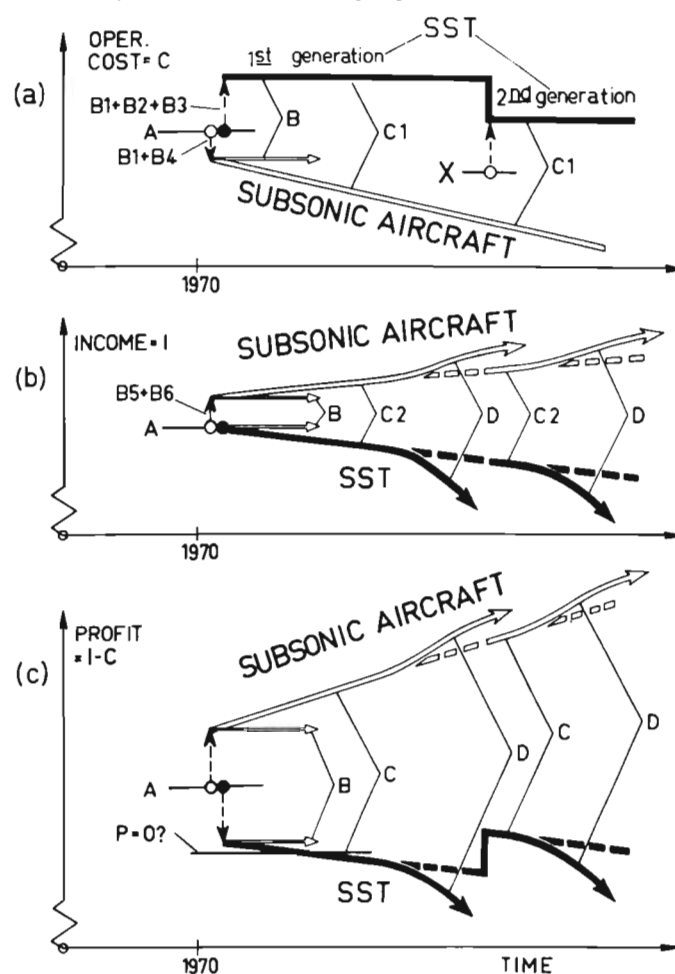
Fig. 26.   Schematic illustration of the "instability" of the economic conditions for supersonic aviation due to competition with successively improved subsonic aircraft. The symbols, *A*, *B*, *B*1, *B*2, etc., are explained in the text. The figure does not indicate the temporarily improved profitability that the SST's might enjoy during the first few "sensation years." The level for zero profitability shown in Fig. 26*c* does not, of course, indicate an exact level or time of occurrence, it is merely intended to show that there is a level below which the SST operation will suffer losses.

PHASE C: "DYNAMIC" CASE; AERONAUTICAL PROGRESS TAKEN INTO ACCOUNT, BUT EQUAL FARES ASSUMED. New types of subsonic aircraft can be developed at an at least 10, probably 15 to 20 times higher rate than the one at which new types of SST's can be put on the market, if the number of SST's of each type is not to be so small as to necessitate completely prohibitive purchase prices at break-even production. This implies that aeronautical improvements, for instance yielding lower operating costs, will be realized more rapidly and with less risks of failure in the subsonic than in the supersonic field. Assuming, thus, that new SST's are not introduced more frequently than would be justified on pure economical considerations, it seems inevitable:

(C1) that the difference in operating cost between SST's and competing subsonic aircraft will grow more or less indefinitely over and above the difference that would apply in the "static" case, B Fig. 26(a) and

(C2) that the difference in average payload factors, and thus in revenue, between the subsonic aircraft and SST's will also continue to grow, Fig. 26(b). The reason for this is that there would no longer be a balance in appeal but a growing passenger preference for the new subsonic types of airliners, because they would be successively improved not only in comfort (spaciousness, low cabin-noise levels, etc.) but also with regard to substantial reductions in ground times (by virtue of STOL or VTOL properties and reduced external noise).

On the other hand, if it is attempted, in spite of the limited supersonic market, to develop basically new SST types at nearly the same rate as new subsonic types are developed, the economic consequences would be even worse: either great losses to the SST manufacturers unable to sell the new types in sufficient numbers, or losses to the SST operators because they must either scrap their older SST's before they are amortized or sell them at a loss on the very poor secondhand market for SST's.

PHASE D: "DYNAMIC" CASE; APPLICATION OF DIFFERENT FARES. In judging the real "dynamic" development it is, however, necessary to take into account that it will probably not be possible in the long run to uphold the same fare level for subsonic as for supersonic aircraft: The increasing difference in operating cost between the two categories and the widening "span" between subsonic fares and subsonic seat-mile costs are bound to "break through" in one way or another. This might begin with low-fare charter operation and proceed with "second-line" subsonic long-range aircraft. However, for reasons of competition with the latter category, operators of "first-line" subsonic aircraft of new types —the operating cost of which is likely to be successively reduced, for instance by LFC—are likely to be increasingly unwilling to maintain too high fares, as they would gain much more by reducing the fares and thereby expand the market.

Retaining unnecessarily high subsonic fares would also meet increasing opposition from the general public. In fact, a veritable "fare war" appears to be the most probably course of events.

The result of appreciably higher fares for SST's than for subsonic aircraft serving the same routes would obviously be a rapid decrease in the SST load factors. The growth of the difference in profitability between SST's and subsonic

aircraft would thus accelerate, as is illustrated by the diverging arrows in Figs. 26(b) and (c).

It is believed that in particular this last phase of the probable course of events supports the observations made in the beginning of this chapter that the economy of SST operation possesses features of an "instability problem" and that the reason for this lies in the coexistence of subsonic aviation. This observation can now be more accurately formulated:

As long as SST's cannot be developed which have so much lower "standard operating costs" than contemporary subsonic long-range aircraft as to offset the effects of all the "static" and "dynamic" factors which favor the subsonic and/or disfavor the supersonic aircraft, it will not be possible to find either any magnitude, large or small, of the volume of supersonic aviation, or any fare level, high or low, at which economic "equilibrium" between supply and demand will occur, yielding a profit to both manufacturers and operators of SST's; either one or both of the two industries are bound to suffer great losses and the losses will grow with the number of SST's produced.

Conditions for Successful Supersonic Aviation

To express quantitatively the conditions for supersonic aviation to permanently attain a stable and profitable status at the side of subsonic aviation, is, of course, very difficult. It depends upon a great number of intangible factors, and also upon when the SST's are introduced—i.e., whether or not they are to appear before the progress in subsonic aviation has begun to stagnate. If SST's are introduced in the early seventies, it should follow from the analysis above that, to be reasonably certain of lasting profitability, the following, "pure" economic condition must essentially be complied with:

1. The first generation SST's must, in order to compensate for the anticipated spectacular advances in subsonic aviation, have a considerably lower actual direct *operating cost*—probably in the region of 20 percent lower—than modern subsonic long-range aircraft in operation when the first SST is introduced, and this operating cost should be based upon (a) merely $\frac{1}{2}$ to $\frac{2}{3}$ of the average utilization of competing subsonic aircraft, and, (b) on an appreciably more cautious amortization policy. This will imply that the "standard operating cost" —based on the same amortization rate and nearly the same utilization as subsonic aircraft—has to fall below the subsonic level by an even greater percentage.

This is a necessary but not a sufficient condition for successful supersonic aviation. Three other necessary conditions are:

2. It must be ascertained, in advance, that *sonic booms* will not cause appreciable operative restrictions due to opposition‡ in any countries which will be overflown if SST's fly on most long-range air routes existing today and anticipated in the future; obviously, any appreciable geographical restrictions or

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‡ In judging the probable opposition, it would be fallacious to consider only the theoretical, or mean, values of boom overpressures. The inevitable great scatter in boom intensities, including "super-bangs" due to unsteady flight or to atmospheric conditions (during supersonic acceleration and climb as well as en route), must be taken into account, because occurrences of above-mean overpressures will be sufficiently frequent to largely govern public response. (See Part III.)

deviations from the flight-altitude profile, optimized for fuel consumption, would greatly hamper the use and economy of the SST's.

3. Sufficient knowledge about physiological and genetic hazards of *cosmic radiation* at the supersonic flight altitudes must have been achieved, so that the SST passengers can be definitely assured that the hazards are negligible. If this is not ascertained, many passengers will prefer to fly at subsonic speeds for this reason alone.

4. The SST's, and their operation, must have a *level of safety* that is *at least equal* to that of scheduled subsonic aviation, and this must to a great extent be *proven in advance* on the basis of statistical methods and adequate laboratory testing. To comply with these requirements is indeed extremely difficult, as will follow from Part III of this paper. However, if they are not complied with, the adverse consequences with regard to passenger confidence will be more serious than for new subsonic aircraft types, because many SST passengers would be likely to combine, mentally, occurrences of SST accidents (inevitable as with any type of aircraft) with the sensations or inconveniences of SST flights, such as the high accelerations and decelerations, the steep floor angles in climb, and landing, and comparatively high interior noise level, in particular during acceleration periods. Only quite convincing and scientifically proven statements to the effect that the statistical risk of flying with an SST is not greater than for a subsonic aircraft can, at least partly, offset the impact on passenger confidence that SST accidents will have. This aspect is particularly important.

- because experience shows that most new types of aircraft have a "learning period" of many years, during which the accident and incident rates are higher than the average, although it might eventually fall down to the average, and
- because the accident and incident rates are likely to be higher and the "learning period" longer for a new SST type than for a subsonic type (as a consequence of its complexity in general, its many radically new features and the effects of kinetic heating), even if the "potential" safety level of the "debugged" SST were the same as for subsonic aircraft.

Conditions (2), (3), and (4) will be dealt with in some detail in the subsequent Parts of this paper, but they must be considered also in analyses of the economy of supersonic aviation. With regard to the "pure" economic condition (1), *it does not seem possible, at the present and foreseeable state of the art, to attain the very low operating cost required for lasting profitability of the SST's as long as substantial improvements of subsonic aircraft remain to be made.*

This conclusion would have to be modified only if and when such advances of a radical nature are made in supersonic technology—for instance with regard to light structures or reductions in fuel consumption—*that are not about equally applicable and efficient for subsonic aircraft*; if they are, the competitive situation vis-à-vis subsonic jets would not be changed.

Thus, the most rational policy to adopt would obviously be postponement of developing any supersonic transports until most of the conceivable remaining improvements in subsonic aviation have been fully explored.

The Short- and Long-Term Consequences of a Premature Introduction of Supersonic Aviation

In view of the fact that decisions to develop prototypes of one or more SST projects appear imminent, it is important to try to foresee the short- and long-term consequences of such decisions being followed by series production of SST's and their introduction into commercial use before the four conditions specified above are complied with.

Parallels are often drawn with the course of events when the turbojets were offered on the market: When one major airline decided to re-equip with jets, most other airlines were forced to do likewise for reasons of competition. It seems to be generally contended that the same thing will happen with the SST's more or less regardless of their profitability and unsolved technical problems; supersonic aviation is considered inevitable whatever the consequences.

There are, however, some important differences between the present issue of SST's and that of the jets a few years ago:

1. Whereas the jets offered very substantial and highly desirable time savings over the piston aircraft, the *further reductions in flight time by SST's*, although substantial on long routes, *will be of less value to the passengers*, because the time reduction will approach, or even encroach upon, the "enjoyable time" on board and because the speed will approach the "worthwhile cutoff speed band" (Fig. 12).

2. Whereas *the jets offered great advantages over piston aircraft in two respects— time and comfort*—the improvement in comfort, by virtue of very low cabin noise and practically no vibrations, being considered by many as equally important—*the SST's will only offer an advantage in one respect, time, and this gain will be counteracted by a definite loss in comfort* as specified above. As, furthermore, the time reduction is less needed than with the jet, the net time/comfort gain for the SST passenger will at best be moderate and it might often be questionable or even negative.

3. Whereas the subsonic jets are basically cheaper to operate than piston aircraft, the SST's are likely to have appreciably greater operating costs than contemporary subsonic jets

4. Whereas the subsonic jets technically completely "outmoded" the piston aircraft—to the extent that no more piston aircraft for scheduled operation will be produced—the SST's will not be able to do likewise with the subsonic jets; on the contrary, such aircraft will continue to be built indefinitely and radical improvements will be made during many decades ahead.

It thus seems probable that *history will not repeat itself with regard to another hectic race*—encompassing *all* major airlines—for the latest speed jump now in sight, that of the SST's.

In another way, however, history will repeat itself: The switchover to jets inflicted the airlines with great financial losses in spite of the very pronounced public appeal of the jets and their low operating costs. This was not only because too many jets were bought but also because of remaining competition with piston aircraft, perfectly usable for many years ahead. This economic lesson is

likely to be experienced again, but in a much more aggravated way for the reasons specified above, in particular because *the SST's will meet a steadily increasing, instead of a fading, competition with the slower category of aircraft they try to surpass.*

The consequences of this were discussed above in a general way and with emphasis on radically new types of subsonic aircraft being continuously introduced. Now an attempt will be made to visualize in some detail *what will happen during the first few years* after production SST's are offered on the market, say, in the early seventies, in the first place disregarding introduction of new subsonic types.

Most likely some leading airlines in the SST-manufacturing countries will order SST's either before or soon after the first prototype has flown, provided, of course, that the purchase price is compatible with operating costs that are regarded competitive with that of subsonic aircraft. This calls for fairly big series of some 200 SST's of one and the same basic type, whereas *the initial orders can hardly amount to more than a few dozen SST's.*

Either one of two alternative courses of event is then likely to occur:

Alternative A. One is that practically *no other airlines will order SST's* until and unless:

- the "initial SST operators" have had a considerable financial success, based, *inter alia*, on such a strong public preference for flying supersonic that the demand is likely to be sufficient also for additional SST operators,
- the experience has clearly indicated that public reaction to sonic-boom disturbances is so weak that appreciable operative restrictions are very unlikely to be enforced by any governments even if the frequency and worldwide extension of supersonic flights is greatly increased,
- the experience has also shown either that there has been no appreciable tendency on behalf of passengers to prefer subsonic flying for fear of cosmic radiation or that any such tendency has been successfully counteracted by indisputable evidence that the fear is unjustified, and,
- the safety record with the SST's has been such that there is no obvious reason to fear that their safety level might be inferior to that of subsonic aircraft.

The minimum time for acquiring adequate knowledge in all these respects is probably about five years. This *"experience period"* will thus take us to the middle or latter half of the seventies. Even if it is assumed that the experience gained is sufficiently positive in all the four respects, *the SST manufacturers* would be put in a most difficult position as they would have to stop production for several years while waiting for additional orders. This will be expensive and the losses will be enormous if no or only small additional orders are obtained after the "experience period" has elapsed.

In this alternative, *the initial SST operators* might well have considerable success during the first years (provided, of course, that the sonic-boom reactions are not too severe) because a great many passengers will like to fly by SST's, not only for reasons of time gain, but also out of curiosity, for the sensation of

it and for gaining comparative experience with subsonic aircraft. Thus, there might, during these first "sensation years," be a much greater demand than supply of supersonic services.

There will, however, from the very beginning be severe competition with the subsonic long-range operators, who will do their utmost to persuade passengers to continue to fly subsonic. To this end, these operators can, for instance, refer to well-established safety records, to proven reliability, and to superior "subsonic comfort," and they are likely to still more improve the comfort in many respects. Their position has probably also been strengthened by acquisition of some of the subsonic airliners at low prices which the SST operators had to sell when they reequipped with SST's.

Furthermore, the question of a non-uniform fare level will probably be acute at an early stage, partly as a result of the increase in subsonic transport capacity. It is, in fact, difficult to see how a joint interest and pressure from both the subsonic operators and the general public to reduce subsonic fares below the SST level can be withstood for very long. If an appreciable fare differential is applied, that is likely to critically reduce the load factors of the SST's, in spite of their small number in this alternative and continued profitable SST operation would be questionable. In view of this, the subsonic operators will probably decide not to order any SST's.

If, on the other hand, equal fares are enforced, the lower actual operating costs for the subsonic airlines will enable them to sharpen the competition with the SST's by improvements in comfort. The initial success of the SST operators is thus likely to fade after the first "sensation years." It seems probable also in this case that only few, if any, of the subsonic operators will order SST's after the "experience period" has elapsed.

Alternative B. The other alternative development of events is that *a number of major airlines will, for reasons of competition, order SST's soon after the orders from the initial SST airlines.* It seems, however, unlikely that many of the medium-sized and smaller airlines will follow suit, in the first place because it will be more difficult for them to produce the large capital required for buying SST's and also because they will easily get in unfavorable positions in the pooling agreements or mergers that will probably be made between SST operators due to the high productivity (small fleets) of SST's.

In this alternative, the number of SST's ordered in the first "round" will, anyhow, be much greater than in Alternative *A*, but it will probably still be far from the magnitude required for *the SST manufacturers* to break even at acceptable purchase prices. It seems reasonable to assume that a total of at most 50 to 75 SST's will be sold, possibly to be divided between one European and one U.S. type. The prospects for the manufacturers thus seem rather gloomy, unless they get substantial orders in a "second round" within a few years.

With regard to the *SST operators*, the immediate effect of their acquiring a total of some 60 SST's, is that they must dispose of an even greater number of subsonic jets than in Alternative *A* to operators who have tentatively decided to remain subsonic. The consequences of the resulting overcapacity in subsonic

services will be threefold: The secondhand prices of these subsonic aircraft must
be set very low, there will be an even more severe competition from the subsonic
operators than in Alternative A and these operators will, on the average, enjoy
reduced operating costs because of the low prices of their secondhand jets.

Thus it will be even more difficult than in Alternative A to uphold a uniform
fare level, and, again, an appreciable fare differential would be disastrous for
the SST operators. Alternatively, subsonic operators who break out of the
international fare agreements still in force and apply the low fares possible with
cheaply acquired equipment will prosper, as will charter operators, thus reducing
the uniform-fare market.

Considering, finally, that the initial success of the SST operations during the
first one or two "sensation years" will be less pronounced because of the greater
supply of supersonic services, it appears that Alternative B will be even worse
for the SST operators than Alternative A. Consequently, it seems improbable
that many of the operators, who tentatively decided to remain subsonic, will
order SST's at a later stage. The SST manufacturers will thus also suffer losses,
although not quite as great as in Alternative A.

To sum up—and disregarding the possibility of supersonic aviation being
heavily subsidized—the insoluble dilemma that the joint family of SST manu-
facturers and operators will find itself in is:

- that it is necessary for the manufacturers that most long-range operators
  of the world should order SST's so that break-even production, at reason-
  able selling price, can be exceeded,
- that, while it is necessary for the initial SST operators to acquire the SST's
  at such large-production price, it is at the same time necessary for them
  to stay practically alone in the market in order to meet competition from
  as few supersonic newcomers as possible, this being the only way in which
  they can retain high SST load factors, and thereby avoid heavy losses also
  after the first few "sensation years".

There might, of course, be different opinions about whether or not the course
of events in about the first five years of SST operation will be quite as unsuccess-
ful for the supersonic enterprise as indicated by the two main alternatives out-
lined above. It is, therefore, important to observe that in the short-term analysis
above, the effect of introduction of radically improved types of subsonic airliners
was not taken into account and that it would be unrealistic not to count with
such advances, as they will have grave repercussions on the development of
events also in the first few years of supersonic activity: It should be obvious that
the appearing of considerably improved subsonic types before 1975, such as a
long-range LFC airline with, say, 25 percent reduction in direct operating
cost—or definite prospects that such an advanced type will appear before 1980
—would make the subsonic operators quite firm in their decision not to re-equip
with SST's, even if the "experience period" would reveal a greater initial success
with SST operation than could first be expected.

Considering next the *long-term consequences of a premature introduction of
SST's*, the last observations lead to a conclusion of paramount importance for
the future of civil aviation: *The SST-manufacturing countries will have an obvious*

interest in a stagnating subsonic development, because substantial subsonic advances will easily "kill" the marginal prospects for successful supersonic aviation.

It is thus hard to believe that these countries, which will spend billions of dollars on the development and production of SST's, will at the same time spend very considerable efforts and sums of money in the most efficient way conceivable of counteracting the success of the SST's; the more successful they are in creating improved subsonic types, the less prospects will they have to be successful in the production, selling, and operation of SST's.

Subsonic developments will, of course, not be actually suppressed in the SST-manufacturing countries. On the contrary, I do believe that such advances will be promoted to a certain extent also in these countries. It must be observed, however

● that the devoting of efforts and money in the SST-manufacturing countries to develop low-operating-cost, and V/STOL, near-sonic aircraft are likely to be much less than if they had not decided to go ahead with an SST development program,

● that, consequently, and in view of the fact that the aircraft development and production capacity of the SST-manufacturing countries is very great, the realization of the prospects in sight of appreciably decreased subsonic fares—as well as of successive decreases in airport distances—will be seriously delayed, and

● that, almost regardless of the efforts in the subsonic field in the SST-manufacturing countries, the great potential subsonic advances will, however, come about anyhow, although delayed, as a result also of research and development work in other countries.

In view of this last observation together with the previous analysis, it appears rather inevitable that the supersonic enterprise will develop into a definite failure if judged by normal commercial criteria about profitability. Considering the tremendous investments—in development and production of the SST's and in operation facilities, etc.—it is, however, hard to believe that the natural consequences of this failure will be drawn: abandoning supersonic aviation until the conditions for it have matured. On the contrary, strenuous efforts are likely to be made, by the parties primarily involved, to conceal the failure and decrease its implications—e.g., by subsidies to SST operators, by compensations to SST manufacturers and by actions of various kinds that favor supersonic and disfavor subsonic aviation, as in the field of aviation trade agreements.

Thus we have to foresee an increasingly severe internal struggle and tension in civil aviation, within the SST-manufacturing countries as well as internationally.

The Need for Supersonic Aviation

This turmoil might go on for several decades. It will by itself be most detrimental to civil aviation. Even more serious is, however, the fact that the promising prospects now in sight of aviation becoming a really cheap means of

mass transportation within economical reach of people in the medium- and low-income brackets in all countries, will be delayed and realized only at a slow pace.

Thus, the two lines of development—great and rapid subsonic improvements and SST's—are incompatible. In the choice between the two, it must be regarded as more essential to strive for cheap and rapidly expanding subsonic air transportation for the great masses than to enable those, who already fly, still comparably few, to save a few hours per flight.

The supersonic line of development will not increase but instead rather decrease the rate of expansion that civil aviation has enjoyed up to now, whereas concentration on V/STOL, BLC, low noise, and safety is likely to bring about even an increased growth rate.

In view of this, it is of paramount importance to reconsider thoroughly the real *need* for flying at supersonic speeds as distinct to the possible passenger appeal, or preference, in comparison with flying at near-sonic speeds.

There are two more reasons for this reconsideration: For the first time in its history, aviation would, by extensive supersonic flight, be likely to inflict serious harm to *other people* than aircraft occupants or persons living close to airports, because of the *sonic boom*. This is almost certain to cause annoyance and even serious disturbance, as well as rather often damage to property, within areas of the earth—the wide "boom carpets"—at least a hundredfold larger than the noise-affected areas around airports. Furthermore, *cosmic radiation* at the supersonic flight altitudes might cause harmful physiological effects to the occupants of the SST's, and give rise to diseases and sufferings for the next and future generations. (Part III.)

It seems to me that *any one of these adverse consequences of supersonic aviation* —the disastrous effects to the healthy development of civil aviation and the harms and hazards of sonic booms and radiation—*appears to be out of all proportion in relation to the moderate net gain in the time/comfort balance* that the SST's might at best offer over present and future near-sonic aircraft.

Fortunately enough, there seems to be a growing conviction in support of this standpoint, for example among the airlines. The party really concerned, the general public providing the air passengers, has still not been asked (with the exception of the limited Swiss Gallup investigation referred to above) whether they would prefer a maximum amount of subsonic improvements— with regard to lower fares, and improved safety, comfort, regularity, and availability as well as developments allowing shorter airport distances—to a few hours' reduction in flight time. There can, however, be little doubt about their preference.

Evidently, there must be reasons other than considerations for the passengers and the airlines that cause governments and a number of aircraft manufacturers in some of the major countries to make such strenuous efforts aiming at the introduction of SST's in commercial aviation at the earliest possible date. These other reasons have also been repeatedly stated, the two main ones being national *prestige* and general *economical considerations* (outside the airlines), in particular for keeping the aircraft industry occupied and for stimulating trade

by reduced travel times for businessmen. These motives bear undoubtedly considerable weight; the significance of national prestige cannot be denied in these days, and the importance of promoting economy and thus standard of living is obvious.

With regard to prestige, it might, however, be repeated that *a failure of the supersonic enterprise would mean a loss of prestige.*[4] Furthermore, in these days of an intense space race, no doubt mainly motivated by prestige reasons, it seems justified to point at *the great differences, with respect to the prestige aspect, between interplanetary space activities and civil supersonic aviation*:

Contrary to space activities, the success of which is wholly dependent on government decisions and investments, the prospects of successful supersonic aviation do not entirely—not even mainly—depend on the amount of money and brainpower that are devoted to the enterprise: *The success, or failure, of the SST's will dominantly depend on the ticket-paying passengers all over the world.* Whereas there is only one way of getting to other planets, i.e. by spacecraft, there would be two competing means of flying on long ranges within the earth's atmosphere, SST's and near-sonic aircraft, and the SST's cannot be commercially successful unless they are preferred by the passengers.

There is, therefore, an apparent danger in mixing the prestige aspect into commercial aviation, as that could easily obscure, and be harmful to, the basic prerequisites for its sound development and prosperity.

Also the general economic motives will stand or fall with the commercial success of civil supersonic flight: Even if the tremendous development cost for the SST's are covered by governments, the manufacturers cannot prosper on production that is far below break-even level. This is, however, of no concern for anyone outside the SST-manufacturing countries. What is of worldwide concern is the adverse effects on the whole of civil aviation—and thereby also on economic progress in general—of premature introduction of supersonic aviation.

Finally, the aspect of stimulating trade by further decreases of flight time, seems to be a motive of questionable importance. Also the busiest of executives and businessmen are human beings who, besides short travel time, need to be in good shape upon arrival for their important meetings and for this a high comfort level might be more important than gaining the very "last" few hours. In particular with regard to long eastbound or westbound flights—the majority of all long-range flights—it is worthwhile to consider the recent medical findings about the effect of the time phase-shift, which often will make the value of further reductions in flight time illusory.*

Nevertheless, it cannot be denied that some executives and business men and, occasionally, other people sometimes do have a real need for very short travel times. The important point is, however, that this small group is entirely insufficient as a basis for supersonic economy, in particular as such people would to a dominant extent only use very conveniently scheduled daytime SST flights; they will usually not spoil part of the night by using inconveniently scheduled SST flights, but these must also be filled for profitability.

* See footnote, page 33.

A POSSIBLE COMPROMISE

Should, in spite of all, decisions be made to develop prototypes of SST projects now contemplated in Europe and the U.S.A., it seems worthwhile to consider a policy implying a limitation of the SST activity to extensive test flying of a limited number of prototypes. To be effective, such a policy would require a general agreement among the ICAO and/or IATA Member States not to introduce SST's in commercial aviation for a considerable period, for instance before 1990.

The advantages with the moratorium would be:

1. It would be possible to achieve valuable service experience with regard to the critical problems of kinetic heating, sonic boom, and cosmic radiation. With respect to kinetic heating, about two decades of flying with a few prototypes, yielding perhaps some 50,000 hours of flight per aircraft, would hardly be sufficient to assess the fatigue qualities, including safe life, with the same confidence as is now achieved with regard to "cold fatigue" of subsonic aircraft types by means of testing in high-frequency fatigue machines—with large sample sizes and/or with numbers of load cycles far beyond the corresponding service life and water-tank tests. Anyhow, a considerable amount of valuable information for the particular type of SST in question would be accumulated, although the value of the experience would be very limited for application to other designs, materials, and Mach numbers.

The suggested testing period would be ample for assessing public acceptance with regard to sonic boom if test flights are made all over the world and are conducted in a realistic way, for instance with regard to the high frequency of flights that would occur in many regions if extensive supersonic flying is realized at a later stage.

Whether a testing period of two decades would be sufficient for full assessment of the cosmic radiation hazard is more difficult to say, but in this respect laboratory research might give valuable supplementary information. In particular, the testing time would be of value for gaining experience with regard to the feasibility of systems for warnings of solar flares—for instance, whether avoiding descents can be safely and sufficiently rapidly conducted—and the extent to which operations would have to be disrupted in actual commercial service.

2. Extensive test flying of a limited number of SST prototypes would appear to be sufficient with regard to prestige; it would show that SST's can be built and that at least a great many of the technical problems have been solved.

3. A moratorium with regard to commercial supersonic aviation until about 1990 should be used for concentrated efforts in order to realize all promising schemes for improving subsonic aviation, in particular with regard to V/STOL, noise, and LFC. Subsonic aviation could in this period be developed into a cheap and convenient means of mass transportation. Furthermore, such a development would give a firm indication of the competition that supersonic aviation were to meet, should it be decided to introduce SST's at a later stage.

4. Finally, the suggested moratorium period should be devoted to strenuous efforts in order to solve the most urgent and difficult problem of all that civil aviation is confronting, that of safety.

To avoid misunderstanding, I wish to point out that I do not recommend this compromise, as I do not think that the gains in experience and prestige are worth the tremendous costs for the development and extensive test flying of a number of SST's. The compromise seems, however, infinitely better than to proceed with series production of SST's and subsequently introduce them into civil aviation.

THE CASE FOR THE TRANSONIC TRANSPORT

The above analyses have dealt with supersonic transports in the usual sense of the word, i.e., capable of Mach numbers of 2 or higher. Some experts have pointed out, however, that a "just supersonic" transport with a Mach number of about 1.1 or 1.15—which could be called a transonic transport (TST)—might be considerably better in many respects than Mach 2 and higher Mach number SST's.[39] The reasons for this would be that the TST would be much simpler to design and build (for example, no kinetic heating problems), that it could possibly be designed and operated to generate no sonic booms, and that the cruise altitude would not have to be so high as to subject the crew and passengers to appreciable radiation hazards. It might be added that such a development would be confined to the portion of the flight-time/speed curve for which the time reduction in relation to speed increase is still quite appreciable (Fig. 9).

Such a project seems worthy of closer studies, in particular in order to find out whether the sonic boom can be eliminated and the operating costs can be competitive with improved types of subsonic airliners. A successful TST with laminar flow control for low operating cost and/or low noise-level plus VTOL or STOL capability, in order to reduce the ground-time losses, would be particularly attractive. It would represent a much greater advancement in civil aviation than a successful SST as it is at present conceived.

HYPERSONIC SPEEDS ABOVE 5,000-MILE RANGE

For ranges above about 5,000 miles, the gain in travel time by supersonic speeds would be of such a magnitude that it would outweigh even a rather noticeable difference in the overall "per hour" comfort level. However, on the basis of the present and foreseeable state of the art, it does not seem feasible to design an SST for such ranges with a reasonable payload.

For very long ranges it has been suggested that hypersonic transports, HST's—i.e., aircraft flying at Mach numbers higher than 5—might be feasible in the 1980s.[40–42] According to one suggestion, the speed would exceed 15,000 mph—about Mach 20—at an altitude of some 200,000 feet, the engines would develop no less than 300,000 pounds thrust, the maximum acceleration would be three times the force of gravity—believed "not to be unbearable for a person in normal health"—the external surface of the vehicle would glow red from the aerodynamic heating, and the passenger could be shot from London to Australia in a few hours. The technical problems involved are admitted to be "formidable," but they are all believed to be soluble as a result of "fallouts" of space technology.

I will neither question that this *can* be done, nor that it *might* be done mainly for prestige reason. What I do question is the *need* for traveling that fast and uncomfortably, the *economy* of the project and thus the *sensibleness* of the scheme. In other words, *should* it be done? My answer is "No," for the following main reasons.

The fact that the maximum worthwhile cutoff Mach number is "only" about 4 to 5 for distances from 5,000 to 12,400 miles, which is half of the earth's circumference (Figs. 11 and 12), might serve as a first indication that a Mach 20 aircraft would be rather senseless. A more definite proof of this is, however, the meager market: the HST's would be entirely unpractical below some 5,000 miles and the total world market for all ranges longer than this is only 3 to 4 percent of the total market. The potential HST market is even less, because the market analyses are based on total journey length according to the passenger's destinations, disregarding intermediate stops. Such stops are today mainly due to refueling, but there is no doubt that a large percentage of long-distance travelers *wish* to make intermediate stops—even if they could be thrown in one jump from one continent to another—either because they wish to see interesting places on the way, or because they have business along the route.

For a market of only one or two percent of the world aviation market the development and production costs for the few HST's required would be staggering. Hypersonic flight would be grossly uneconomical also for most of the other reasons specified above with regard to supersonic aviation.

Furthermore, most prospective hypersonic passengers—i.e., extremely busy businessmen—not specifically trained as cosmonauts—would find it rather pointless to "save" even a whole day if they then needed perhaps a week to be fully restored after the excitement of having been shot as a part of a bullet or, rather, a meteor.

Briefly, Earth is much too small to render commercial hypersonic aviation sensible in the foreseeable future.

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PART II: SAFETY

DEFINITION OF SAFETY IN CIVIL AVIATION

In a broad treatment of safety in aviation, it is essential to consider all detrimental effects of aviation on the occupants of the aircraft and people on the ground, as well as severe damage to the aircraft and to property on the ground. It is therefore suggested that safety in civil aviation be divided into two main divisions—flight safety and public safety.

Flight safety would comprise:

(a) Flight fatality safety, referring to occupants of the aircraft killed in air accidents.

(b) Flight injury safety, referring to injuries to the occupants of the aircraft of a physical or mental nature due for instance to accidents, to an exceedingly high noise or vibration level, or to somatic effects of cosmic radiation.

(c) Severe damage to, or loss of the aircraft.

Public safety would comprise:

(a) Public fatality safety, referring to people on the ground killed in air accidents.

(b) Public injury safety, such as injury to people on the ground in air accidents and highly disturbing airport noise, sonic booms by SST's and genetic effects of cosmic radiation.

(c) Material damage on the ground due, for instance, to air accidents or sonic booms.

I have confined myself to dealing only with flight fatality safety, airport noise and the two new phenomena connected with supersonic aviation, sonic booms and cosmic radiation. As the last two problems will only appear if supersonic speeds are introduced, they will be discussed in Part III of the paper, Speed versus Safety.

FLIGHT FATALITY SAFETY

METHODS OF MEASUREMENT; PAST DEVELOPMENT OF SAFETY AND PRESENT LEVEL

Flight fatality safety can be measured in a great many ways, such as the number of fatalities per 100 million passenger-miles or per million passenger-hours, or number of flights per fatal accident, etc. It seems to be commonly agreed that there is no one method of expressing the safety level that is superior to all others; it all depends upon the purpose of the statistics.

With the main philosophy that I am advocating, there is little reason to go deeply into the question of which method of measurement should be used for particular purposes. I will, however, express the general view that as traveling is becoming a rather normal way of spending a no longer negligible part of one's life span, the *risk per hour of exposure* during the journey is tending to become a more and more natural way of expressing the safety level. However, for the purpose of studying the trend in the development of flight fatality safety, and

also for setting goals with regard to safety, the most commonly used yardstick, the passenger fatality rate per 100 million passenger-miles is perhaps to be preferred.

Figure 1 shows the development of passenger fatalities per 100 million passenger-miles for U.S. domestic airlines (the curve being based on averages for five consecutive years), and for the ICAO member states—thus almost the whole world except the U.S.S.R. and China.

The figure clearly shows that the safety record was steadily and quite strikingly improved up to about 1953. The sad fact is, however, that for about a decade no clear trend of improvement can be observed, as the fatality rate, for the ICAO states, has been oscillating around 1.1 fatalities per 10^8 passenger-miles since about 1953. Assuming an average speed of 220 mph, this fatality rate corresponds to 2.4 fatalities per million passenger-hours. If it is furthermore assumed that 80 percent of the passengers are killed in the air accidents, three aircraft would crash for every million hours of flight. For an average service life of 10,000 hours this means that, on the average, one aircraft of every 33 would suffer a fatal accident. These facts lead to two important questions:

Is the present safety level satisfactory with regard to public confidence in aviation today?

What is the need for improvement of the safety level, considering the future growth of civil aviation?
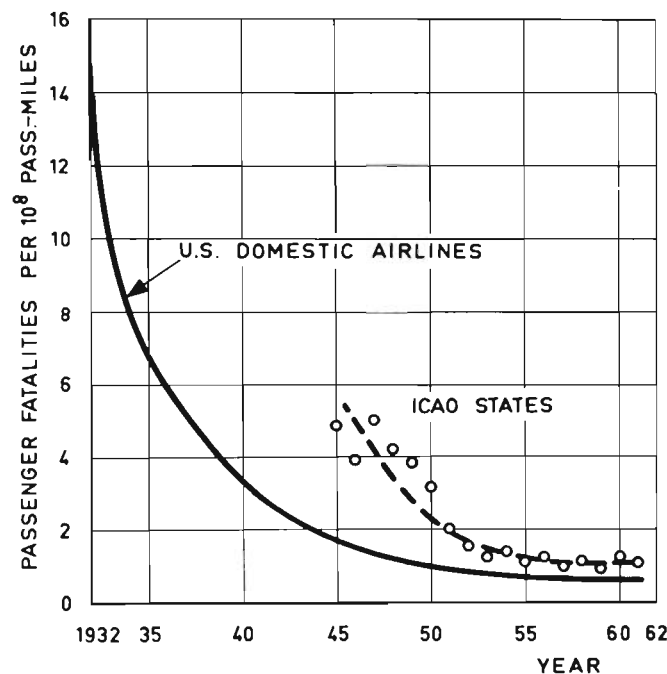

Fig. 1. Passenger fatalities per 100 million passenger-miles as a function of time.

IS THE PRESENT FLIGHT SAFETY LEVEL SATISFACTORY?

With regard to the first question, there are many people within aviation who have expressed the view that the present flight safety level is rather good because of the fact that the risk involved in flying on scheduled flights is so very small. The risk corresponding to 1.1 fatalities per 10^8 passenger-miles implies that one could fly about 3,700 times around the world, which would take about 50 years of continuous flying, before one reached an even chance of being killed in an air accident.

The view has even been expressed by many that we have, in fact, struck an optimum balance between safety and economy: a substantial increase in safety would cost so much that most people, if they had a free choice, would prefer to take the risk according to the present safety level rather than to pay the correspondingly increased fare.

In order to study the question more deeply, Fig. 2 has been prepared. The figures to the right are the average number of fatalities per 1,000 million passenger-miles during the last five years for scheduled flying, in the ICAO states, and for private cars, railways, and buses in the U.S.[1-2] In the diagram to the left, these rates have been transferred to the number of fatalities per million hours of
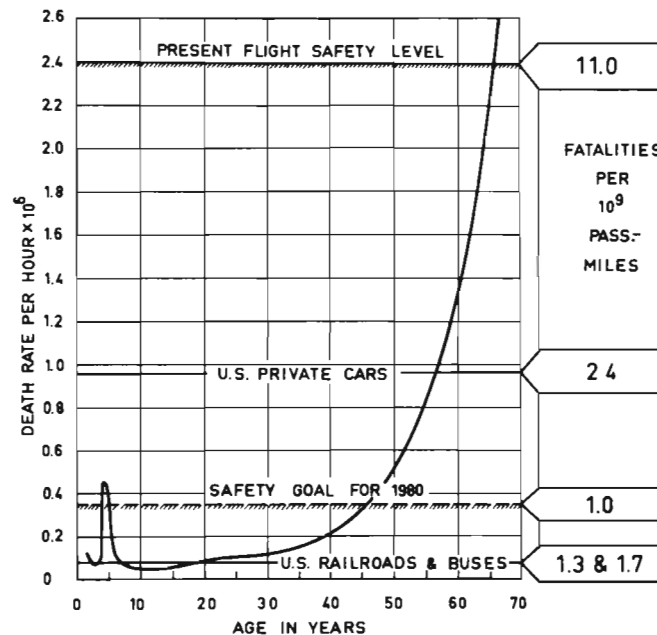
Fig. 2. Fatalities per 1,000 million (billion) passenger-miles and the corresponding risk per million hours of exposure for flying by scheduled aircraft according to ICAO statistics and for traveling by private cars, railroads, and buses in the U.S. For the transfer from the basis of passenger-miles to hours of exposure, the following average speeds have been assumed: aircraft, 220 mph; private cars, 40 mph; railroads, 60 mph; buses, 45 mph. For comparison, a curve for the average death rate per hour as a function of age according to official Swedish statistics is included.

exposure. For comparison a curve for the average death-rate per hour as a function of age according to official Swedish statistics, is also indicated.

On a passenger-miles' basis, it is more than twice as risky to go by private car than to fly, but in my opinion this comparison is not relevant, because there is a big difference between paying a ticket for being safely transported from one point to another, and driving one's car where the risks depend to a large extent on one's own skill and judgment. Commercial passenger aviation should only be compared with commercial surface transportation, and the fact that, on the basis of passenger-miles, it is some 6 to 8 times more dangerous to fly than to go by train or bus is significant.

On the basis of hours of exposure, the risk when flying is about 30 times higher than the risk when going by train or bus and, incidentally, about 2½ times higher than going by car.

It might also be observed that for a 40-year-old man, the risk per hour of being killed in a passenger aircraft is more than 10 times higher than if he were merely going about his daily life.

Thus there can be no denying that passenger aviation runs at an appreciably higher risk level than commercial surface transportation. Still I think it is correct to say that flying is safe. The risk level is so small that any one individual can completely forget it and be advised to fly.

But I do not think that the statistical risk is the important point. The all-important question is, in my opinion, Is the present flight safety level so high as to induce a sufficiently high *confidence* in aviation on the part of those who normally fly as well as those who have not yet flown?

I maintain that this question must be answered by a definite "No," because I am convinced that most people consider flying as being considerably more adventurous than using surface vehicles. In particular I think this applies to the great majority of people who have not yet flown at all, some 75 percent in the U.S. and some 97 percent for the whole world. There can be little doubt that civil aviation would have expanded much more rapidly up to now, had the accident rate during the last two or three decades been for instance only $\frac{1}{10}$ of the actual values.

One basic reason for the lack of confidence in aviation, is that as man is not born with wings, leaving the ground is more or less subconsciously thought of as being inherently unnatural and risky. This feeling is supported by reading about a steadily increasing number of catastrophic air accidents in the newspapers. Furthermore, many people quite correctly feel that the chance of survival in an air accident is very much smaller than in most accidents with ground vehicles.

Most people have a sufficiently high regard for human life to consider each passenger killed in an aircraft as a tragedy. There is growing evidence that people are becoming more and more alarmed by the great number of air accidents. As examples I wish to quote the following two recent statements from aviation magazines:

> It does not seem right that death should have become a statistic, to be computed and predicted by the slide-rule men. It is a deplorable philosophy that predetermines airliner fatalities per this or that, and accepts the inevitability of death for

a proportion of those who travel by air. A dead passenger is not a statistic to be related to miles or hours, but a human life destroyed as a result of circumstances which could, nearly always, have been avoided.

and

The tragedy in loss of human life alone cannot be written off. . . . Passenger safety is paramount. During March (1962) alone, 313 persons died in major air disasters. This must stop.

These and many similar expressions of anxiety confirm the statement I made 4 years ago[3] that it is the absolute number of accidents and people killed per month or per year that governs the public confidence—or, rather, lack of confidence—in aviation, and not the relative or statistical risk related to hours of flight or passenger-miles. In particular, the feelings about aviation of the general public, regular passengers as well as nonfliers, are influenced by how often they read or hear about major air accidents in the newspapers or on the radio, or look at the disasters on the TV screen. Recent investigations have also confirmed that fear is often regarded as the major disadvantage of flying.[4]

Lately there is evidence that also the airlines have become more and more concerned about "the fear problem."[5] They are "expected to employ more psychology and less statistics in future campaigns against one of the industry's greatest handicaps to building a mass market of air travel—the fear of flying."

I do not think such campaigns will ever be an efficient remedy. Major air accidents will always stir up adverse public reactions and I think rightly so. *There are no other efficient means of fighting the element of fear than by making aviation safer.*

To sum up, I think we have to admit:

- that the general public has never had, and does not have today, the same confidence in the safety of aviation as in the safety of surface transportation,
- that this lack of confidence is mainly due to the absolute number of catastrophic air accidents and not to statistical risks, and
- that this lack of confidence has been and still is a major hindrance for the expansion of aviation.

THE NEED FOR IMPROVING FLIGHT SAFETY, CONSIDERING THE FUTURE GROWTH OF CIVIL AVIATION

Looking now more deeply into the future, it is evident that flight safety will become an even more crucial problem as civil aviation expands to become, perhaps, the dominant means of passenger transportation. Let us therefore start with an attempt to estimate the long-term growth of passenger aviation for some 50 years ahead.

To make such a forecast with any certainty is, of course, a hopeless task even if one disregards the possibility of major wars or severe economic recessions; there are too many intricate and intangible factors that govern the growth of

aviation—one of them being safety itself. The curves shown in Fig. 3 should, therefore, be regarded as a possible projection into the future of scheduled passenger aviation rather than a forecast in the normal sense of the word. For the curve for the ICAO states, it is assumed that the growth rate gradually tapers off from the present level of about 12 percent per year to some 5 percent at the end of the century, when it is assumed that the volume is 10^{12} passenger-miles per year—i.e., about 14 times more than today.

For the whole world, a passenger transport volume has been assumed which gradually increases from 1.25 times the ICAO traffic volume in 1965 to 1.5 in 1980 and is then maintained at a 50 percent higher value than the ICAO volume. In the year 2000, the whole world traffic would be 1.5×10^{12} passenger-miles per year. If, at that time, 10 percent of the approximately 6,000 million people then populating the earth will fly each year, they will on the average spend about 10 hours per year in the air. In particular in view of the enormous short-haul markets that will be opened up by V/STOL aviation, this does not seem improbable.

Figure 4 shows the same projection into the future in linear scale. If it is assumed that we cannot appreciably improve on the present fatality rate of 11 fatalities per 10^9 passenger-miles, these curves indicate also the absolute number of fatalities, the scale to the right. In the beginning of the next century, around 30,000 people would then be killed each year in the whole world in scheduled passenger aviation.
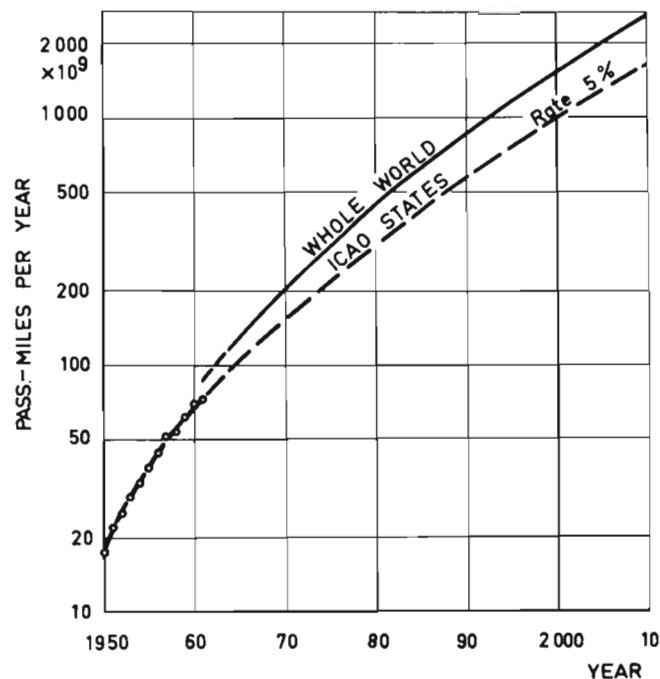

Fig. 3.   Possible development of scheduled aviation, semi-log plot.

In addition to this development we have to reckon with a steadily increasing volume of *charter aviation* as well as *general flying*. Up to now charter aviation has displayed a considerably worse safety record than scheduled aviation. Even if the difference in safety can be decreased, I do not think that the safety level will ever be the same. I have come to the conclusion that with reasonable assumptions of the growth of charter aviation, this kind of flying will probably result in even greater absolute numbers of fatalities than scheduled aviation around the turn of the century. The total number of fatalities would then be some 60,000 per year, around the year 2010 due to about three or four big newspaper-headline air catastrophes every day, and then increase very rapidly.

This is over and above the accidents in general aviation which will probably grow to become by far the greatest part of all civil aviation, and which will with certainty continue to display a much worse safety record than passenger aviation.
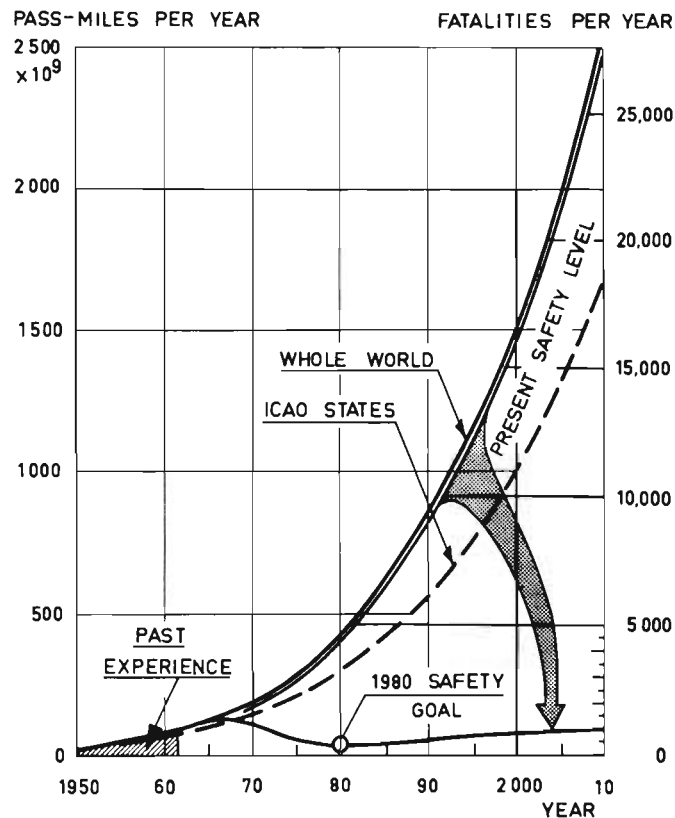
Fig. 4. The upper curves indicate the possible development of scheduled passenger aviation for the ICAO states and the whole world, according to Fig. 3, but in linear scale—the scale to the left. The same curves read on the scale to the right indicate the corresponding number of fatalities per year if the present safety level is retained. The lowermost curve indicates the number of fatalities per year for the whole world corresponding to an improved development of safety according to the dotted curve in Fig. 5—the scale to the right.

Reading and hearing about several major air catastrophes and numerous "minor" air crashes every day will make even regular air travelers feel uneasy and it will no doubt strengthen the determination of those who have not yet flown not to do so. This conclusion is believed to be right even if some allowance should be made for people getting used and hardened to the death toll of aviation.

Therefore I am convinced that if flight safety cannot be radically and rapidly improved but instead continues at the present risk level, this will constitute the most serious hindrance conceivable to a sound and rapid growth of civil aviation. It follows that *there can be no more efficient means of promoting civil aviation than making it much safer than it is today.* This is an unconditional demand if the long-term expansion of civil aviation is not to be severely hampered by lack of public confidence.

FLIGHT SAFETY GOALS

Two things are thus of paramount importance:

- to define safety goals which at the same time comply with the demand of insuring full confidence in aviation regardless of its growth, and are realistic, and
- to find new and radical ways of improving the safety level so as to meet these goals.

Both these tasks are of such scope and difficulty that they can only be efficiently dealt with by a team of experts on flight safety, and outstanding scientists, including statisticians. One possibility would be that ICAO forms such a flight safety team and on the basis of its work produces the necessary standards. The following proposals, which to a large extent are based on the suggestions made in Ref. 3, are mainly meant as a basis for discussions.

For both problems, the time factor is important. One must reconcile oneself to the fact that flight safety cannot be noticeably improved overnight, nor in any short period of time. The present inadequate safety level is to a large extent a consequence (a) of decisions and actions that were taken (or not taken) 10 to 15 years ago, with respect to regulations and operational facilities, etc., and (b) of the knowledge and skill that prevailed when the present fleets of aircraft were originally designed and built.

It would, therefore, be meaningless to set a continuously changing safety goal. The only feasible way seems to be a policy of stepwise improved goals, fixed for certain points of time, and correspondingly sharpened safety standards, as indicated by Fig. 5.

As a background for such time-fixed safety goals it is, however, of interest to calculate the continuous improvement of the safety level that would theoretically yield a constant absolute number of fatalities. As the present number of passenger fatalities per year in scheduled aviation, around 800 for the ICAO states, is causing considerable concern among the general public, I have assumed that a satisfactory level of confidence in such aviation would require a reduction to less than half. On the basis of the assumed growth of scheduled aviation, 400 fatalities per year for the whole world would correspond to a development of

the fatality rate as indicated by the double-lined curve in Fig. 5. This curve might be considered as a theoretically desirable but, in practice, unattainable development.

With regard to the suitable points of time when subsequent, fixed goals for the safety level should be set, I think that an interval of about 15 years would be practical. I therefore suggest, preliminarily, that the first goal is fixed for the year 1980. For this goal, I propose *an average fatality risk of the even figure of 1.0 in 10^9 passenger-miles*, implying about 450 fatalities per year. This goal would mean an improvement compared with the present safety level by a factor of about 11 on a passenger-miles' basis.

It is, of course, not necessary to fix the subsequent goals at this time; it is, in fact, better to postpone the setting of the goals until some 20 to 25 years before the "goal time" so as to gain experience with regard both to the improvement of the safety level that has been obtained during a considerable portion of the previous period and to the development of public confidence. I have, however, suggested ranges for safety goals for 1995 and the year 2010—as indicated in Table 1 and marked in Fig. 5—mainly in order to illustrate the idea of step-wise improved safety standards.
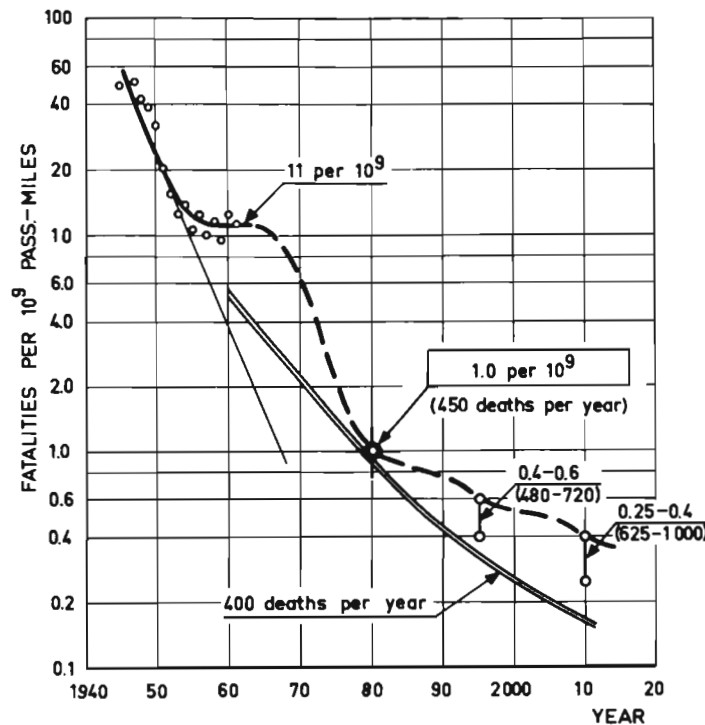

Fig. 5. A possible development of the fatality rate according to the goals suggested (dotted curve). The successively reduced rate required to limit the absolute number of fatalities to 400 per year is also shown by the double-line curve.

Table 1

Goal number	By year	Passenger-miles/10^9 (Fig. 4)	Maximum fatality rate per 10^9 passenger-miles	Number of fatalities
1	1980	450	1.0	450
2	1995	1,200	0.4 to 0.6	480 to 720
3	2010	2,500	0.25 to 0.4	625 to 1,000

The 1995 and 2010 goal ranges would correspond to a moderate increase in the absolute number of fatalities. Whether or not this is acceptable—or unavoidable—should be a matter for further considerations.

The dotted curve in Fig. 5 illustrates a possible development of the actual fatality rate, should it be possible to attain the goals at the fixed points of time. It might be of interest to observe that the rate of improvement required for the attainment of the 1980 goal is about the same as was actually achieved before 1953.

The analyses and proposals made in the following will be confined to the suggested 1980 goal of one fatality in 10^9 passenger-miles. Assuming an average block speed of 350 mph, this corresponds to *a risk of exposure of 0.35 per million hours*—i.e., an improvement by a factor of about 7. If this goal can be complied with, scheduled aviation would be somewhat safer than going by train and buses on a passenger-mile basis, but flying would still be about four times more risky than commercial surface transportation on an hour-of-exposure basis. On this basis, the general goal indicated by the Flight Safety Foundation to make flying "the safest means of transportation" would still not be met by the proposed 1980 goal.

The suggested goal might, therefore, prove to be insufficient to induce full confidence of the general public in aviation. We must remember that flying will always to some extent be considered as an unnatural and thus adventurous way of moving from one point to another and that air accidents will continue to be much more dramatic and final with regard to chance of survival than traffic accidents on the ground. It is imperative that these facts are compensated for by a safety level that reduces the number of accidents to very rare occurrences.

For a rational approach to the flight safety problem, it is, of course, the risk of an accident happening to the aircraft, rather than the risk of a passenger being killed, that must be the basis of efforts to improve safety. Again, it can be asked whether the risk of an accident to the aircraft should be related to aircraft hours, aircraft miles, number of flights, or to the total service life of the aircraft expressed in any one of these three quantities. This question was discussed at some length in Ref. 3. It was concluded that the number of fatal accidents per aircraft hour appears to be the most practical concept, a fatal accident being defined as one involving one or more deaths. The main reason for this, is that the annual utilization of the aircraft, and its parts, as well as its total service life, is usually expressed in hours of flight. It should, however, be emphasized that there will probably always be a need to transfer the accident rate or risk from one basis to another when considering particular aspects of flight safety.

For using aircraft hours as the basis, it is desirable to obtain an idea of the probable, or at least possible, future development of aviation in terms of aircraft hours. In Fig. 6, the development of average speed and of number of passengers per aircraft is estimated, yielding the product, passenger-miles per aircraft hour. This in combination with the possible development of passenger-miles per year according to Fig. 3 gives a possible development of aircraft hours per year, Fig. 7. Needless to say, this estimate is even more uncertain than the previous estimate in passenger-miles, but should serve the purpose of forming a basis for the statistical discussions in the following.

Assuming, as a consequence of improved "crashworthiness," that on the average 70 percent of the occupants are killed at each accident, the 1980 safety goal would correspond to *one fatal accident in 2 million aircraft hours*. This is six times smaller than the present failure rate. The goal implies that, assuming an average service life of 10,000 hours, one aircraft out of every 200 (instead of one of every 33) would crash. Even on this basis, the goal can hardly be considered as being too high.

In Fig. 8 the lowermost curve gives the development of the total number of accidents per year in scheduled aviation for the whole world that would correspond to the development in aircraft hours, according to Fig. 7, and an improvement of safety on the basis of passenger-miles, according to the dotted curve in Fig. 5, assuming, furthermore, a continuously improved crashworthiness corresponding to about 80 percent of the passengers of aircraft involved in fatal
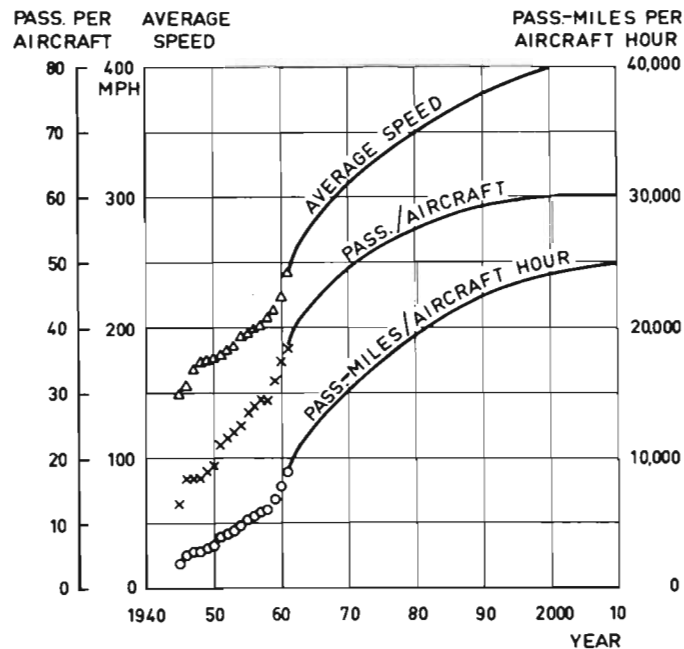
Fig. 6.   Possible development of average speed, passengers per aircraft, and passenger-miles per aircraft hour for the ICAO states.
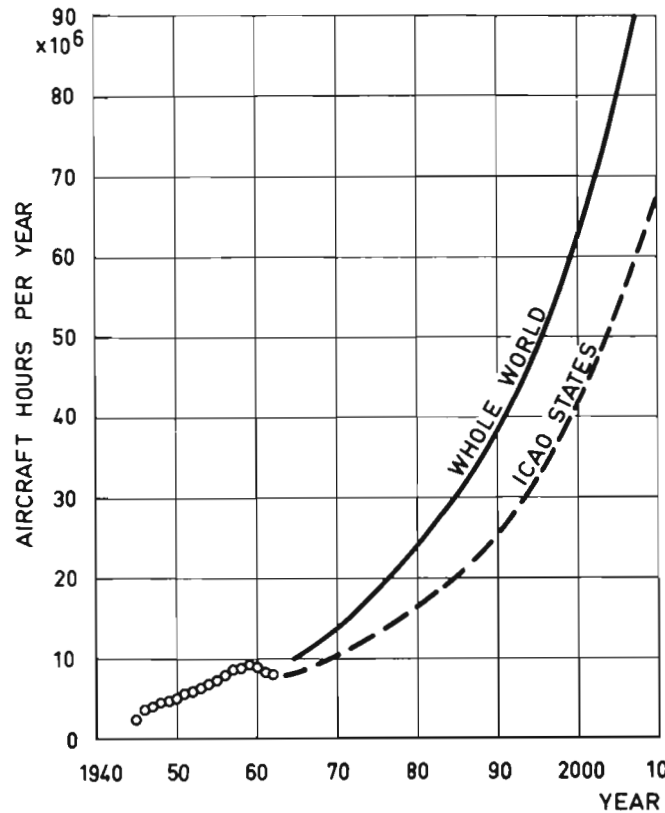
Fig. 7.   Possible development of aircraft hours per year according to Figs. 3 and 6.

accidents killed in 1960, 70 percent in 1980 and 65 percent in 1995. This develop-
ment would result in a total of about 1,000 aircraft accidents during the 45 years
from 1965 to 2010.

For comparison, the uppermost curve indicates a development if no improve-
ment in flight safety, on the basis of passenger-miles, would be made (thus a
constant figure of 11 in 10^9 passenger-miles) except in crashworthiness. This
development would yield a total of about 12,000 aircraft accidents in the period
from 1965 to 2010—i.e., twelve times more than if the safety can be improved
as assumed.

In Fig. 4, the lowermost curve indicates the number of fatalities per year
corresponding to the same improvement in safety. Between 1965 and 2010, a
total of 35,000 passenger and crew members would be killed in the whole world,
to be compared with a total of some 500,000 fatalities, should the present safety
level remain.

For the other main branches of aviation, in particular charter, general and
freight aviation, it will probably not be feasible to set the safety goal equally
high as for scheduled passenger aviation, but no suggestions will be made in
this paper.
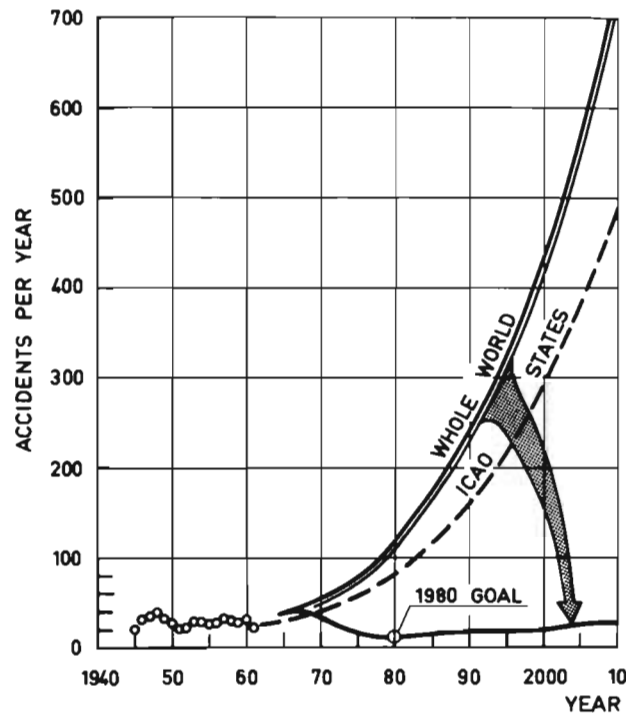
Fig. 8.   Possible development of total number of accidents per year in scheduled aviation corresponding to the development in aircraft hours (Fig. 7). The upper curves indicate the development if no improvement in flight safety on the basis of passenger-miles is made, except in crashworthiness. The lowermost curve gives the number of accidents for the whole world, assuming an improvement in safety according to the dotted curve of Fig. 5 and a continuously improved crashworthiness as assumed in the text.

THE STATISTICAL NATURE OF FLIGHT SAFETY

It is comparatively easy to suggest goals for flight safety but it is, obviously, infinitely more difficult to propose actions which will insure that these goals are reached, and indeed for the aviation community to comply with such proposals.

Before presenting my views on this subject, I will briefly discuss the statistical nature of flight safety, the present methods of insuring safety and the value of past experience.

In Fig. 9(A) the area of the large rectangle represents the accident rate of about three accidents per million aircraft hours that has characterized scheduled aviation for several years. Thus the area also represents the average total risk level during the past years. The rectangle comprises a great many, arbitrarily sized small rectangles, each representing various risks of fatal accidents. All these small rectangles are intended to illustrate the well-known fact that the

causes of air accidents are, indeed, legion. As we are dealing with small prob-
abilities, the sum of all the risks is equal to the total risk level.

The regrettable fact is that our knowledge of all these risks—in particular for
aircraft of new types—is utterly limited. The only thing we know for certain is
that the total failure rate during about the last 10 years has been of the order of
magnitude of three in one million hours for a very inhomogeneous mixture of old
and fairly new aircraft types and for quite varying operational conditions.
Furthermore, we can *presume* that this failure rate also indicates, at least
approximately, the present risk level and the risk level in the near future.

Besides this, we have merely some qualitative notion of a great many *con-
ceivable risks*. These might, at best, comprise a major part of the total risk level
as illustrated by the figure, provided that a maximum amount of experience and
imagination is utilized in conceiving potential risks.

It is important to realize, however, that a great many of the risks of fatal
accidents are today hardly imaginable or conceivable, even by the most out-
standing experts on safety. A main reason for this is, as is proved by many acci-
dent investigations, that an accident is very often caused by a quite unlikely and,
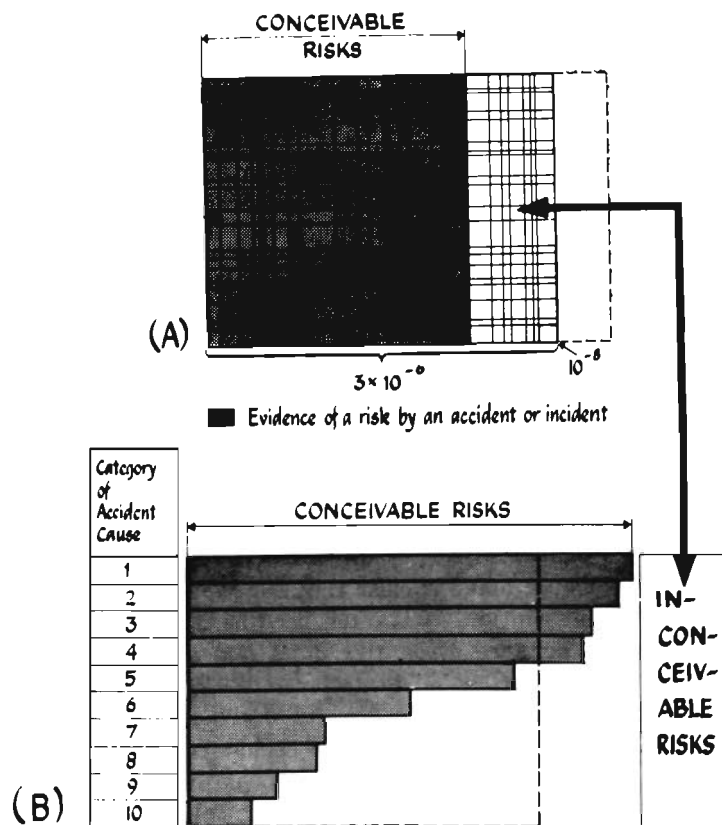

Fig. 9.   Schematic illustration of the total risk level as composed of numerous conceivable
and inconceivable risks.

above all, practically unforeseeable, fatal combination or coincidence of more than one failure or error, the occurrence of each of which might be harmless or, anyhow, not result in a catastrophe. It is all these unforeseeable coincidences that account for the fact that a great proportion of all new accidents differ from previous accidents in one way or another.

Returning to the conceivable risks, there has, in most cases, been no evidence in the past that an accident has actually occurred as a result of the risk. Nevertheless the risks have been, or could at least have been, conceived, or anticipated —in rare cases even quantitatively—e.g., in airworthiness requirements. These very often prescribe that the design—for instance with regard to the strength or function of a particular piece of structure or equipment—should be such that the risk of a serious occurrence is "*extremely remote.*" This is an expression that is, indeed, very frequently used in the safety standards, although it is rather poor guidance for the design and operation of aircraft.

For a minority of the conceivable risks there has been evidence in service that the risks have led to accidents or serious incidents. Such risks might have been unforeseen before the accident—or incident—which then made the risk conceivable. Accidents, and incidents, usually lead to stricter regulations, and the aim of such actions is often said to prevent repetition. In reality, however, the corresponding risks are merely reduced more or less considerably. Such reduced risks are illustrated by the small black rectangles in Fig. 9(.4). (It might be emphasized here that if the figure is taken as illustrating the accident rate in the past for civil aviation, then the black rectangles—indicating the rate of accidents that have actually occurred—should be bigger so that the sum of them equals the whole area representing the total rate of three accidents in one million hours of flight.)

It is obvious, however, that, as we know very little about both the magnitude and the number of all the risks, we cannot say for sure that the present risk level of about three accidents in one million hours of flight will be retained even in the near future. The risk level, for scheduled aviation, at this very moment— or in 1963 or 1964—*might* be either higher or lower. The possibility of a higher risk level is illustrated by the extension with dotted lines of the rectangle in Fig. 9a. In particular, I think that one cannot neglect the possibility of an increased total risk level after the introduction of a new type of equipment, such as subsonic jets or new types of VTOL aircraft.

This brief discussion should make it clear that *one should use the expression "level of safety"* with great caution. It is often used as if it were a known or measurable quantity, for instance *when it is stated that a new type of aircraft will, or must, have the same level of safety as present or contemporary aircraft. This, in my opinion, can be little more than wishful thinking,* because the overall safety level can only be measured by records of accidents that have occurred and because our *quantitative* knowledge of the risks is so utterly limited. In particular, it should be observed:

- that we are dealing with a statistical phenomenon, flight safety, comprising an almost infinite number of possible adverse events, the occurrence of

each of which is "extremely remote"; but just how remote, in quantitative terms, is at present in most cases impossible to say,

- that the fact that the total probability of an accident is the product of a very great quantity (the number of risks) and an extremely small one (the average risk of the various possible accident causes), might well make the resulting total probability rather far from "extremely remote," and finally
- that one must not believe that the fact that a particular risk might be conceivable makes it possible to reduce it to zero.

It is customary to group causes of air accidents under a few main headings, such as accidents at takeoff or landing, a critical number of engine failures, collisions, system or instrument failures, design and manufacturing errors and static or fatigue failures in the structure. I do not intend to discuss this grouping of accident causes into such categories in this paper, but I wish to point out that the grouping can be made in many ways, and will by necessity be rather arbitrary. In Fig. 9b, it is schematically assumed that air accidents can be grouped into 10 main categories. It is then also assumed that all "coincidence causes," when there is more than one occurrence that contributes to the accident, are referred to the category that appears to be the most significant; for instance, if there is an instrument failure during an ILS approach which contributes to an accident, this might be referred to the category of approach and landing in marginal weather.

PRESENT POLICY FOR INSURING FLIGHT SAFETY

With regard to the present method for insuring safety, the efforts that are being made by authorities, by manufacturers and—not least—by the Guggenheim Aviation Safety Center and the Flight Safety Foundation under the outstanding leadership of Mr. Jerome Lederer, are indeed impressive. The growing activity in this field is also evident by the rapidly increasing literature on various aspects of flight safety, as is exemplified by Refs. 6–29. The efforts have up to now followed two main directions:

One is to formulate stringent airworthiness requirements and other regulations pertinent to safety—such as for training of flight personnel—as well as to strive for a high standard in the design and manufacture of the aircraft and ground equipment in order to make the risk of fatal failures, errors or other serious occurrences "extremely remote," and to modify and extend such standards as development of aviation poses new problems. This main line of action is based on previous experience and, to a limited extent, on statistical evaluations of the probability of foreseeable, dangerous occurrences, such as the probability of meeting a gust exceeding the strength of the wing.

The other main policy is the careful examination of every accident in order to find out its cause and to see to it—for ins nce by new regulations, by instructions to the operators or by modifications in design manuals, etc.—that repetition is prevented or, rather, made "extremely remote."

The joint intention behind all these efforts is to continuously build up or accumulate a fund of knowledge and experience that will make flying safe.

For the sake of simplicity, this policy might be called the *Accumulated Experience Method*.

This present policy can be said to be in a continuous and hard race against time. The all-important question is: will it win this race or not? In other words, will it succeed in continuously decreasing the fatality rate roughly in proportion to the growth of aviation, or will it fail to do so? And, if it fails to do so, will it be able to at least keep the present fatality rate constant? Or will it not even be able to do that, with the result that the absolute number of accidents grows even faster than the volume of aviation?

Although it is, of course, not possible to answer these questions with any certainty, I personally feel rather pessimistic: I believe that even if the Accumulated Experience Method is appreciably intensified, which is probable due to pressure of public demand as the absolute number of accidents grows, it is unlikely to succeed in doing better than keeping the fatality rate constant. However, I really fear that *aviation will suffer a continuous increase in the fatality rate, if we do not make an entirely new and radical approach to the flight safety problem, in addition to intensifying efforts*. Briefly, the reasons for my pessimism are as follows.

1. In the first place, the mere fact that no noticeable improvement of the fatality rate has been made during the last 10 years—in spite of the rapid advances in technology and increased flight-safety efforts—tends to indicate that there is very little reason indeed to hope that the fatality rate can be brought down appreciably by present methods alone. With regard to safety, aviation seems to have come to a stalemate in very much the same way as the car traffic on the roads, for which a high accident rate appears to be inevitable almost regardless of whatever actions are taken and safety propaganda is made.

2. Furthermore, I do think that the very nature of air-accident causes is such that *the method of "chasing accidents as they occur in order to prevent new ones" appears to be inherently unable to catch up with the occurrences*. This is so not only because a great proportion of the risks are completely unforeseeable, but also because of the *practically infinite number of ways in which things can go wrong—* even in conceivable ways—as explained above.

These observations do not, of course, in any way belittle the importance of careful accident investigations.

3. A third reason is:
- that a very great proportion of all accidents occur during takeoff and landing,
- that it is probably inevitable that this will be so also in the future,
- that the future great increase of short-haul aviation, mainly as a consequence of V/STOL developments, will bring about a much greater increase in airport movements than in direct proportion to the growth of aviation in aircraft or passenger-miles. The simple reason for this is that, given a certain annual aviation volume, the number of takeoffs and landings is inversely proportional to flight distance, and
- that, consequently, *the rate of accidents during takeoffs and landings is likely to grow faster than the volume of aviation*.

4. A fourth reason is the increase of air traffic as such. Given a certain quantitative and qualitative standard of air traffic control and collision avoidance equipment, it can hardly be disputed that, for purely statistical reasons, the risk, or rate of collisions will increase as the air traffic grows in any particular region of the air space. In particular, the intense congestion of V/STOL air traffic around cities—corresponding to the great increase in takeoffs and landings —will in the future pose a formidable problem for air traffic control and collision avoidance equipment.

THE VALUE OF "PAST EXPERIENCE"

Supplementing these thoughts and as a further background for the proposals to be made, I wish to say a few words about what I would like to call *overconfidence in "past experience."*

Let us take the simple case of throwing a die for proving, by "experience," that the probability of obtaining, for instance, a four is 1 in 6. Everyone would certainly find it self-evident that it is not sufficient to throw the die once or twice, nor even six times. It has to be thrown a considerable multiple of six —for instance 60 times.

Exactly the same rule is valid for assessing the level of safety by flight experience, but, for unknown reasons, this does not seem to be generally appreciated. The only difference is, however, that when it comes to flight safety, we are dealing with very much smaller probabilities than 1 in 6.

Let us assume, for instance, that compliance with the present overall safety level—about one fatal accident in 300,000 hours—has to be proved for a new type of aircraft on the basis of flight experience; and there is, in fact, no other way of proof when it comes to the total or overall safety level. Then a multiple of 300,000 hours has to be flown, for instance 5 times as much—i.e., 1.5 million hours, in order to reveal the average failure rate. It is obviously not conceivable for the aircraft manufacturer to produce flying hours of this order prior to deliveries to the airlines; that would take about *50 years with a fleet of some 10 test aircraft.*

The only conceivable way in which the safety level for a particular aircraft type can be demonstrated, is by means of actual service by airlines during a considerable number of years. Even this is, however, bordering on what is impossible in practice to achieve; for the above example it would take about five years if the fleet of aircraft of the type in question amounts to 100 aircraft. For anyone who agrees that the present safety level must be improved considerably—for instance by a factor of 6 on the basis of flight hours, as suggested above—it is important to observe that *proving such an improved safety level by service experience would take one or more decades even with a fleet of several hundred aircraft.*

The statements made above are illustrated by Fig. 10 in which the expectation of future fatal aircraft accidents are indicated corresponding to a development of the safety level according to the dotted line in Fig. 5 in combination with an assumed growth of aviation in aircraft hours according to Fig. 7.

The difficulty in assessing the safety level by flight experience turns into a definite impossibility when it comes to determining the safety with regard to

any one particular accident cause, such as failure of the wing due to static over-
load. If the risk of such occurrences must not exceed, say, as high a value as one
in 10^7 hours, then a multiple of 10^7 hours, for instance some 50 million hours, must
be flown. As it is obviously impossible to produce flying hours of this order to
verify even a rather low safety level with regard to a specific accident cause, other
means must be found to assess the safety with regard to specific causes. In
particular, one must resort to laboratory and other tests as well as
mathematical/statistical evaluations, to be conducted before new aircraft and
ground facilities, etc., are approved and put into service.

It should be clear from the observations made above that *we just cannot wait
for accidents to happen* and only then find out, by "past experience," whether or
not the accident rate—be it the average rate or the rate with regard to any
particular accident cause—is too high, or is satisfactory by any one reasonably
high standard.

It is, furthermore, instructive to look at the past and future growth of aviation
in linear or true scale instead of in the semilog plot usually employed. As is
shown by Fig. 4, presentation in true scale indicates quite strikingly that the
development in the past—the past experience—almost disappears compared
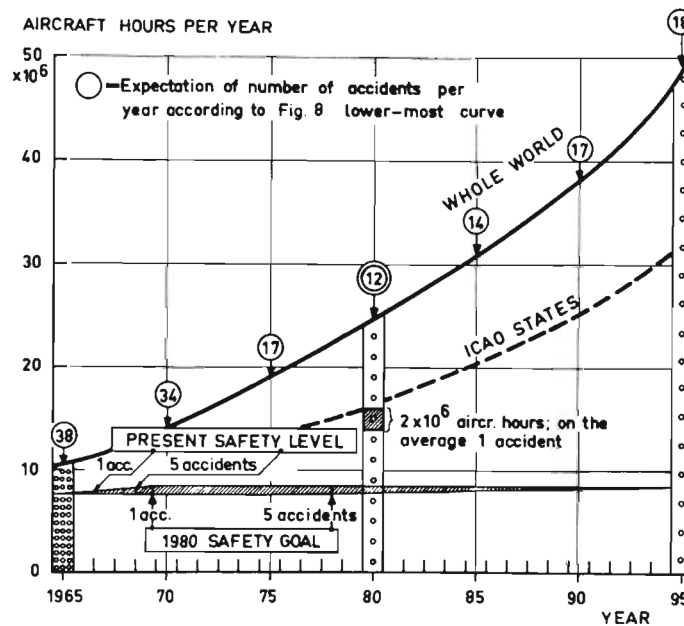
Fig. 10. Development of aircraft hours per year according to Fig. 7 from 1965 to 1995,
including expectation of number of accidents corresponding to a successive radical improve-
ment in safety according to the dotted curve of Fig. 5 and the lowermost curve of Fig. 8.
The shaded area represents traffic carried out by a fleet of 300 aircraft—successively
delivered and withdrawn from service—with an annual utilization of 3,000 hours per
aircraft. On this area are indicated the expected time until 1 and 5 accidents occur (*a*)
corresponding to present safety level and (*b*) if improvement is made so as to comply with
the safety goal for 1980.

with the future growth. In fact, during the next four to five decades a traffic volume will be produced that is some 30–50 times as large as the volume produced up to now. It must also be considered that future types of aircraft and their operational conditions will differ greatly from the aircraft and conditions in the past, which thus form a very poor statistical basis.

These observations should, I think, be rather sobering and should reduce the belief in past experience to its actual value: essentially, *the only lesson that can be learned from past experience is to avoid repetition of previous mistakes.*

UNIFORMITY IN SAFETY STANDARDS

Two specific conclusions can be drawn from the examples given above regarding the difficulty, to prove by flight experience, that the safety level is satisfactory:

1. The nonoccurrence, even during a decade or more, of accidents or serious failures due to a specific cause, can hardly be proof that *the safety level for a specific type of aircraft with regard to the said specific accident cause* complies with a sufficiently high standard.

2. The nonoccurrence, even during several years, of fatal accidents, for a specific airline or type of aircraft, due to any causes, can hardly be proof that the *overall safety level* complies with a satisfactorily high standard.

I really think that, in particular, this last observation should be given a great deal of consideration because the logical consequence of it is that, with regard to every type of aircraft, the manufacturers should adopt the basic philosophy that *one has to think of each type of aircraft as if it were the only one existing throughout the world.* This principle would counteract the rather common but dangerous attitude or opinion, that for an aircraft type that has not been produced in great numbers, a lower safety level could be allowed than for a type produced in great quantity, because the smaller "population" of the former type runs a smaller risk of suffering accidents. Such an attitude is not compatible with a responsible outlook on safety in aviation; for one thing it would lead to an increase in the total accident rate, the greater the number of different types of aircraft that are introduced.

Exactly the same applies to the operators: each airline, regardless of size, should look at its activity as if it covered all scheduled aviation of the world. In particular, a small airline should not be satisfied with a higher accident rate than the average—or according to any set safety goal—merely because the absolute number of accidents the airline would suffer would be small, or even zero, in a limited period of time.

Furthermore, it follows from the two conclusions specified above that a fleet of aircraft of a specific type, or an airline, not complying with a certain required safety level, *might contribute to a reduction of the overall safety level even if the aircraft or the airline have not met with one single accident*; the too many and/or too high risks are present but they just have not as yet "come to the surface" by resulting in accidents or serious incidents. The reason for this might not only be a limited service time, but also the unforeseeable "play of chance" characterizing statistical phenomena.

It is also evident that the safety level—in particular with regard to specific accident causes—for each aircraft type or airline must, in principle, be *much* higher than just required for being "reasonably sure" that no accidents will happen even during rather long service periods.

The above observations lead to a *basic* demand of *uniformity* with regard to the standard of safety for each main branch of aviation. Each branch, for instance scheduled aviation, can in many ways be divided into a number of "elements"—e.g., aircraft types or airlines. For each way of division, the sum of the number of flight hours for the "elements," during a certain period, equals, of course, the total number of flight hours for the whole of aviation of the branch under consideration. Uniformity in safety means that, whatever the safety goal is, *the maximum accident rate or risk should, in principle, be applied for each "element" regardless of its size*—i.e., number of aircraft of a specific type or size of a particular airline.

With regard to the "elements" discussed above—airlines and fleets of aircraft of specific types—the obvious reason for a uniform safety standard is that, if it is not applied, it would be necessary to agree internationally on exactly how the size of an airline or of a fleet of aircraft should be permitted or required to deviate from the desired average safety level—i.e., permitted to be lower if the size of the "element" is small, or required to be higher—as a compensation for the below-average "elements"—for the cases where an airline is very large or the number of aircraft of a certain type is great. Such discriminations would, obviously, be highly impractical, not to say almost impossible, to enforce, for many reasons. One reason is that one cannot usually know the ultimate size of an "element"—an airline as well as the fleet of an aircraft type might grow almost indefinitely—another is that it would be unjust to "punish" for instance a successful type of aircraft, that enjoys big orders, by requiring a safety level much above the average.

In one particular respect *an exception from the basic demand of a uniform safety level* should, however, be considered and that is with regard to the number of passengers carried, thus *the size of the aircraft*. With the philosophy advanced in this paper, there seems to be strong reasons for requiring a higher safety level for very large aircraft than for small ones, in the first place because an accident involving several hundred passengers is considerably more detrimental to public confidence than are minor accidents.

On the other hand, to introduce such a discrimination for different sizes of aircraft would meet with some practical difficulties; for instance, the various risk levels and the sizes of the aircraft to which they should apply, could hardly be set without considerable arbitrariness. It should also be borne in mind that different requirements would be difficult to apply with regard to some accident causes of an operational nature, for instance collisions between aircraft of different sizes.

In weighing these and other pros and cons for having two or more safety standards with regard to aircraft size, I have come to the conclusion that such a differentiation should preferably be made, in spite of the difficulties indicated, mainly because reducing catastrophic accidents with large airliners to quite

infrequent occurrences, is of paramount importance for public confidence. At least for such aircraft, safety in aviation should equal or surpass the safety of trains and passenger boats. Moreover, it should be easier, in principle, for a large airliner to comply with a higher safety level, for one thing because it can more easily carry a considerable amount of sophisticated safety equipment. Another reason is that the large airliners usually fly on longer routes than small aircraft and therefore make less frequent takeoffs and landings, the two phases of a flight which are connected with comparatively high risk levels.

Furthermore, it might be found exceedingly difficult to comply with the proposed safety goal—a maximum of about one accident in 2 million aircraft hours—for the future vast short-haul, V/STOL aviation, in particular because of its high frequency of takeoffs and landings. The risk level for such aviation could be significantly increased—without increasing the total number of accidents per year—if the risk level for the large, mainly long- and medium-range aircraft were appreciably decreased. A higher risk level for short-haul aircraft could probably also be "tolerable" with regard to public confidence, because the average size of such aircraft is likely to remain comparatively small.

There must evidently be an optimum way in which differentiation of risk levels with regard to aircraft size could be made in order to attain a maximum public confidence in safety for a given total amount of efforts and money devoted to improving safety.

However, I will not venture a quantitative proposal in this respect at this time, except expressing the following view: If it is agreed upon to introduce, for instance, two different safety levels—say for aircraft having more and less than 75 seats—I think that the ratio between the safety levels should be made fairly appreciable, for instance a factor of at least 5. Thus, an improved safety goal for large airliners in scheduled traffic corresponding to a risk of one accident in 5 or 10 million aircraft hours, might well be considered. At the same time, the risk level for the category of smaller aircraft could be increased from one in 2×10^6 to about one in 1×10^6 aircraft hours.

A NEW APPROACH FOR IMPROVING FLIGHT SAFETY

As a supplement to the present "Accumulated Experience Method," I suggest a new approach of a mainly statistical nature. This approach is a further development of the suggestions made in Ref. 3, and it might be called the "Allotment of Probability Shares" Method, or the APS Method, according to its most characteristic feature. It comprises 10 main points listed in Table 2.

Point 1: To agree internationally on high but yet attainable flight safety goals is the very basis for the proposal. The corresponding "Maximum Total Risks" should preferably be expressed as the average probability of a fatal accident per aircraft hour. For each main branch of aviation—scheduled, charter, general and freight aviation—different values of the Maximum Total Risk should be contemplated for two or more categories with respect to aircraft size. In all other respects the risk level should be uniform, as motivated above.

Table 2. THE "ALLOTMENT OF PROBABILITY SHARES" METHOD

(The APS Method)

1. Agreement on *Flight Safety Goals*, to be expressed in "Maximum Total Risks," for the various main branches of aviation.
2. Adoption of the *Sharing Principle*, i.e., dividing, for each main branch of aviation, the Maximum Total Risk into "Probability Shares" to be allotted to various accident risks.
3. Intensified efforts to conceive of as many accident risks as possible.
4. Allotment of a main Probability Share for all the conceivable risks and the remainder of the Maximum Total Risk for the nonconceivable risks.
5. Distinction, for the conceivable risks, between statistically *nontreatable* and statistically treatable accident risks and identifying as many of the latter as possible as at least partly statistically controllable.
6. Allotment of a main part of the Probability Share for the conceivable risks to the statistically noncontrollable risks and the remainder to the statistically controllable risks.
7. Adoption of principles for determining Probability Shares for statistically controllable risks and establishing requirements for such shares.
8. Development of methods for treating statistically as many of the conceivable risks as possible and for compliance with the requirements regarding such risks, mainly by applying the fail-safe principle.
9. Efforts to transfer as many of the conceivable accident risks as possible from a statistically noncontrollable to a statistically controllable nature.
10. Allotment of Probability Shares for various kinds of conceivable but statistically noncontrollable risks, and efforts to reduce such risks.

The safety goals should stepwise be made increasingly severe in the future in order to keep the absolute number of accidents at low values in spite of the growth of aviation.

Point 2: To adopt the sharing principle—i.e., to divide the Maximum Total Risk into "Probability Shares," is the most characteristic point of the APS Method. The big difference between this approach and the present "Accumulated Experience" Method is the following: whereas by the latter method innumerable probabilities of fatal occurrences—which are usually unknown and thus might be either "extremely remote" or fairly appreciable—are added to each other, yielding an unknown and largely uncontrollable total probability of accidents, the APS Method aims at a limitation of the probability of accidents to a maximum level, that of the Maximum Total Risk, by slicing up this probability into shares to be allotted to various accident risks.

In doing so, the Maximum Total Risk should first be divided into main groups of risks which should then be divided into subdivisions—or "subshares"—to be in turn, if feasible, divided further into sub-subdivisions, etc., down to distinct "Basic Risks" for which further subdivision would be impractical or impossible.

Thus, instead of adding probabilities in an unknown way, the principle of sharing a "Probability Cake" of a limited size should be adopted. *If this is not done, it seems hardly possible to determine the acceptable risk level with regard to any one specific accident cause on a rational basis.*

Point 3: To conceive of as many risks as possible, is a most important first step in the application of the APS Method. It calls for strenuous efforts—on the part of manufacturers, airlines and airworthiness authorities—by experts on

flight safety. Ample experience of accidents and incidents as well as pronounced intuition, with respect to foreseeing the possibility of improbable occurrences and coincidences, are essential. To the extent possible, the present magnitude of various risks and groups of risks should be estimated as a basis for the application of the APS Method.

Point 4: To judge about an appropriate distribution of the Maximum Total Risk between the conceivable and the non-conceivable groups of risks is obviously a difficult task. *The Probability Share for the non-conceivable risks should rightly be made greater—leaving a smaller share for the conceivable risks—for radically new categories or types of aircraft*, such as direct-lift VTOL aircraft or SST's, which differ greatly from conventional types. *If this is not done, it will not be possible to insure the same level of safety for radically new designs and operational conditions as for conventional ones.* This is because new features must involve a greater number of non-conceivable risks—some of which are likely to be relatively great—as compared with old or new types of aircraft based on conventional principles.

Point 5: A statistically controllable risk is defined as a risk that:

(a) is treatable by means of statistical mathematics—e.g., for airworthiness on the basis of large sample-size laboratory tests, and

(b) is dependent on such design and other parameters—e.g., stress level or length of inspection intervals, that can be controlled, so as to insure that the risk is limited to a predetermined magnitude with an acceptably high confidence.

The great advantage of statistically controllable risks is that *the risk level can, in principle, be limited at will to a very small maximum value. This is, in fact, the basic prerequisite for appreciable and predictable improvements of flight safety.*

Point 6: The appropriate relation between the total risks corresponding to statistically controllable and noncontrollable, conceivable accident causes must, of course, be made in conjunction with studies of the extent to which the statistically controllable risks and thus their sum can be reduced to very low values. This is thus dependent on the next point:

Point 7: It is important to agree on guiding principles or rules for the internal subdivision into Probability Shares for the various statistically controllable risks. Only then will it be possible to establish quantitative requirements in airworthiness and other standards without undue arbitrariness. One basic principle must obviously be that risks, which are extremely difficult to reduce, would be given greater Probability Shares than risks that can more easily be cut down. The penalties involved in reducing a risk with regard to weight and cost must, of course, also be taken into consideration.

It should also be considered whether or not degrees of "excusability" for various types of accidents should be applied as a supplementary guiding principle for subdividing Probability Shares. In Refs. 3 and 30 the author suggested the concept of an "excusability scale" for various accident causes. It was, for instance, maintained that accidents due to engine failure were more readily understood by the general public—even if not actually "excused"—and thus, perhaps, somewhat less detrimental to the confidence in air safety, than were

structural failures. Of the latter category, static failures, for instance due to flying into a very severe thunderstorm or a jet stream, should be placed higher up in the "excusability scale" than catastrophic failures due to structural fatigue. The reason for this would be that the passengers should rightly demand that collapse of the structure under fairly good flying conditions—which might happen in the course of a fatigue failure—should "never" occur; such accidents should be regarded as completely inexcusable.

With regard to the quantitative formulation of requirements for statistically controllable risks, these must be divided into main groups for risks pertaining to airworthiness, to operation and to combined conceivable accident causes of a statistical nature. Another question to be considered, mainly one of suitability, is whether, in some cases, the airworthiness, or any other, requirements should specify the Probability Shares, which would thus form the quantitative part of the requirement, or whether the Probability Share should merely be the basis for the requirement, which is then to be expressed in other terms than statistical. Up to now, airworthiness requirements of quantitatively estimated risks have only—in the few cases where such estimates have been made—been expressed in other terms than statistical, for instance gust load factors for wing structures. The first mentioned method, which is a more clear-cut statistical approach, has been suggested by the author with regard to safety against fatal fatigue failures.[3,30]

Point 8 is most important, because if a risk can be statistically treated, it can also in most cases be statistically controllable, partly or wholly, and then made very small. (Some risks might be statistically treatable but not or only to a limited extent controllable—for instance, flying into clear air turbulence or encountering meteorites.)

There are two main, well-known methods or principles with regard to design for safety, the "safe-life" and the "fail-safe" principles. As they are of particular importance for proving compliance with safety requirements expressed in, or based on, statistical terms, they may be briefly discussed here.

Both principles are applicable not only to aircraft structures but also to the various devices and systems essential for safety, on board the aircraft or on the ground. The following definitions are believed to be generally acceptable.[31-32]

- According to the *safe-life* principle, a certain low maximum probability of fatal failure of a structure, device or system during *a specified service or limit life* shall be assessed by due consideration for the scatter in life.
- According to the *fail-safe* principle, a certain low maximum probability of failure of a structure, device or system shall be assessed by a *combination* of (*a*) *design features*—usually a high degree of redundancy—such that one or more partial or element failures lead to only a limited reduction of structural strength or other properties essential to safety, with (*b*) *inspections*, or automatic warning, ascertaining the partial or element failures to be detected for subsequent repair or replacement.

If replacements are not made, fail-safe designs have also, in principle, a limited life with regard to safety—the "fail-safe limit life"[31]—although the life

is not such a significant feature as for safe-life designs. This might, in particular, be the case for structural fatigue if the length of the inspection interval has to be reduced, as the service time increases, to unfeasibly short durations—for instance shorter than the flight duration—in order not to exceed the maximum probability of failure.

The most important advantage of the fail-safe principle is that it makes it possible to insure an extremely low maximum level for the "total" risk of fatal failure of the structure, device or system, because fatal failure will only occur when there is a coincidence or combination of element failures. The risk of partial failures can, therefore, be allowed to be fairly great. As only these greater risks have to be assessed by laboratory tests, it is possible to insure a very low total maximum risk level without having to determine the always quite uncertain "tail end," for extremely low probabilities, of the probability distribution function.

This is in contrast to safe-life designs, for which the risk of fatal failure is equal to the risk of an element failure. To assess such risks—which obviously have to be exceedingly small, in particular if an improved and controllable level of flight safety has to be achieved—with an acceptable confidence, the sample size of the tests must usually be unfeasibly large. The situation might be improved by applying an extremely short service life of the device or structural part, implying frequent replacement, but this will often be uneconomical. In some cases application of an exceedingly low stress level might also yield a sufficiently low probability of failure of a safe-life structure, but this will usually result in excessive weight.

For the reasons indicated, it is suggested that ICAO and national airworthiness authorities should:

- recommend that the safe-life principle should only be used in exceptional cases where the application of the fail-safe principle would meet with extreme difficulties, and
- prescribe satisfactorily high confidence levels that should be applied in statistical analyses of test results for proving compliance with Probability Shares allotted to safe-life structures and devices.

Point 9: Over and above the efforts to identify as many of the conceivable risks as possible as statistically controllable (Point 5) it is most important to transfer, to the greatest feasible extent, statistically noncontrollable risks to a statistically controllable nature. The ideal, but unattainable, goal would be to make all risks statistically controllable and then to limit the risks to extremely low values.

This line of development obviously calls for adoption of new principles for the design and operation of aircraft. It is therefore a long-term business, mainly connected with the design of new types of aircraft. However, even if the results in improved safety will not appear until many years have elapsed, making as many risks as possible statistically controllable is vitally important for a continuous future improvement of the safety level.

The main way in which accident risks can be made statistically controllable is by eliminating, wholly or partly, the human factor in the operation of aircraft

and replacing it by fail-safe mechanical, electronic and similar devices. An important example is the development of fully automatic landing techniques.

Point 10: It might at first sight seem meaningless to subdivide the main Probability Share for all the conceivable but statistically noncontrollable risks (Point 4) into subdivisions for various kinds of such risks. This is important, however, mainly because one then gets a yardstick with which the actual records of accidents, attributable to such kinds of risks, can be compared. It must be remembered that the fact that a certain risk or type of risk is not at all, or at least not easily, statistically treatable does not mean that nothing can be done about it. Once the risk is conceived, it can be subjected to requirements, and if the number of accidents due to a specific kind of risk appreciably exceeds the Probability Share allotted to it, then the requirements should be made more stringent.

One example is collisions. It is exceeding difficult to treat the collision problem adequately by statistical mathematics, but if the number of accidents due to collisions exceeds the Probability Share allotted to this category, this will serve as a warning signal to sharpen the regulations and to improve the ATC control and collision avoidance equipment as well as to find new approaches to the collision problem.

The APS Method is illustrated, very schematically, by Fig. 11, which is a development of Fig. 9. The present risk level for scheduled aviation with an expectation of about three accidents per million aircraft hours is represented by the areas of Fig. 11(A). As compared with Fig. 9, a greater number of risks have been conceived within the various main categories of accident causes, resulting in a smaller total risk, or Probability Share, for the inconceivable risks (Points 3 and 4). Furthermore, a considerable portion—greater than at present—of the conceivable risks has been identified as statistically treatable and partly controllable (Points 5 and 6).

As a consequence of technological advances, some conceivable risks, or groups of risks, hitherto not statistically controllable, have also been transferred to the statistically controllable side (Point 9). This is illustrated in Fig. 11(A) for the categories of accident causes Nos. 6, 7 and 8, the areas having been detracted from the areas to the right of the dividing line between statistically controllable and noncontrollable accident causes.

On the basis of these preparatory actions, which might refer, for instance, to a new type of aircraft or to scheduled aviation as a whole, the total risk level is attempted to be reduced to one accident per 2 million hours. Fig. 11(B). In the first place, this is achieved by radical reductions in the magnitudes of the various statistically controllable risks. This is brought about mainly by new requirements specifying extremely low maximum probabilities for such risks (Point 7), and by complying with the requirements by application, to the greatest possible extent, of the fail-safe principle on the basis of advanced mathematical/statistical methods (Point 8).

Secondly, the conceivable but statistically noncontrollable risks are reduced (a) by more stringent airworthiness and other regulations as well as by improvements in education and training of pilots and other personnel important for

flight safety, and (b) by improved standards with regard to design and manufacture of aircraft and ground facilities, etc. (Point 10). This reduction is in essence brought about by employing the same or similar methods as are used at present according to the Accumulated Experience Method. The significant difference is, however, that the efforts are guided by quantitative evaluation, for instance based on statistical records, of the probabilities of failure for such risks or groups of risks.

Figure 11(C), finally, serves to illustrate, for the example of the risk of catastrophic fatigue failures in aircraft structures, how the Probability Share for a statistically controllable kind of accident risk (which might be the accident category No. 8) should be subdivided into statistically independent probabilities of failures. For the case of structural fatigue, I have previously suggested that this Probability Share should be of the order of one in 10^9 hours of flight.[3,30] If this goal can be attained, catastrophic fatigue failures will be likely to occur, in scheduled passenger aviation over the whole world, once in about 30–40 years.
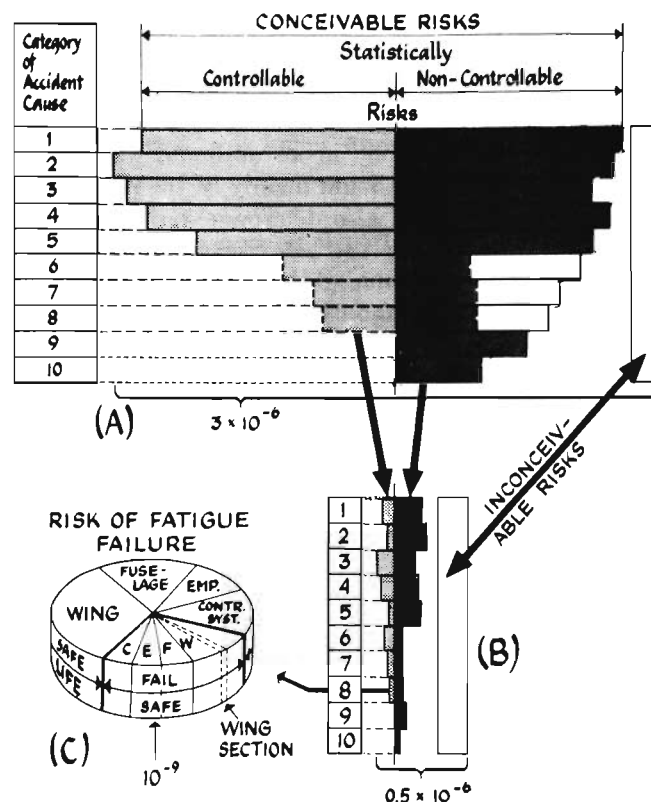
Fig. 11. Schematic illustration of application of the APS method in order to improve flight safety. Fig. 11a is a development of Fig. 9b, and Fig. 11b illustrates how the total risk level is decreased by a factor of 6. Fig. 11c exemplifies subdivision of the probability share for failure due to structural fatigue into one "subshare" for the safe-life elements and another for the fail-safe assemblies, and the further subdivision of these "subshares."

This might be satisfactory for public confidence in safety with respect to such completely "inexcusable" accidents, but it could, nevertheless, be questioned whether we should not attempt to reduce the risk by a further factor of 10 (Ref. 31).

For achieving such a very high safety level, every effort should first be made to avoid completely all safe-life elements, so that the whole Probability Share of 10^{-9}, or 10^{-10}, per hour can be allotted to all the fail-safe structural assemblies for further subdivisions—into "Subshares"—for each assembly such as the wing, fuselage, control systems, etc. However, if safe-life designs cannot be avoided, it is usually efficient with regard to weight to allot a major portion, say 90 percent, of the fatigue Probability Share to the risks for the safe-life elements (even if there is only one such element present in the aircraft). As indicated above, the reason for this is the extreme difficulty to ascertain, for safe-life elements, a very small maximum probability of failure during a reasonably long service life with a satisfactory confidence.

In connection with this example, it might be pointed out that *the application of the APS Method has to be a joint responsibility between authorities, manufacturers and operators.* Appropriate requirements for maximum Probability Shares for potential accident causes such as structural fatigue failures, should be the responsibility of airworthiness authorities, whereas how to comply with the requirements—*inter alia* by subdividing, in an optimum way, the prescribed Probability Share into "Subshares"—should mainly be the responsibility of the manufacturer. In doing so, he should also determine and prescribe inspection frequencies, required for maintaining the safety level corresponding to the "Subshares" for the various fail-safe designed structures and devices. Then it should be the responsibility of the operator to conduct the inspections according to the prescriptions of the manufacturer.

It might finally be emphasized that there is no contradiction between the present Accumulated Experience and the APS Methods; both are required. It is equally important to intensify all possible efforts according to present methods, as it is to adopt and bring the supplemental APS Method into full effect.

The costs and difficulties involved will indeed be great. However, I can think of no investment that will bring greater dividends in the form of a sound and profitable development of civil aviation than to spend a great proportion of available resources of money and brainpower on improvement of flight safety, according to both methods.

We have certainly not struck an optimum balance between safety and economy in civil aviation and we will probably never do so; improvements in safety will always pay.

AIRPORT NOISE

Airport noise—including noise produced during ascent and descent of the aircraft—has become a highly undesirable by-product of aviation and has developed into a controversial issue between aviation and communities. This situation of conflict will undoubtedly become increasingly serious as aviation

continues to grow in the decades to come, unless efficient action is taken in order to counteract further noise increases.

In my opinion, such actions must be agreed upon internationally. At the International Congress of the "Association Internationale contre le Bruit," Salzburg, May 1962, a proposal was made with the subject title "International Long-Term Planning Aiming to Limit Airport Noise."[33] The principal thoughts behind this proposal and its main points will be summarized in the following.

In a long-term perspective, it is obviously in the interest of aviation to create no more disturbance around airports than is compatible with reasonable demands for quietness by the neighboring population. If this is not done, the communities will to a large extent (a) not allow the existing airports to be utilized to their maximum capacity, and (b) not be willing to erect new airports close to the cities or within the city boundaries.

The importance of avoiding such restrictions, for the healthy future growth of civil aviation, simply cannot be overestimated. Considering in particular the spectacular future prospects of V/STOL-aviation, there can be little doubt that *successful developments to reduce engine noise would contribute much more to reductions in total travel time for the majority of air passengers than further increases in flight speed.* The obvious reason for this is the very substantial gains in ground travel time that will follow from close-by airports—in particular V/-STOL airports—which as a rule will only be erected if the noise disturbance can be kept within acceptable limits.

The main difficulties in limiting airport noise lie in the facts:

● that it is not only the maximum noise levels during takeoff that cause annoyances and complaints; the *frequency of noise occurrences* both of maximum and lower levels, as well as the *duration* of each noise occurrence contribute to the total noise disturbance, and

● that there is in general no real incentive for the manufacturers to reduce the noise level of new aircraft types apart from keeping below a certain, usually very high, maximum value.

The proposal made in order to overcome these difficulties, is based on the assumption that there must be a certain relationship, with respect to disturbance effect, between number of noise occurrences and their peak noise levels. A specific quantitative relationship of this kind had been suggested by the Swedish Aircraft Noise Committee.[34] According to this, a decrease of the noise level by 10 db would yield a tenfold increase in number of noise occurrences without the disturbance effect being changed.

The main points of the proposal are that the aircraft should be classified in *aircraft noise classes* indicating noisiness, that the airports should be classified in *airport noise classes* indicating noise sensitivity with regard to built-up areas, and that *an international airport noise register* should be kept, preferably by ICAO, giving information, for each airport, about, *inter alia,* airport noise class, the time when noise saturation is expected to occur (a) with no flight restrictions, and (b) if successive restrictions are applied. Such flight restrictions should normally consist of prohibition of aircraft belonging to the highest aircraft noise

classes, in order to allow a greater number of aircraft movements with more quiet aircraft.

The idea of aircraft and airport noise classes is illustrated by Fig. 12. The noise sensitivity of an airport, and thus its airport noise class, is, *inter alia*, dependent on the distance between the main runway and the "significant observation point" near the houses which are closest to the runway. For simplicity, the noisiness of aircraft—determining the aircraft noise class—with respect to "significant observation points" at various distances from the takeoff point is only illustrated as being dependent on takeoff distance and climb angle, whereas in reality the noise level of the powerplant itself is usually even more significant.

The proposal is believed to overcome the two main difficulties indicated. The main advantages are thought to be:

- that both the manufacturers and the operators would have a direct, quantitatively determinable, interest in developing quieter aircraft, and
- that, in the planning of new airports, noise could be taken into account on a quantitative basis so as to enable the community to weigh the great advantage of a nearby airport against a predictable maximum noise disturbance around the airport.

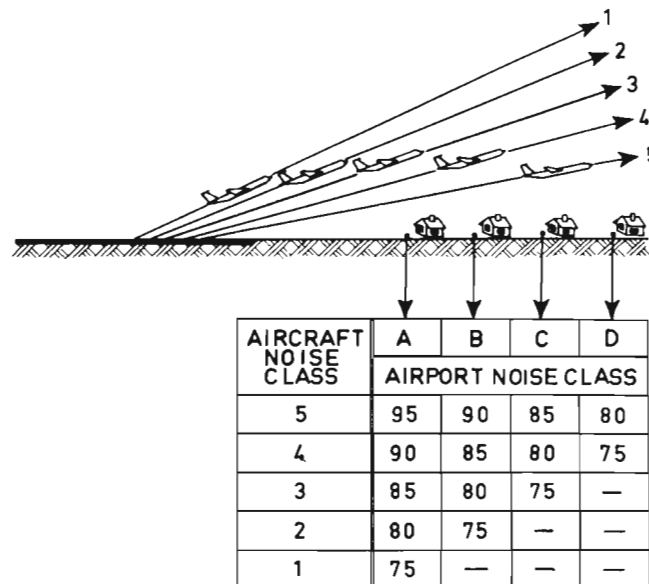| AIRCRAFT NOISE CLASS	A	B	C	D
	AIRPORT NOISE CLASS			
5	95	90	85	80
4	90	85	80	75
3	85	80	75	—
2	80	75	—	—
1	75	—	—	—

Fig. 12. Illustration of the principle of defining aircraft and airport noise classes. The figures in the table indicate the noise level—for instance in $dB(A)$, at the "significant observation point" of the airport, which usually is a point near the house, or houses, closest to the main runway.

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PART III: SPEED VERSUS SAFETY

SUBSONIC AVIATION AND SAFETY

The question whether or not there is a relationship between speed and safety is pertinent with regard to both high cruising speeds, in particular speed increases into the supersonic regime, and to the low-speed end—i.e., stalling speed as well as zero speed for VTOL.

Considering first subsonic speeds, there seems to be little evidence in the past that a close or obvious causal connection exists between *cruising speed and flight safety*. The impressive improvement in the fatality rate up to about 1953 was brought about simultaneously with a continuous increase of the average speed. However, this parallelism in development does not, of course, prove that the increase in cruising speed contributed to the improvement in the safety record. Nor can any direct conclusions be drawn from the fact that the fatality rate has almost stagnated since about 1953, i.e., during the period when rather spectacular speed increases were brought about by the turboprops and turbojets.

If we disregard statistics and try to judge technically the possible causal relationship between speed and safety, there seem to be no reasons why flying at an increased speed would, per se, increase the risks—provided, of course, that the aircraft is designed to withstand the higher loads and is operated so as to prevent collisions with other aircraft or the ground. These are, however, most important provisions.

With regard to structural safety, the two Comet accidents in 1954 should be recalled. Although these were not directly caused by the speed increase as such, it can hardly be denied that there was an indirect relationship between the accident cause (lack in fatigue strength of the pressure cabin) and the relatively large speed increase made, as the latter required an appreciable increase in flight altitude and hence in pressure differential.

In the first place, two direct lessons were learned by these accidents, which were clear examples of a completely unforeseen accident cause. One was that there is a great need for realistic full-scale structural testing of complete assemblies, whenever the design or loading conditions differ appreciably from previous experience; this particular case led to the very efficient method of water-tank testing, introduced by Dr. P. B. Walker.[1]

The other lesson was that only by these accidents was it convincingly demonstrated that the current airworthiness requirements (implying application of a factor of safety on *static load* to insure sufficient *fatigue life*) were entirely inadequate, although these requirements had been heavily criticized before.[2,3]

Even more important is, however, the general lesson to be learned by these occurrences, namely that developments in civil aviation should be performed cautiously and in moderate steps, both with regard to speed and to the number of radically new features introduced at one and the same time: The introduction of merely *one* radically new feature (jet propulsion for the case of Comet I) can result in unforeseen—or unforeseeable—secondary accident causes. However, as this lesson has now been learned in subsonic aviation and as near-sonic speeds

have been achieved for medium- and long-range jetliners, there is no reason why speed increases into the transonic regime could not be made also for other categories of aircraft without adverse effects on airworthiness.

With respect to operation and disregarding first the takeoff and landing phases, it is almost exclusively the risks of collisions between aircraft that might be increased as speed goes up, mainly because of the limited reaction time of the pilot. However, this increase in risk can be counteracted or compensated, or even more than compensated, by improvements in air-traffic control and collision-warning equipment, together with more stringent regulations with regard to separation distances, etc.

The takeoff and landing phases are for conventional types of aircraft, i.e., "long takeoff and landing aircraft," characterized by movement at a high speed on and close to the hard and "unforgivable" ground, whereby rather precise maneuvers are required. The importance of these two phases with respect to safety is borne out by the fact that more than half of all accidents in commercial aviation occur in connection with leaving and returning to ground. There can be little doubt that increases in the takeoff and landing speed must necessarily be accompanied by increased risks at given levels of pilot skill, of stability and handling qualities of the aircraft, of equipment for facilitating the maneuvers, and at given regulations with regard to runway length in relation to takeoff and landing distances, etc. In principle, one can, of course, visualize improvements in these respects sufficient to compensate for the adverse effect on safety of increases in takeoff and landing speed, but in practice this is very difficult to achieve.

Available statistics do not actually prove that the relative number of takeoff and landing accidents has increased, parallel with the increases in takeoff and landing speeds that have developed. However, this, in my opinion, is not the important point. What is important is that very appreciable future reductions of the number of takeoff and landing accidents is a "must" for achieving the urgently needed improvement of the overall level of flight safety.

As is well known, the continuous increase of the takeoff and landing speeds— i.e., essentially of the stalling speed—has been caused by the desire to achieve higher and higher cruising speeds. *It is, in fact, this interconnection between cruising and stalling speeds that constitutes the only significant causal relationship between subsonic cruising speed and safety.* With respect to safety, it is a most deplorable fact that the many improvements that have been made to increase the maximum lift coefficient of the wing have usually not been utilized to reduce the stalling speed but used instead to decrease the wing area and thereby to reduce drag and thus increase flight speed.

It is hardly worthwhile speculating whether or not a more cautious development in the past would have contributed more to the growth of civil aviation (by virtue of a higher public confidence in safety due to fewer accidents) than the actual course of development by which the passengers have rather rapidly enjoyed attractive time savings due to the emphasis on high cruising speed. As, however, the cruising speed for modern jetliners has now reached very high values—below ranges of 2,000 miles, often approaching the "Worthwhile Cutoff

Speed Limit"—it is, in my opinion, altogether important to concentrate, from now on, on achieving lower stalling speeds. Further increases in subsonic cruising speed (for categories of aircraft that have not already been designed for near-sonic speed) should be striven for only if they can be achieved without increases in stalling speed or, still better, simultaneously with decreases in stalling speed. Strenuous efforts in this direction would, in fact, imply one of the most important aeronautical developments conceivable for the furthering of civil aviation.

As a matter of fact, the development towards higher and higher takeoff and landing speeds appears recently to have reached its climax. This has, at least partly, been brought about by what can be called a refusal on behalf of communities to provide longer runways than some 10,000 to 12,000 ft. There can be little doubt that this has contributed to make the aircraft designers more inclined to concentrate on improved high-lift devices and to utilize the improvements primarily for reduction in stalling speed rather than for further speed increases.

It thus appears that very important technical prerequisites are at hand for a future development in subsonic aviation that is most favorable with regard to safety in the critical takeoff and landing phases. It is then obviously extremely important that these prerequisites are, so to speak, followed up by successive introduction of more stringent regulations, at least for new types of aircraft, with respect to such parameters as accelerate-stop distance and stalling speed. As is well known, there is a widespread contention that accelerate-stop distances for the first generation long-range jetliners are hardly satisfactory, considering normal day-to-day operating conditions including, in particular, occurrences of slippery runways.

The introduction of new types of aircraft with reduced takeoff and landing speeds will necessarily be a slow process. It is therefore most important to try to improve safety with respect to takeoff and landing also by other means, in particular because these stages of operation account for most accidents. Only two examples will be mentioned here.

One possible way would be to utilize the developments now in sight towards full, or almost full, automatic landing techniques not primarily to achieve better regularity in low-visibility weather but rather to improve safety in such weather conditions: Improvement in regularity by such developments should be brought about only when the new techniques have manifested themselves as a means of improved safety.

Another way would be to agree internationally on a requirement that civil airports, at least those for commercial aviation, should be equipped with arresting gears in order to reduce appreciably the hazards due to overshooting in landings and interrupted takeoffs. Such arresting gears have been erected on many airports and have already prevented many overshoots from resulting in fatal accidents.

The issue of speed versus safety is of a somewhat different character with regard to *VTOL aircraft and aircraft with pronounced STOL properties* as compared with conventional aircraft. The reason for this is that for such aircraft there is no or fairly little relationship between the minimum and cruising speeds. The safety of VTOL and STOL aircraft constitutes therefore a special field for

research and development. In view of the anticipated spectacular growth of V/STOL aviation, this area of the science of flight safety is of utmost importance and must to a great extent be treated by considerations other than those applicable for conventional aircraft. The stability and maneuvering problems at zero or low speed pose, for instance, special problems which seemingly can be met only by application of rather sophisticated mechanical, electronic, and other systems.

V/STOL aircraft present special problems differing from those of conventional aircraft also with regard to the number of engines required with respect to safety. In general, the failure of a certain percentage of the engines is more critical for V/STOL than for conventional aircraft. Consequently, it is, in principle, necessary for V/STOL aircraft to have a greater number of independent power-plants at a given reliability of the engines.[4,5]

In these two, as well as in other, respects it appears to be particularly important that the safety of V/STOL aircraft is insured by application of the fail-safe principle, guided by quantitative statistical requirements and methods. Such a basis for the safety of V/STOL aviation would be obtained as a consequence of an adoption of the APS method proposed in Part II of this paper.

Once the special safety problems connected with V/STOL aviation in this way are under control, it is conceivable that such aviation will be even safer than flying with conventional aircraft because of the steep angles at which V/STOL aircraft can leave and approach the ground.

To sum up, the following conclusions are drawn:

1. *Crusing speeds* close to the speed of sound can be achieved, also for categories of aircraft which have not yet attained such speeds, parallel with an essentially improved safety level successively brought about, as advocated in Part II, provided

- that, besides a general statistical approach to the whole safety issue, strenuous efforts are made to lower takeoff and landing speeds and distances,
- that the regulations with regard to accelerate-stop distance in relation to runway length are successively sharpened in the decades to come,
- that efficient means are installed, for preventing overshoots during landing from resulting in fatal accidents, preferably on all civil airports, and, naturally,
- that the ATC regulations adequately keep in pace with the speed increases as well as with the intensified air traffic.

2. In the low-speed end, *V/STOL aviation* can also be introduced on a large scale without hampering successive improvements in safety, provided

- that V/STOL developments take place in a cautious way, implying, in particular, that few—if possible only one—radically new features are introduced simultaneously on each new aircraft type, and
- that in particular stability and control as well as "engine-out" performances are assessed on the basis of the fail-safe principle, guided by adequate quantitative statistical requirements and methods.

SUPERSONIC AVIATION AND SAFETY

In contrast to conditions in the subsonic regime, there can be little doubt that introduction of SST's will in many ways affect safety in civil aviation. Using the definitions made in Part II of this paper, the interrelation between supersonic speed and safety can be grouped into four main aspects:

- The flight safety of the SST itself and its operation.
- The influence of the operation of SST's on the flight safety in subsonic aviation.
- The effects on public-injury safety of sonic booms.
- The effects on flight-injury safety of cosmic radiation at high supersonic flight altitudes.

THE FLIGHT SAFETY OF THE SST AND ITS OPERATION

GENERAL ASPECTS

With regard to flight safety in supersonic aviation, no conclusions can be drawn from the past experience of subsonic developments indicating rather limited interrelation between speed and safety. The reason for this is threefold:

1. Subsonic speed increases in civil aviation have, ever since the time of the Wright brothers, been made in fairly moderate steps, usually only some 10 to 20 percent at a time (see Fig. 2, Part I). When a much bigger speed jump, of some 60 percent, was taken in 1952 by Comet I—without adequate military background experience of large jet transports—it was accompanied by serious accidents, although the cause, as mentioned, was only indirectly connected with the speed increase. Only when this speed jump was repeated six years later, and was backed up by military experience, was the speed increase insured with a safety level usually considered as satisfactory.

In comparison, a Mach 2.2 SST would mean an unprecedented leap in speed of no less than about 150 percent (for Mach 3, 250 percent). With such increases, *"ballistic" speeds will be reached,* which will bring about special safety problems of an operational nature, as will be discussed later.

2. Probably even more serious than the big speed increase as such is the fact that the SST's will fly in what can best be described as a new "medium," because the air behaves in a pronouncedly different way at supersonic speeds (causing, in particular, wave drag and kinetic heating) and because the SST's will fly at a much higher altitude than previous types of civil aircraft. For these reasons, supersonic flight cannot be achieved without *simultaneous introduction of an unprecedented number of radically new design features.*

3. With rather few exceptions, great speed increases by new commercial aircraft types have not been made since World War I without military aircraft of similar design and size having achieved the higher speed several years earlier. If there ever were such a need for military background experience, it would be for the exceptionally big speed jump—into rather unfamiliar environmental conditions—that is now contemplated in civil aviation. The need for such experience is emphasized by the fact that the integrity of the SST structure, and many of its systems, is time-dependent, to a much greater extent than has ever

been the case before, because of the kinetic heating. Thus, a background experience for SST's, equivalent to that enjoyed in the past, would call for a decade or more of flying with military supersonic transports of closely similar design. Now, it appears that *the SST might be introduced without any really relevant military background experience whatsoever.*

It is probably these three well-known facts that have caused ICAO to stress the importance of adequate safety. In its report of August 1960 the following statement[6] was made:

> Supersonic airliners, when put into commercial use, must . . . have a level of safety equal to that achieved by commercial aircraft in use at that time.

This appears to be quite a reassuring statement, but the great difficulty is to prove compliance with this general safety requirement. As explained in Part II, the overall level of safety for a new type of aircraft cannot be definitely proved in any other way than by extensive service experience: It would, for instance, take about five years of flying with 100 SST's at an average utilization of 3,000 hours per year to show whether or not the safety level of the SST's and their operation were the same as the overall safety level in commercial aviation (and, still, this would only indicate the safety level during the first 15,000 flight hours of each SST).

It can, of course, be objected that this applies to any new type of aircraft. This is essentially correct (although the kinetic heating of the SST's makes their risk level particularly uncertain as flight time is accumulated); and it is, in fact, a main reason why a quantitative statistical approach to the flight-safety problem is so urgently needed. Only by this approach can the level of safety of a new type of aircraft be *partly* predetermined and controlled, namely with regard to a portion of the preconceivable accident causes (see Figs. 9 and 11 of Part II).

Let us therefore make a comparison between a new type of subsonic aircraft and an SST project assuming that both are designed on a quantitative statistical basis. The new subsonic project can be assumed to be designed according to the "one novelty at a time" policy, as has with few exceptions been the rule in the past (for instance, the cantilever wing, stressed-skin construction, the retractable landing gear, the nose wheel, jet propulsion, swept wings, and rearmounted jet engines).

In contrast, the first SST project must, as already explained, by necessity incorporate many entirely new design features in addition to new and severe environmental and operational flight conditions. Just to mention a few examples, the configuration of the SST will differ greatly from subsonic types, for instance the wing and stabilizing surfaces (arrangements such as the canard type and variable sweep of the wing being contemplated), the exceptionally long fuselage, and the unusually high position of the pilot over the ground when landing. Furthermore, new materials for the structure as well as for equipment, and new and complex design principles must be used in order to resist the kinetic heating, the effect of the high ozone content at supersonic flight altitudes, and possibly

also cosmic radiation if this is detrimental to normal types of material. The engines will be of new types and must be equipped with sophisticated variable geometry air intakes to cope with both subsonic and supersonic flow conditions, and the fuel and the many other systems, in particular for cooling and air-conditioning, must to a large extent be designed according to complex and new principles. Automatic instead of manual controls for the maneuvering of the aircraft and handling of its various systems will be even more necessary than with present jet aircraft and will require more sophisticated solutions.[7] In addition to all these new design features, the first types of SST's are likely to have at least the same, probably higher, takeoff and landing speeds as the first generation of jetliners, and thus the present favorable trend towards reduced speeds close to the ground will be broken.

On the other hand, one must take into account the rapid progress in science and technology that is being made, as is so amply demonstrated by the spec-tacular achievements in space technology. In view of this, I have no doubt that practically all of the host of new problems confronting the SST can be technically solved in the common, largely nonstatistical, meaning of the word "solved." This is, however, *not* sufficient when it comes to the high demands on safety that civil aviation must comply with. This is, of course, commonly appreciated in a general way, but I do think it is significant to emphasize that the demands for low probabilities of fatal accidents in commercial air transportation, offered to millions of ticket-paying passengers, differ by many orders of magnitude from the risk level that must be accepted by the crew of spacecraft. One must always bear in mind the very small order of magnitude of the acceptable risk of fatal accidents in commercial aviation (about one in 10^6 hours of flight), and the fact that this total risk is the sum of an exceedingly great number of separate risks (according to all potential accident causes) each of which, therefore, has to be extremely small.

Reverting now to our comparison, it is difficult enough—or, in fact, impossible —to foresee all the potential hazards even for the case of the new subsonic project incorporating only one basically new feature. Every new aircraft type, even if designed and operated according to conventional principles, is accom-panied by not only foreseeable risks, which *can* be coped with, but also by unforeseeable risks, which by nature cannot be dealt with in advance by any technical measures. If merely one radically new feature or operational condition is introduced in an aircraft project, the number and magnitude of in particular the unforeseeable risks are appreciably increased. This is demonstrated in practice by the so-called "learning period" of a basically new type of aircraft, during which period the rate of incidents and/or accidents is higher than the average for older aircraft.[5,8]

The introduction simultaneously of a great number of radically new features, design principles and operational conditions, inevitable with the SST's, must by necessity greatly increase the number and magnitude of unforeseeable risks. In the first place, all the unforeseeable risks directly accompanying each novelty are added together. This is by itself serious. However, over and above this, the introduction of several new features in one development step will often give rise

to a magnifying effect—i.e., to additional accident risks—and, again, only a portion of these will be preconceivable.

One reason for this is that the various structural assemblies and systems of new designs are not always "statistically independent" of each other. Thus, one, by itself harmless, fault or incident occurring in system A (say in the cooling system) might increase the risks of serious failures of one or more other systems, B, C, or D, the proper functionings of which are dependent upon the proper functioning of system A. It is, furthermore, quite conceivable that faults in two or more systems occurring during one flight might lead to a fatal accident even if there are no interactions between them and even if each fault alone would not be disastrous. The crew might just be able to cope with one such major defect at a time, but not with two or more simultaneously.

However, even if this magnifying effect could be disregarded, the fact that the total magnitude of the unforeseeable risks must increase at least in proportion to the number of technical and operational novelties is most significant as the SST and its operation must incorporate a dozen or more radical novelties rather than the traditional policy of one or two. This makes it, indeed, very probable that the sum of the unforeseeable risks for the SST's will be not only greater than the sum of their preconceivable risks, but also greater than the average risk level in scheduled aviation. This would mean that

- even if every effort is made to conceive of as many accident risks as possible for the SST and its operation, and
- even if all the conceivable risks could be made statistically controllable and then be reduced to such exceedingly small values that their sum would be a negligible quantity (say 1 percent of the average accident rate in scheduled aviation), and
- the factual total risk level for supersonic aviation (then consequently comprising mainly unforeseeable risks) will be appreciably higher than for subsonic aviation.

As, however, it is, for weight and other reasons, not possible to reduce the conceivable risks to a negligible quantity in comparison with the average risk level, *it is concluded that the sum of the preconceivable and unforeseeable risks in supersonic aviation will necessarily be much greater than the present average for civil scheduled aviation.*

To sum up,

- it will not be possible to demonstrate compliance with the ICAO requirement of the same overall safety level for SST's as for subsonic aircraft, and
- the flight safety of the SST's will, in all probability, be appreciably inferior to that of contemporary airliners.

These general statistical observations will now be supplemented by brief discussions of two safety problems, pertinent to the SST, for which it appears to be particularly difficult to insure acceptably low probabilities of fatal accidents, namely the structural safety of aerodynamically heated structures and the operational safety at supersonic speeds.

STRUCTURAL SAFETY OF AERODYNAMICALLY HEATED STRUCTURES

The aerodynamic or kinetic heating will have two somewhat interrelated effects on the safety and reliability of SST structures compared with subsonic aircraft: The *scatter* in fatigue life and other fatigue properties in actual service will be greater, and it will be more difficult to *predict* the reliability and safety of the SST structures.

With regard to *scatter*, one has to consider the combined effects of

● the "*inherent scatter*" defined as the scatter in fatigue properties between nominally identical structural parts and assemblies subjected to identical loading and heating "histories" typical for service conditions, and

● the "*service-experience scatter*," defined as the variations in the load/temperature histories that individual SST's will experience during their entire service life.

The "*inherent scatter*" in the essential fatigue properties (such as the life until initiation of the first crack, the crack propagation rate, the number of cracks that will appear in a certain life increment, the reduction in residual strength due to cracks, etc.) is for any structural parts and assemblies mainly due to variations in the material itself and to variations in the manufacture. If these variations are the same in subsonic and supersonic structures, it seems inevitable that a structure that is subjected not only to cyclic stresses but also to repeated cycles of heating and cooling—giving rise to thermal stresses and possibly also creep and changes in static strength and elasticity—must display greater deviations from the mean values of the fatigue properties than a "cold" structure merely subjected to repeated loading cycles in a temperature region having negligible thermal effects. The main reasons for this are

● that there is a greater number of basic material properties, such as those depending upon the chemical composition, which will display variations significant for the heat/load fatigue properties, and

● that manufacturing tolerances, in particular in splices and interconnections, will cause variations in heat conductivity characteristics.

How great the difference in the "inherent scatter" between SST and "cold" aircraft structures with regard to fatigue properties will be for various kinds of structural components is, of course, impossible to estimate at this stage. To assess this is, in fact, a research field of fundamental importance for the design of SST's. It calls for large sample size testing, but this can only to a limited extent be carried out with small specimens. For reasons explained later, nominally identical full-scale structural parts and assemblies closely representative of typical SST designs must be tested in great numbers in order to assess the scatter with a sufficient confidence.

With regard to the "*service-experience scatter*," which depends entirely upon operation and the properties of the atmosphere, it is, obviously, hardly possible to made an adequate comparison between long-range subsonic aircraft and SST's, because for the latter the new parameter of high temperature is introduced. The most important thing is, however, not this scatter as such but the

scatter in fatigue life and other fatigue properties that *results* from the service-experience scatter. Nevertheless, a comparison with regard to the scatter in service experience is of some significance.

To begin with, it seems probable that the scatter in gust loads for long-range subsonic aircraft is greater than it will be for SST's. The main reason for this is the fact that one has to expect greater variations in the operation of subsonic jets with regard to climb and descent procedure as well as route length and cruise altitude, together with the fact that the number of gusts in the subsonic flight profiles is probably greater than in typical supersonic flight patterns. For the SST's, climb and descent through the more turbulent air at low altitudes takes place in a shorter time and their high cruise altitudes between 60,000 and 80,000 ft are believed to be less gusty than the "subsonic" flight altitudes, although severe jet streams and turbulent conditions have been observed also in the stratosphere.

The introduction of high temperatures affecting the SST structures will, however, mean a new scatter source with respect to "service experience." This will very appreciably add to the scatter in the gust and other fluctuating loads (such as the cabin pressure loads) and thus magnify the scatter in the resulting fatigue life of the various elements of an SST structure. Considering first the scatter in temperature as such, the actual external surface temperature at various points of the SST structure is the most significant parameter. As this is closely dependent upon the adiabatic wall temperature, the scatter in surface temperature arises mainly from variations in ambient temperature and in Mach number at supersonic cruise altitudes.

The deviations from the temperature of the ICAO standard atmosphere at any altitude in the significant bracket of about 40,000 to 80,000 ft is quite appreciable, considering geographical, seasonal, and day-to-day variations. As high ambient temperatures are the most significant, it should be noted that the temperature in the stratosphere in some geographical regions is often some 10 to 15°C above standard and that deviations of as much as 20° to 25°C might occur occasionally.[9,10] Now, the increment in adiabatic wall temperature will be the same as the increment in ambient temperature, if the speed in mph is constant, but will be considerably greater if the speed in Mach number (and thus the dynamic pressure) is kept constant. The wall-temperature increment will, for instance, be nearly twice the ambient temperature increment for a Mach 2.2 SST and 2.6 times for a Mach 3 SST. Comparing operation on different routes having different overall ambient temperatures, a Mach 2.2 SST can thus rather often be subjected to increases in adiabatic wall temperatures of some 20 to 30°C, and increments as high as 40 to 50°C might occur occasionally during the service life. Thus the adiabatic wall temperature of a Mach 2.2 SST could increase from the nominal value of about 130°C to about 170 to 180°C. If aluminum-based light alloys are used, it is, therefore, probable that speed restrictions, possibly accompanied by changes in flight altitude, have to be imposed with regard to the atmospheric temperature (which will adversely affect fuel consumption), but even so, appreciable variations in surface temperature can hardly be avoided.

The surface temperature will also vary as a consequence of variations in ambient temperature along the flight route at one and the same flight, in particular when flying into regions of exceptionally high temperatures. In this case the air speed in mph will be given and the increment in adiabatic wall temperature will be equal to the increment in ambient temperature. To counteract this effect, the speed will have to be reduced before entering the hot zone. However, even if such speed adjustments are attempted, appreciable variations in surface temperature during the flight will be inevitable.

Comparing next the scatter in fatigue life and other fatigue properties that will *result* from the "service-experience scatter," it might be recalled that for "cold" structures the sequence in which high and low fluctuating loads are applied, as well as the detailed composition of the load cycles, greatly affect the fatigue life.[11] Now the introduction of high temperatures does not mean only introduction of one more variable; it means in fact introduction of a virtually infinite number of new and greatly varying conditions with respect to temperature/load/time histories. Thus the appreciable "service-experience scatter" with regard to surface temperature will result in great variations between different flights in the detailed internal pattern of increases and decreases in temperature. As a consequence there will be great variations between flights in the pattern of thermal stresses while the "heat front" moves into and out of the structure during the course of acceleration to and deceleration from supersonic cruise speed, as well as during supersonic cruise when a more or less stationary internal temperature distribution is established. These heating and cooling histories and their thermal effects are, furthermore, intermixed with and superimposed upon the—also varying—histories of fluctuating loads.

In judging the implication of this additional scatter source of high temperature, it should in particular be observed that the simultaneous occurrence of transient thermal stresses and high "load stresses" due to high gust loads are likely to lead to appreciable plastic deformations in highly stressed portions of the structure more often and/or in a greater number of locations for the case of SST than for subsonic structures for which such deformations are only caused by high stresses due to loads. It must, inter alia, be observed that the elastic-plastic properties (the stress-strain curve) of the material might be locally impaired under the influence of some 10,000 to 20,000 temperature cycles during a total heating duration of the order of 25,000 hours. Likewise it would appear that unintentional, deleterious buckling—temporary or permanent—of spar webs and the like will more easily occur in the SST structures, even considering that comparisons are difficult to make between conventional subsonic structures and the more sophisticated design that are likely to be used in the SST's (utilizing, for instance, special strain-relieving techniques).

Plastic deformations and buckling are often beneficial with regard to fatigue in the places where they occur, but the significant aspect is that they do in many cases have an adverse effect in other regions. The main reason for this is that such deformations will sometimes cause appreciable changes in the stress distribution both for complicated major fittings and in fail-safe designed structural assemblies. After such redistributions have occurred, other portions of the

structure than those that have been deformed will be subjected to a higher overall stress level. Thus the subsequent fatigue loading conditions, with respect both to the mean stress and to the stress amplitudes, might locally be appreciably more severe than the pattern calculated or measured for the "virgin" structure.

For the reasons indicated it seems inevitable that the "service experience scatter" will result in a much greater scatter in the fatigue life of structural parts of SST's as compared with the case of subsonic aircraft, even if the "inherent scatter" in the fatigue properties of the structure were negligible in both cases.

Thus not only the "inherent scatter" in significant fatigue properties but also the scatter in fatigue life resulting from the "service-experience scatter" will in all probability be considerably greater for the case of SST's than for subsonic aircraft. The combined effect therefore will be an even greater difference in the total scatter in the fatigue properties essential for safety and reliability.

For subsonic aircraft structures the knowledge about the "inherent scatter" in fatigue has now grown to the point where the order of magnitude of the standard deviation can be at least roughly predicted.[12] We have also today a rather good knowledge of the "service-experience scatter" and its effect on fatigue life for subsonic aircraft. This knowledge is of great importance with regard to the possibility of designing subsonic aircraft structures so as to insure a required structural safety.

In contrast, it seems at present impossible to estimate how much greater the total scatter in the fatigue properties of SST's will be. To obtain about the same knowledge of the total scatter in the fatigue life of SST structures as for subsonic structures hardly appears to be possible in the foreseeable future, considering the nature and tremendous cost of the testing that it would involve. Nevertheless, such a knowledge obviously would be necessary for assessing the safety and reliability of SST structures with the same confidence as that obtainable for subsonic structures.

Such a knowledge is also needed for estimating the required testing time, because with increased scatter it will be necessary to apply higher "safety factors on life" for SST structures than for subsonic ones. This applies not only to safe-life parts but also to the various elements or portions of fail-safe assemblies. The reason for this is that the safety of a fail-safe structure for a given inspection schedule is dependent upon the probability of failure of the elements of the structure.[13,14]

A simple example might be presented: It is assumed that the allowable probability of an "element failure" in a fail-safe subsonic structural assembly is of the order of 5 percent during a service life of 40,000 hours. It is furthermore assumed that for the elements of a subsonic structure the standard deviation, with regard to the "inherent scatter," of the logarithm of the service time to failure (assuming log-normal distribution) is[12] 0.15, and that the standard deviation for the total scatter, thus incorporating also the effect of the "service-experience scatter," is increased to 0.2. This implies that the required mean life of the elements would be about 85,000 hours in actual service. If, now, the standard deviation for the total scatter in the fatigue life of corresponding elements of an SST structure is twice as big, i.e., 0.4, then the required mean

life of the SST elements would be about 180,000 hours. The safety factor referred to the mean life would thus have to be more than twice as big for the SST structure as for the subsonic one.

The bigger scatter in life and other fatigue properties has three main implications:

● The safety factor on life and thus the testing time for each specimen must be much longer for SST elements than for subsonic elements for this reason alone.

● The stress level for the SST structure has to be reduced merely to account for its bigger scatter in fatigue life in order to insure safety and an acceptably low defect and repair rate.

● To obtain the same confidence in the assessment of the scatter, a considerably greater number of nominally identical specimens must be tested for the case of SST structures than for subsonic structures. (It should, however, be observed that an increase in sample size reduces the demand on testing time for each specimen.)

These observations lead us over to consider the second main aspect, namely *the possibility to predict the safety and reliability of SST structures*. This possibility is mainly dependent upon:

● the feasibility of conducting an adequate amount of fatigue testing in particular with regard to *testing time*, and

● *the great total scatter as such* in the fatigue properties of the SST structure.

Over and above the need for greater safety factors on life there are three main reasons why the testing time for development and checking of SST structures with regard to fatigue will be much longer than for subsonic structures:

1. The most important reason is that, whereas fatigue testing of "cold" structures can be conducted in rather short time using high-frequency machines, the introduction of elevated temperatures will make this impossible or greatly reduce the possibility of accelerating the te ts in relation to actual service time. In the first place there is, in principle, no reliable means of "compressing" the testing time when temperatures are involved high enough to cause appreciable changes in the basic properties of the material (such as tensile strength and the elastic properties) or permanent deformations, in particular due to creep: The test specimen has to be subjected to heating during a testing time that must be even longer than the portion of the service life when the SST will be kinetically heated, because a safety factor on life has to be applied. Thus, if, for instance, the supersonic portion of the service life is 20,000 hours and the safety factor has to be 4, then one single test would take 80,000 hours, i.e., about 10 years.

It is thus most important to determine whether, in particular, creep can be neglected (avoidance of appreciable changes of the material properties due to the kinetic heating being a more basic prerequisite). At first sight this seems possible; with a proper choice of material the relatively low 1 g stress level that must be applied for SST structures* will probably not cause a permanent strain

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* The main reasons for this lie normally in the greater magnitude of the acceleration increment due to the critical gust load (e.g., 50 fps), temperature effects on the material, thermal stresses, and the greater number, for a given service life in flight hours, of both air-ground-air cycles and gust loads.

exceeding the magnitude (0.1 to 0.2 percent) usually considered acceptable with regard to permanent deformation of subsonic structures after application of the limit load. Whether or not this criterion for permissible permanent strain is adequate when it comes to creep is, however, an open question.

First, it is hardly possible in local regions of the structure (for instance within complicated fittings) to prevent the 1 g stresses from being appreciably higher than the nominal, or design, 1 g stress level. There might thus be appreciable *local creep* even if this does not result in noticeable permanent deformation of the whole structure. The same as for the local plastic deformation, discussed above, due to short-time application of high loads and transient thermal stresses, local creep might improve the fatigue life, in particular where it occurs, but again the significant thing is that it might impair the fatigue life of other locations, mainly due to redistributions of the load and stress patterns. This is important, because creep, even if it is below 0.1 percent strain, will continuously cause such changes in the stress distribution throughout the service life. Furthermore, these changes, although perhaps very moderate, will be superimposed on the changes in stress distribution that might occur as a consequence of local plastic deformation due to repeated transient thermal stresses and "load stresses" as discussed above. Finally, it should be observed that there is evidence that creep is accelerated by alternating stresses.[15]

It thus appears that even if the overall stress/temperature combination is such that the creep strain for the main portions of the structure will be well below say 0.1 percent, it might be advisable to conduct "full-time" heat/load tests on SST structures—i.e., apply a testing time equal to that of the supersonic flight time multiplied by an adequate safety factor. To eliminate the long time for supersonic cruise *might* thus be unsafe as the test may not then represent what really happens in the structure in actual service.

Let us nevertheless assume that the creep effects can be safely neglected. Then testing involving heating cycles will still appreciably increase the total testing time for an SST structure, because of the fact that it takes some time for the test structure to attain equilibrium conditions with regard to temperature in simulating the effects of acceleration of the SST to supersonic speed and deceleration to subsonic speed. It is necessary to run the test until stationary thermal conditions have been established in order to simulate the actual thermal stresses. To accelerate appreciably the tests by applying higher skin temperature than in reality is not feasible, because that would give erroneous thermal stresses and unduly great creep and similar effects.

2. In addition to these effects on testing time of the kinetic heating, the time for testing of such SST structures for which the fatigue life is dependent mainly upon number of flights (e.g., landing gear and pressure cabin) will be increased over that of testing structures of subsonic long-range aircraft, because the SST's will on the average make a greater number of flights during the service life. Even if due consideration is given to the range flexibility of the subsonic aircraft, implying that they might make a great number of comparatively short flights, a Mach 2 SST is likely to make at least some 50 percent and a Mach 3 SST some 100 percent more flights than the subsonic jet.

Thus also the "cold" portion of the tests with certain SST structural assemblies will be considerably longer than for structures of comparable subsonic aircraft. This is important for the case of full-scale testing of heavy components and assemblies as the time for such "cold" tests is appreciable; it cannot be "compressed" as much as tests with smaller specimens.

3. The third main reason for the long testing times for SST structures is the fact that the extreme complexity of their internal stress/strain conditions makes it necessary to resort to full-scale testing to a much greater extent than is required for subsonic structures. For the latter, small-specimen tests give rather reliable background design information with regard not only to the basic static and fatigue properties of the material (using so-called coupon tests) but also to the properties of built-up components containing, for instance, riveted or welded joints. The great advantage with small-specimen testing is that it is relatively cheap and can be rapidly conducted, and it is therefore possible to employ large sample sizes which lend themselves to reliable statistical evaluations.

When appreciable temperatures are involved, this is much less feasible and for many important cases not at all possible: High-frequency machines can be used for assessing certain of the fatigue properties significant for SST materials, namely *after* very long periods of heating (in loaded or unloaded conditions) as well as *during* the application of a constant high temperature for the same time as that required for the high-speed fatigue test. Such tests are valuable, and are used, mainly for selection and development of heat-resistant materials.

The thermal stresses in SST structures—the most significant effect of kinetic heating—can, however, hardly be reproduced in a fully representative way by testing small specimens. The reason for this lies in the fact that the transient and stationary thermal stresses in any region of the heat-effected structure are dependent upon the very presence of the adjacent structural regions. It is thus not possible to "cut out" a small coupon and yet retain its actual stress and strain conditions.

The need for resorting mainly to full-time- or, at least, long-duration-full-scale tests for SST structures has a much wider implication than if it were only a question of check-tests of the final design. The designer must have a considerable amount of reliable design information upon which the design can be based. As this cannot be obtained by large sample size, small-specimen testing to even nearly the same extent as for "cold" structures, there is a much greater need for full-scale testing of vital components and structures representative of the intended design. Considering, for example, the wing structure, the time required for such preliminary tests simulating a service life of 40,000 hours is likely to be some 5,000 or 10,000 hours (thus about a year or more) if creep effects are assumed to be negligible. If creep and similar effects are to be investigated, the testing time would be of the order of 25,000 hours—i.e., three to four years, depending upon the time required for inspections. These testing times should be multiplied by appropriate factors of safety, the magnitude of which depends upon the sample size as stated above. The factor will probably have to be something like 3 to 5 considering a sample size of about 100.

It is thus not only the great total scatter as such in the fatigue properties of SST structures that calls for much bigger sample sizes than those normally used for full-scale testing of subsonic structures. This is also motivated by the desirability of reducing the required safety factor on time that must be applied in the long-duration full-scale tests of major portions of SST structures in the course of the development work. For cost reasons it is, however, not feasible to conduct full-scale long-duration tests of SST structures with sample sizes of the order of 100. With all likelihood no more than about a dozen tests with a typical major structural component or assembly will be run simultaneously (for example, four test series with three different load/temperature histories representing significant possible service experience with regard to factors such as, how early in the service life particularly high values of load and/or temperature occur). Such a limited sample size can yield only a rather rudimentary idea of the total scatter. Thus the possibility of applying small safety factors on time for the development tests appears to be very limited indeed.

It should, furthermore, be observed that the designer cannot as a rule strike the optimum solution or a satisfactory detail design at once. New or modified solutions or appreciable reinforcements are often likely to be needed during the design stage, and the modified designs can hardly be fully relied upon without new tests. Thus the total program for structural testing in the development stage will in many cases comprise two or more phases of subsequent testing of vital components or portions of main assemblies, and the testing time for each phase should include factors of safety chosen with due consideration of the small sample size that can be applied.

Finally, there is an even greater need for SST structures than for subsonic structures to conduct full-scale testing of the final designs of the various main assemblies, such as the pressure cabin, or at least substantial portions thereof. This is necessary both for demonstrating compliance with safety requirements and for indicating to the customers that the defect rate during the whole service life is likely to be acceptable. For such final tests a considerable safety factor on life should be applied, as has been customary in the past.

To sum up, for the four main reasons of
● much bigger total scatter in the fatigue properties,
● the impossibility to simulate kinetic-heating effects by high-frequency testing machines,
● the great number of flights during the service life, and
● the much greater need for full-scale testing,

I am convinced that the total amount of testing that would be required for efficient development of SST structures and for assessing their safety and reliability *with the same confidence* as that currently obtainable for subsonic structures is several orders of magnitude greater than that required for subsonic structures. As such extensive laboratory testing just is not economically feasible to conduct—disregarding that it would take a decade or more—it does not appear to be possible to predict the safety and reliability of SST structures with even nearly the same confidence as that with which safety and reliability of subsonic structures can be presently assessed.

Over and above the impossibility to predict safety and reliability of SST structures satisfactorily on the basis of laboratory testing, the greater total scatter in the fatigue properties of the SST structure makes it much more difficult to base the predictions on service experience, than for the case of subsonic structures. This should be obvious, because the greater scatter implies that it will be less possible to draw conclusions from fatigue cracks, element failures, or other incidents that occur with an SST structure after a certain service life. In principle, the time until such incidents occur should be divided with a greater safety factor for the SST's than for subsonic structures in order to have the same safeguard against other aircraft, with less flight time, experiencing the same defects. It follows that the "lead time" on SST test aircraft (flying without passengers) must be much longer for being equally sure that defects, serious incidents, or accidents do not occur on aircraft which are put into service at a later date before such occurrences are experienced by the test aircraft.

Even more important than the impossibility to predict the safety and reliability of SST structures is, however, that the (largely unknown) actual safety level most likely will be appreciably inferior to that of subsonic structures: The structural weight is a very critical factor for the economy of SST's. The designer can therefore not indiscriminately apply very low stress levels merely to obtain margins of safety on the basis of rough estimates for lack of sufficient testing. If margins are applied by adding material in some locations, this might be adequate for some SST's which will be subjected to a certain service experience, but might be inadequate for other SST's which will experience quite a different load/temperature history. For reasons of utilization and other economical considerations, it will not either be possible to substantially improve the safety level of fail-safe designed SST structures by applying considerably shorter intervals between thorough inspections than are normal for subsonic structures.

In conclusion it thus appears that, on the basis of the present and foreseeable level of the art,

- the safety level of SST structures is likely to be appreciably inferior to that of the structures of comparable subsonic aircraft, even if structure weight and inspection frequency are increased to the limit compatible with reasonable demands on payload, utilization, and low operating costs, and that
- it will not be possible to predict the level of safety and the defect rate with the same confidence as that with which the safety and reliability of subsonic structures can be assessed.

Operational Safety at Supersonic Speeds

Let us for a moment assume that the aerodynamic flow conditions were the same at the speeds intended for the SST's as at subsonic speeds, that no kinetic heating existed, and that no radically new design features had to be introduced into the SST design. Then, it is still inevitable that its high speed as such, of some 1,400 to 2,000 mph, will pose some rather serious operational safety problems, about which practically no experience exists. From a recent NASA study[16] may be quoted:

In summary, this airplane (the SST) appears to function very much like a projectile. Once launched it must proceed along a very precisely controlled flight path with little or no delays and with a large degree of dependence on automatic flight control and stabilization systems and rapid automatic traffic control over the entire route. The capability of the pilot to assume manual control with the safety, economy, and schedule reliability required of commercial transportation is highly questionable.

The speed of an ordinary rifle bullet is about 1,600 mph. With introduction of SST's, civil aviation would enter the era of ballistic speeds. What does this mean with regard to operational safety and regularity? Only a few observations will be made to indicate the nature of the problems.

In the first place, there is the problem of collision with other aircraft. For a speed of Mach 3 and a bank angle of 30 degrees, the "initial distance" at which a turn must be started to provide a one-mile lateral separation between two aircraft on a head-on collision course is about 30 miles.[16] The time until passing (or collision) is about 25 sec. For a Mach 2.2 SST the initial distance is about 20 miles. Such distances are in practice beyond visual range, which is of the order of 5 miles in good visibility. This implies that there will be less than 5 sec from seeing the other SST until collision. "Last second" sharp turns, subjecting the passengers to accelerations exceeding their weight, would still not prevent collision, because they would require initial distances of some 12 to 20 miles. Considering also the reaction time of the pilot, it should be clear that the SST pilot will be in a helpless situation for the head-on collision case if he has to rely only upon direct visual means for collision avoidance. Essentially, this also applies to the general case of two aircraft, only one of which has to be supersonic, being on collision course at any bearing angle.

It might be objected that collision avoidance on the basis of the pilot's visual range capability is bordering to what is in practice possible for the present subsonic jets; it calls for intense and incessant attention on behalf of preferably two crew members. This is correct and is, in fact, a strong reason why one should not exceed the border to the impossible before a fully satisfactory solution of the present collision-safety problem has been found.

It is, of course, conceivable that the answer both for high subsonic and for supersonic speeds lies in appreciable improvements in radar equipment. There are, however, obvious and well-known difficulties. One is that it is not sufficient merely to detect another aircraft as a "dot" on the radar screen. The other aircraft might not be on collision course and an evasive turn might instead lead to collision. The "dot" must obviously be followed during a certain minimum time and the situation has to be evaluated by an electronic computer. Such collision-avoidance equipment might have to be automatic in order to effectuate positive control of the aircraft and eliminate human reaction time and judgment. Because of the longer time available the problems involved are evidently easier to solve for subsonic than for supersonic speeds.

For subsonic aviation the collision hazard has led to regulations with regard to altitude separation and the like. Such regulations will undoubtedly be the main basis for preventing collisions also for the case of SST's. At first sight, one

is induced to feel that this solution is equally feasible to apply for SST as for subsonic traffic, or easier because of the less dense traffic at supersonic flight altitudes. There are, however, special difficulties for the case of the SST's that must be borne in mind. The SST must for minimum fuel consumption make a continuous climb in supersonic cruise, with an altitude increase of some 10,000 ft. Considering, in particular, traffic with SST's with different speeds, the continuous climb might have to be replaced by a level cruise pattern with step climbs applying altitude separation between the steps. This would imply a penalty in fuel consumption, and it might not be possible to conduct the changes in angle of attack (and flight path in the vertical plane) at each step without severe magnification of sonic-boom overpressures due to focusing effects. Alternatively, precisely defined sloping "corridors" for continuous climb in cruise might be prescribed.

From a purely navigational point of view, such procedures seem feasible as long as the traffic intensity is moderate. Planning for future SST operation must, however, obviously take into account rather dense traffic on many routes. According to the study by Convair,[17] the supersonic traffic demand between New York and the west coast of the U.S. will on the average call for some 50 round trips every day by 1975. Assuming that 90 percent of the passengers desire to depart and arrive between 0800 and 2400 hrs local time, the flights would on the average have to be made at about 15-min intervals. In view of peak-season traffic and to meet normal passenger preference for morning and late afternoon flights, the frequency might have to be increased to one SST departing every 10 min during such periods. Similar traffic intensity must be anticipated sooner or later on other important SST routes and route systems.

Regardless of whether the principle of continuous climb or step climb is applied, a number of laterally as well as vertically distributed corridors with an adequate diameter must be prescribed to cope with dense SST traffic. This will increase the total areas affected by sonic booms (public safety), and the turns required for such lateral spreading might imply sonic-boom focusing effects. Apart from this, it will apparently be increasingly difficult as traffic grows to reconcile such ATC demands on a multitude of confined corridors with the optimum flight altitudes and Mach numbers of the SST's with regard to fuel consumption. The required deviations from the optimum flight profile will often be particularly great, because one profile is closely dependent upon standard atmospheric conditions, with respect to temperature. It will be difficult, or impossible, to adjust a complete system of many flight corridors to changes in the atmospheric conditions from one day to another as well as during a day or along the route. It is therefore obvious that *as SST traffic grows there will be an increasingly severe conflict between demands on collision safety and operational economy.*

This conclusion applies also for the climb portion of the flight. As about $\frac{1}{3}$ of the fuel is consumed during the climb phase, deviations from the optimum climb procedure, in particular with respect to the height for acceleration to supersonic speed, will involve penalties in the form of additional fuel weight. The optimum climb procedure is, however, closely dependent upon atmospheric

conditions, in particular the location of the upper limit for the tropopause. Furthermore, sonic-boom considerations are likely to still more emphasize the need for exacting climb (as well as descent) procedures, and these considerations are likely to imply further deviations from the fuel-optimum climb path.

Over and above the collision problem in the usual sense of the word, supersonic aviation will encounter virtually *a new "collision" problem, that of hitting regions of precipitation in various forms such as rain, sleet, hail, and clouds of ice crystals.* The effect of flying into such regions is much more severe at supersonic than at subsonic speeds. Flight experience has shown that rain will erode the enclosure of the radar of the aircraft, the radome, in a short period at Mach 2 flight speeds. Flying through hail at supersonic speed will probably result in rapid damage of the radome and probably also of the skin in spite of oblique impact angles (see Ref. 18, Fig. 1).

The conclusion drawn by FAA in Ref. 19 is:

> The supersonic transport must be designed for effects of rain and hail encountered at supersonic speed unless it can be shown that contact can be avoided.

FAA also indicates that "it may not be possible to construct radomes impervious to rain or hail erosion or damage at supersonic speeds." Considering also damage by hail to the skin, possibly to an extent endangering safety, the all-important question is whether "contact can be avoided." In this respect, FAA states:[19]

> Rain or hail may be present in cumulo nimbus clouds which extend to altitudes of 75,000-80,000 feet in the tropics and somewhat lower altitudes in temperate latitudes. Weather radar will probably be installed on supersonic transports. However, it may not be possible to rely on this equipment to avoid rain or hail since (1) the equipment now used by civil operators has a range of approximately 100 miles and (2) the radius of 15° banked turn for a speed of Mach 3 is approximately 160 miles, hence, avoiding action may subject passengers to uncomfortable accelerations.

Furthermore, to avoid safely "precipitation collision" a *much* greater lateral (or vertical) margin must be applied than the one-mile lateral distance referred to above for the case of avoiding collision with other aircraft. ICAO has stressed this aspect by the statement:[20]

> If, on the other hand, lateral avoidance is not possible; e.g., because of the number or depth of the danger areas, then the possibility of carrying out the flight will depend on the relation between size of the hail, ice or water particle, and its potentiality for inflicting structural damage on the aircraft.

The same as for the case of safety in supersonic aviation against collision with other aircraft, it is generally contended that a feasible solution to the rain and hail collision problem for the SST's lies in prior knowledge of the weather situation along the route. Whether or not this is an adequate solution is, I think, open to doubt. Obviously, such prior knowledge should preferably be obtained one or two hours before departure time, be finally checked immediately before takeoff, and must cover at least the duration of the flight and preferably also of

the return flight in order to conform with the timetable. The advance knowledge must therefore cover a period of at least some four hours and preferably 5–10 hours.

Even considering that weather-forecasting will undoubtedly be greatly improved in the future, for instance by weather satellites, there seems to remain *a non-negligible risk that the weather along the flight path will change unexpectedly after the takeoff of the SST.* Furthermore, present experience indicates that hail might be encountered in clear air without prior warning from weather radar.[21] It is thus difficult to see how the risk of flying into regions of precipitation can be humanly controlled.

Investigations to determine whether or not the risks of serious hail collision will fall below the probability level acceptable for this particular accident cause cannot be limited to supersonic cruise altitudes above about 60,000 ft. They must cover the regions for acceleration to and climb with supersonic speed as well as the descent at supersonic speed, and thus encompass altitudes down to about 35,000 ft (Fig. 1). Furthermore, one cannot neglect unexpected formations

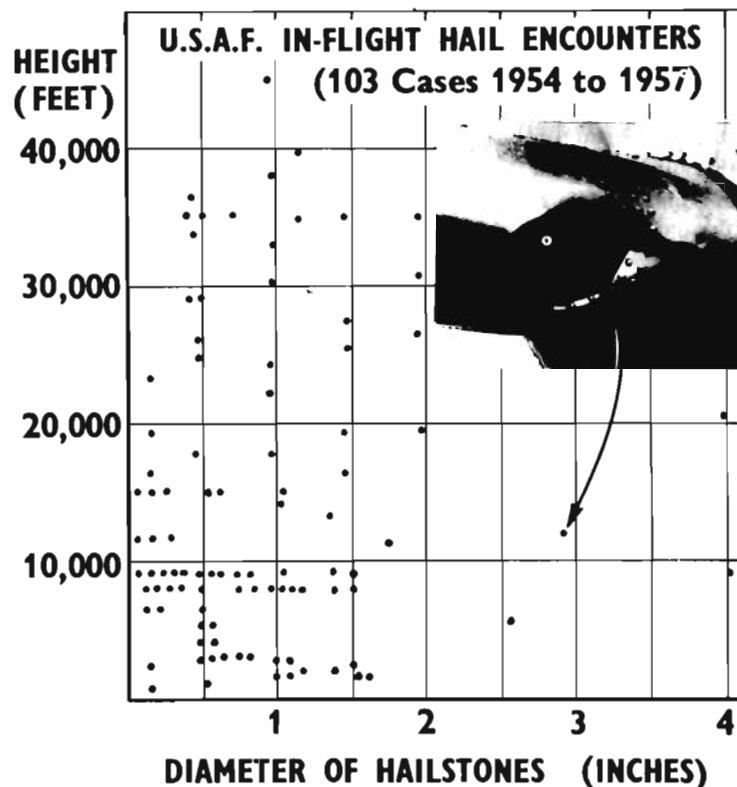Fig. 1. This figure has been reproduced from a paper by D. M. Jameson,[18] in the February, 1961 issue of the *Journal of the Royal Aeronautical Society* by kind permission of the Society. The figure originated from the U.S. Military Air Transport Service. While the structure pictured here is not representative of an SST construction, the diagram does indicate the severity of the problem of hail encounters

of hail below this altitude level, because the SST is practically compelled to climb to the Mach 1 altitude at high subsonic speed. The subsonic jet is in a much better position, as it can slow down, make an evasive turn, and/or choose a new altitude when encountering a region of unexpected precipitation.

It is thus concluded that prior knowledge of the weather along the route and adjustment of the flight path according to this knowledge might *not* be an adequate solution to the "precipitation-collision" safety problem even for the simple case of one single SST flying from A to B.

The really difficult problem arises, however, with the dense SST traffic that must be anticipated in the future on the most important routes, if supersonic aviation is to be at all successful. The appropriate background for judging this safety problem is thus again perception of a stream of SST's flying at short-time intervals within a sophisticated system of a number of laterally and vertically distributed flight corridors, precisely defined all the way from takeoff to landing. The adverse effects of regions of precipitation will then obviously be magnified and more so the larger the regions:

● In the first place, it will be more difficult to change a whole "corridor system" as a consequence of predicted severe weather conditions, than to adjust the flight path of a single SST. The delays in arrival time and in the subsequent takeoff time will, anyhow, be greater.

● Secondly, there might be occasions of such wide extension of dangerous regions that a sufficiently safe change of the corridor system is not at all feasible, e.g., for fuel-consumption reasons. Then cancellations of a great number of SST flights would be inevitable. In this respect it should be observed that hail is often "associated with the hard cores of thunderstorms"[21] and that thunderstorms often move rather fast.

● Thirdly, occurrences of precipitation, unforeseen by the weather forecast (for which airborne weather radar also cannot yield protection), will be a potential danger not only for one but for a number of subsequent SST's.

These observations might suffice to indicate that we have here an extremely complex meteorological/statistical/operational research field that should be adequately explored before supersonic aviation is introduced. As a result it might be found that, even anticipating much improved weather prediction, merely the humanly noncontrollable risks indicated above are unacceptable.

It may alternatively be found that the sum of the humanly noncontrollable and controllable risks for this potential accident cause is deemed acceptable. Most likely this latter alternative would, however, necessitate reduction of the controllable risks to a very low level

● by prescriptions about rather wide flight corridors,
● by application of extreme cautiousness in judging possible developments of the weather, and
● by rather ruthless cancellations of flights or changes in the flight-corridor system, regardless of the consequences with respect to regularity and fuel economy.

Such a policy might work "on paper," but will it work in practice? It seems obvious that SST navigation will pose an unprecedented situation of conflict

between the demands on safety on one hand and fuel economy and regularity on the other. It will be extremely difficult to formulate quantitative regulations regarding the cautiousness that must be applied in judging possible developments of the weather some four to ten hours ahead. Thus, there will be a great room for subjective opinions on behalf of the responsible ATC personnel about the probability of a particular situation developing into a serious "blocking" by precipitation of the intended SST flight corridors. Decisions whether or not to cancel SST flights or to change the flight corridors are likely often to be based on "feelings" that the risks are "extremely remote." With a great number of such so-called "calculated risks," accidents will occur and the accident rate may well be unacceptably high, even if in theory the total risk level were found to be acceptable.

Finally, a few words might be said about *passenger-injury safety and comfort with regard to flying with SST's into regions of turbulence or the like*. As stated in the previous section, the time for climbing and descending through the relatively turbulent low altitudes is shorter with SST's than with subsonic jets. Furthermore, the gust frequency is apparently less at supersonic than at subsonic cruise altitudes, although it is known that clear air turbulence and jet streams extend at least up to 80,000 ft. (Ref. 22). This is all favorable with respect to the total number of gusts. On the other hand, the SST is, as mentioned above, practically compelled to climb to the Mach 1 altitude at high subsonic speed. It then has to proceed to supersonic climb, in supersonic cruise and descent, and in subsonic descent in a rather fixed, preplanned way. This has three implications:

1. In the preflight planning of the flight path it will be more difficult for supersonic than for subsonic operation to adapt the flight path so as to avoid turbulent regions, that have been predicted.

2. Whereas the pilot of the subsonic aircraft, upon entering a turbulent region (predicted or unforeseen), usually can reduce the passengers' discomfort by slowing down, the SST must fly into and through the region at full, or almost full, near-sonic speed in subsonic climb, and at full supersonic speed in the supersonic portions of climb and descent as well as in supersonic cruise.

3. In a turbulent region, the turbulence usually increases gradually towards a maximum in a core. This implies a more sudden increase in severity of the gusts when the region is entered at supersonic speed than at subsonic speed. Thus, there is less time for warning the passengers to fasten the seat belts.

For these reasons it seems probable that the SST passengers will be subjected to *severe* gust loads more often than subsonic passengers. There is also another reason for this, namely that the acceleration increment for a certain gust velocity is likely to be higher for the SST (at least for many conceivable types of design) than for comparable subsonic aircraft encountering a gust of the same severity.

The importance of the aspects (2) and (3) is stressed by the fact that no satisfactory method has been found to forecast clear air turbulence and that it seems unlikely that reliable radar detection of such turbulence can be achieved. It might be added that regions of clear air—and other— turbulence can move and be formed rather rapidly.

To sum up:

● Because collision between an SST at supersonic speed and another aircraft cannot be avoided on the basis of direct visual means and because collision avoidance equipment will be more difficult to design, the lateral and vertical separations that must be provided for SST's by a flight corridor system must be considerably larger than for subsonic operation for the same level of safety.

● It will be very difficult, if at all possible, to find such solutions of the problem of collision with regions of precipitation, in particular hail, that yield an acceptably low probability of accidents due to this particular cause and at the same time are compatible with the demands on fuel economy and regularity, that will be set by operators and passengers.

● There will thus be an unprecedentedly severe conflict between flight safety, on one hand, and fuel economy and regularity, on the other. This conflict per se will imply potential risks over and above the risk level that can be assessed on the basis of meteorological and statistical investigations and evaluations.

● The SST passengers are likely to be subjected to *severe* gust loads more often than the subsonic passengers, and the encounters in supersonic flight will be more sudden.

In addition, one cannot overlook a psychological factor which will be well known to the passengers: For the first time in the history of navigation, the passengers will be surrendered to a vehicle under the command of a captain and crew members who are virtually blind in the sense that they can do very little, if anything, to prevent collisions for the event that the vehicle happens to be on collision course with any objects, be it other aircraft, regions of hail and the like, or regions of severe turbulence.

THE INFLUENCE OF THE OPERATION OF SST'S ON THE FLIGHT SAFETY IN SUBSONIC AVIATION

This is a most important safety aspect which must be considered in a complete analysis of the safety problems introduced by SST operation. As, however, this aspect is very difficult to assess at this time, I will confine myself mainly to stress one point.

Once launched, the SST must proceed along a very precisely controlled flight path. According to most of the published studies, the intended fuel reserve in terms of possible holding time appears to be smaller than for present subsonic operation. Furthermore, the magnitude of the fuel reserve is a more critical factor for the economy of SST operation than for subsonic operation. This is borne out from the fact that the intended fuel reserve amounts to about the same weight as the whole payload.

It follows that appreciable deviations from the predetermined flight plan, *inter alia* in the descent portion of the flight, are a rather serious matter. Considering especially the fact that a substantial part of the fuel reserve might be consumed by adverse atmospheric and operational conditions (such as off-standard ambient temperature and nonoptimal supersonic cruise altitude for ATC reasons) it seems inevitable that the SST's will usually be given priority with regard to descent, approach, and clearance for landing.

This means that subsonic aircraft will often be subjected to holding and delays because of SST operation. Even if this is accounted for by an overall increase in the fuel reserves of subsonic aircraft (a burden on their economy), it does not take much imagination to conceive of situations of conflict, where subsonic aircraft in an emergency (due, for instance, to engine troubles or extremely bad weather) will have less chance of a safe landing than if the SST's had not appeared on the scene.

The above conclusion about the likelihood of priority for SST's with regard to landing clearance does not, perhaps, conform with the intention behind the requirement by ICAO and IATA that SST operation must be "compatible" with subsonic operation.[6,23] It seems, however, rather improbable that the alternative, uneconomical fuel reserves for the SST's, will be applied.

Over and above the indicated direct effect of SST operation on the flight safety of subsonic operation, there is a probably even more serious indirect effect: The great efforts and money that are required for the SST enterprise will inevitably detract from the efforts that could otherwise be concentrated on the urgent task of a radical improvement of safety in subsonic aviation.

SONIC BOOM

To deal adequately with the sonic-boom problem, one must assume that supersonic aviation *will* get extensive worldwide application. This is, in fact, the only correct basis for analyses and judgments about the boom effects, because we can hardly imagine any major branch of aviation which just grows for a time and then stagnates. Even if supersonic aviation is found to be grossly uneconomical by normal standards with regard to profitability, subsidies and other actions will probably be exercised in order to expand the activity, although the rate of expansion might be slow.

In the first place I think one should consider the situation when most of the present routes above some 1,500 miles are traveled by SST's. I have accordingly "bandaged" a globe by boom carpets, of which Fig. 2 shows portions. They look frightening.

Having dealt with the sonic-boom problem rather extensively in previous papers,[24-31] I will here mainly summarize my views.

On the basis of present knowledge, it seems to be generally agreed that there are no prospects for ever finding a solution to the problem, that is, the elimination of the boom or prevention of its ever reaching the ground. This being the situation, I think the first thing that should be done, before any decisions are made leading to the introduction of civil supersonic aviation, is to agree internationally upon *sonic-boom ethics* as a basis for determining acceptable sonic-boom intensities. I have previously proposed the following ten points.[28,31]

1. *The acceptable sonic-boom intensity must be based upon much more stringent considerations than those hitherto applied for airport noise.*

   The areas that will be afflicted are incomparably bigger than those for any other source of noise disturbance experienced by man up to now. In particular it must be observed that the boom carpets will cover large portions of the open countryside where the background noise level is

usually low. While it is, after all, physically possible for most noise-sensitive inhabitants of cities to move away from airports, people in general, including sick, nervous, and old people, would hardly ever be able to escape the sonic-boom thunder, not even by moving out into the countryside.

2. SLEEP DISTURBANCE *at a low background noise level should be the Number One basic criterion for inacceptable boom intensity.*

Undisturbed sleep is of fundamental importance for health and for recovery from illness. It is therefore necessary that the sonic-boom limit for sleep interference should be set so low that a very small percentage of sleepers in bedrooms with open windows and at a low background noise would be awakened. This limit might be as low as 0.3 lb/sq ft,[29] thus much lower than the value of 1.5 lb/sq ft believed by many to be "acceptable." An additional reason for a low sleep-interference limit is that the individual might be adversely affected by sharp booms even without being actually awakened, because a deep, sound sleep might be changed to a lighter and less restful one.
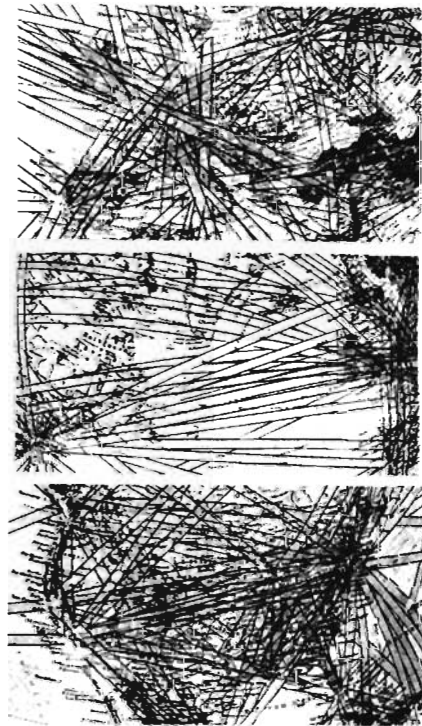
Fig. 2.   Portions of the globe "bandaged" by sonic-boom carpets of 90 miles width. Such carpets will be generated by a supersonic transport weighing 400,000 lb flying in standard-atmosphere conditions at $M = 3$ at 70,000 ft (Fig. 5). Considering side-wind components and deviations from the exact flight route, the affected areas are greater than the carpets shown. They might also roughly represent the areas afflicted by a Mach 2.2 SST flying at 60,000 ft and generating a "nominal" boom carpet about 25 miles wide (Fig. 4).

3. *There should be little or no difference in acceptable boom-intensity level between day and night.*

    There are many people both in communities and in the open country—shift workers, elderly and sick people—that are dependent upon undisturbed sleep in daytime.

4. *The maximum acceptable sleep-interference limit should not be higher for sparsely populated than for densely populated areas.*

    The rights of each individual in accordance with basic democratic and humanitarian principles must be recognized: every single person, who has chosen to live in, or wishes to move into, peaceful areas, should have the right to continued quietness or to obtain peace. It would be ruthless to legalize harm to people merely because they are few in number. If such a jungle law is forced upon us it would be equivalent to neglecting people suffering from uncommon diseases.

5. *The acceptable sonic-boom limit should not be based on "number of complaints."*

    It is the disturbance as such, and its medical implications, not the extent to which people phone or write to authorities that is significant. People who are suffering the most from boom disturbances might be incapable of complaining. Furthermore, people might give up complaining should they find (which is likely) that it has no corrective effect.

6. *There should be very little difference between the acceptable sonic-boom limit over seas frequented by ships and over inhabited land areas.*

    The background-noise level on a modern liner is usually very low, and in any case the crew is required to do shift work. One should also consider the concentration of boom disturbances that will occur on air routes connecting major cities, such as Paris—New York, which are largely the same as for boats.

7. DISTURBANCE IN HOSPITALS *should be the second basic sonic-boom criterion.*

    Unexpected sharp sonic booms might be detrimental to the patients, in particular those suffering from nervous diseases, and could be very dangerous during surgical operations. The "hospital criterion" might thus require an even lower maximum limit for the boom intensity than the "sleep-interference" criterion. Because of the great width of the boom carpets it will normally not be possible to plan the supersonic flight routes, which have to be rather straight, so as to insure that the boom carpets fall with a safe margin (considering side winds) outside all existing hospitals along the route. Furthermore, it should always be possible to erect new hospitals in suitable sites. Thus, the hospital criterion must be regarded as equally applicable geographically as the sleep-interference criterion.

8. *Both the sleep and the hospital boom criteria should be based on the assumption of a fairly high frequency per day of sharp sonic booms.*

    Once supersonic aviation has been introduced, it is likely that the frequency of the flights on each route will steadily increase in the future. It should also be observed that if supersonic aviation is restricted to a

limited number of routes over sparsely inhabited areas, such a concentration would make the daily number of flights over these areas particularly great.

9. DISTURBANCE TO ANIMALS, *in particular animals being bred at fur farms, should be the third sonic-boom criterion.*

It is well known that in particular some fur animals are sensitive to noise and that therefore fur breeders often have suffered considerable losses because of subsonic aircraft flying over fur farms at low altitudes. Sharp sonic booms might be equally or more detrimental to fur animals. Fur farms often exist in large numbers in districts which are sparsely populated. This also speaks against having less stringent boom limits for such regions.

10. *None of the sleep-interference, hospital, and fur-animal criteria should be established on a presumption that people and animals can become accustomed to—or "educated" to—accept sonic booms.*

Whereas it is possible to some extent to get used to the normal, rather gradual types of noise, for instance the increasing noise of a vehicle passing an observer, or of thunder, the sudden and sharp sonic boom occurs without any forewarning whatever. It will, therefore, always be surprising and, for high intensities, even frightening. In particular it should be observed that small children might easily be frightened by unexpected sonic booms; they can never be "educated" to disregard the booms. Furthermore, harmful nervous effects can be inflicted on many grown-up people.

After agreement on sonic-boom ethics, the next step should logically be quantitative determination, i.e., in terms of pounds per square feet (psf) of acceptable sonic-boom overpressures, for the three proposed basic criteria.

In this respect, it is most important to observe the fact that *the acceptability of SST operation cannot be based upon the boom intensity that will be created by straight-course, unaccelerated flights in standard atmospheric conditions.* Experience as well as special sonic-boom tests with military supersonic aircraft in many countries have shown that the deviations above and below the average intensity, or the value according to theory, are very great. The main reasons for this scatter are variations—in and across the flight direction and with altitude—in atmospheric temperature and wind, and deviations from steady flight conditions.

Most of the sonic-boom research carried out up to now has been devoted to developing and checking theories. It has been found that the finally developed combined-volume-and-lift theory agrees very well with measured mean intensities.[36,38,41] Only recently have magnifications in boom pressure due to focusing effects become the object of research.[32-35]

In order to obtain a rough grasp of the normal scatter in sonic-boom overpressures, about 80 flyover test results[36-38] have been statistically evaluated. The various measurements have been adjusted for airplane size and altitude, etc., and have then been normalized by comparison with theoretical values of the peak overpressures directly beneath the flight path. The standard deviation of the probability curve has been found to be about 30 percent.

On this basis, Figs. 3 and 4 for a Mach 2.2 SST with a gross weight of 220,000 lb have been prepared. Fig. 3(A) for the mean values (with 50 percent probability) is of the type usually used for describing the climb procedure required to avoid exceeding of a certain critical sonic-boom intensity deemed to be acceptable, for instance 1.0 or 1.5 psf.[39-41] Disregarding whether such high values will be tolerated at all by the public, Figure 3(B) indicates that a much higher boom intensity, about 3 psf, will be exceeded on the average at a frequency of once for every 100 climbs, thus, for instance, once a week, if there are 15 flights per day.

In Fig. 4, one-half of the sonic-boom carpet (assumed to be symmetric) is illustrated for the same case of 1 percent probability. It should be observed that the boom carpet for the case of steady-flight standard-atmosphere conditions is limited by definite borders, characterized by a finite overpressure. The areas that—on the average once for every 100 fly-overs—will be afflicted by boom pressures, often high enough to cause damage to property, are indeed vast. The width of the whole "cruise carpet," within which people will be very appreciably disturbed, is about 50 miles. It may be noted that the figure should not be interpreted to mean that indicated overpressures or larger values will be attained
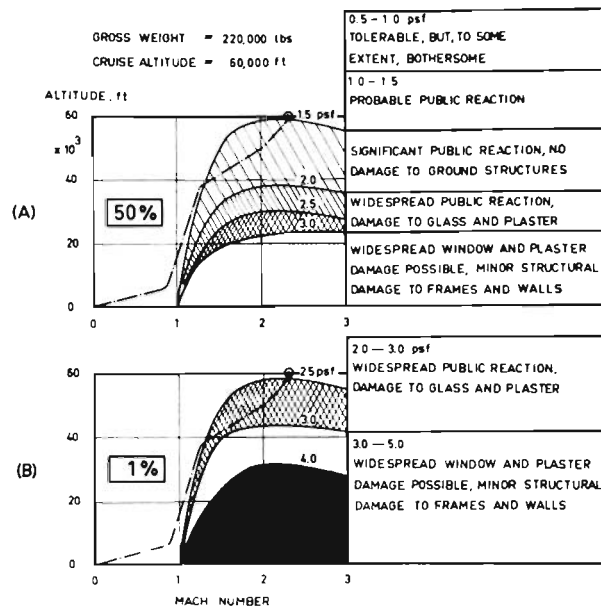
Fig. 3.   The chain-dotted curves indicate the flight profile, in terms of altitude versus Mach number, for climb and acceleration to supersonic speed for a Mach 2.2 SST. (A) indicates the peak boom pressures (i.e., directly beneath the SST in zero wind) according to theory and verified by tests, which with 50 percent probability will be exceeded in practice. On the basis of a standard deviation of 30 percent (B) indicates the minimum values of the peak boom pressures for a probability level of 1 percent. At climb and cruise, overpressures of at least 3 and 2.5 psf, respectively, will on the average occur with a frequency of 1 percent. The judgments of public reaction and damage to ground structures are quoted from Refs. 40 and 41.

Fig. 4.   The minimum intensities within the sonic-boom carpet, for the 1.0 percent probability level, caused by climb and cruise of a Mach 2.2 SST with a gross weight of 220,000 lb. The takeoff, climb, and cruise profiles are the same as in Fig. 3.

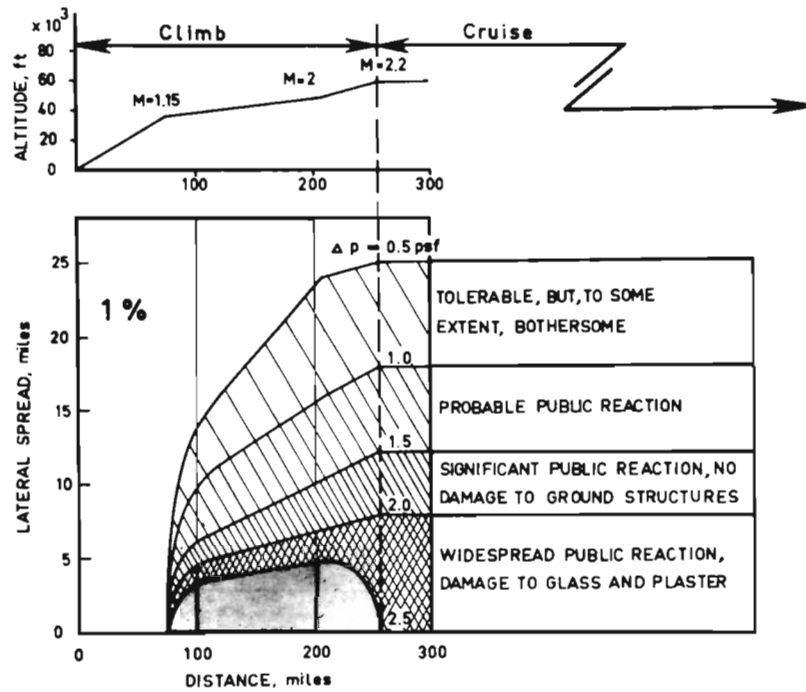at one and the same flight. The figure is intended only to indicate that at any particular point within the boom carpet corresponding to climb and cruise, one must expect the indicated intensities to occur, or to be exceeded, on the average once for every 100 flights.

Using the same standard deviation of 30 percent, Fig. 5 has been prepared for a Mach 3 SST with a gross weight of 400,000 lb flying at 70,000 ft. On the average the peak values will exceed about 2.5 psf (in any place directly beneath the flight path along the entire route) once for every 100 flights. The probability of exceeding lower levels within the 90 miles wide boom carpet is indicated by the curves. In climb this SST should cause peak pressures exceeding 4 psf once for every 100 climbs.

It is realized that the statistical basis for the three figures is rather insufficient; it is essential to obtain much more data to make more reliable evaluations of this kind. I do believe, however, that the indicated scatter in overpressures is of the right order, and I am convinced that if this is so, the very appreciable deviations from the mean values of the boom intensities that will occur quite often will prove to be a most important factor against public acceptance of supersonic aviation.

It is uncertain whether the evaluated measurements are representative for the phenomenon called "super-bang," i.e., particularly large overpressures due

to focusing or strong magnification effects caused by unsteady flight or by atmospheric gradients with regard to temperature and wind. As the areas on the ground affected by such focusing effects are confined to narrow bands, it is unlikely that the few recording instruments used in the tests have caught the overpressures due to focusing, but there will be little chance for widespread built-up areas to escape being hit somewhere by a narrow "focusing band."

As the overpressure in "focusing bands" can possibly be some 5 to 10 times higher than the ideal theoretical value for a standard atmosphere without winds and for steady flight conditions, an urgent research need exists to determine whether or not it is possible to avoid severe focusing effects. Pending such research, I would estimate that even if focusing in the strict meaning of the word can be avoided in standard-atmosphere conditions by very cautiously
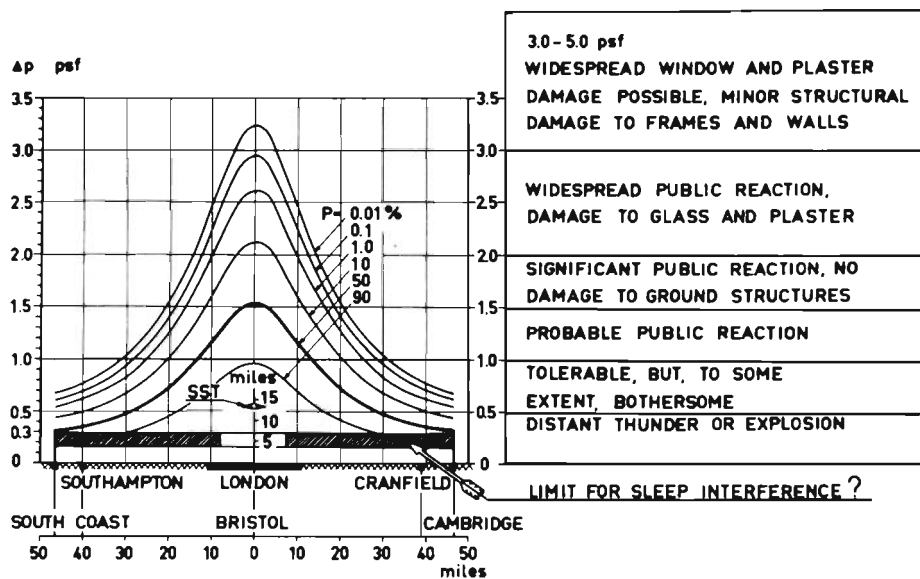
Fig. 5. Cross section of the sonic-boom overpressures for the case of a 400,000-lb SST cruising at a speed of Mach 3 at 70,000 ft. The heavy curve indicates the overpressures according to theory (yielding a peak of 1.5 fps). This distribution is likely to be exceeded, in every section of the boom carpet, on the average for every second flight (50 percent probability). On the basis of a standard deviation of 30 percent, the other curves indicate the probability, or average frequency, with which overpressures exceeding the values of the curves will occur. Light sleepers might be awakened, at a low background noise level, by overpressures exceeding 0.3 psf, and many other sleepers might be subconsciously disturbed without actually being awakened. The curve for 90 percent probability indicates that such sleep disturbances will occur for, on the average, 9 flights out of 10 within about 65 percent (60 miles) of the carpet width. The judgments of public reaction and damage are quoted from Refs. 39–41.

conducted maneuvers, it will not be possible to make any turns or changes in angle of attack without appreciable magnifications of the sonic-boom intensity. Likewise it seems inevitable that the boom pressures for the case of perfectly steady flight will be magnified in many cases where there are overall atmospheric gradients in temperature and wind, as well as cases where there are abrupt changes in these respects, for instance when passing a cold front.

Both with regard to the "normal scatter" (the deviations indicated by the sparse measurements already made) in boom intensities and to the possibility of great magnifications, or even focusing effects, I suggested in Ref. 28 that a "safety factor" must be applied on the mean or theoretical value of sonic-boom overpressures. This suggestion is supported by Ref. 33, in which is stated:

> To prevent ground-level window damage, supersonic flights must be planned to keep focus amplification factors below 10.

We have thus two main principles of assessing such combinations of SST gross weight and flight altitude that will yield sonic-boom effects acceptable to the general public:

(*A*) One is to use the *mean value* of the boom intensities as the basis for "*everyday acceptability*," considering (*a*) that peak overpressures above the mean value will occur, on the average, for every second flight somewhere across *every* section of the entire boom carpet, and (*b*) that disturbingly high overpressures in every section are not confined merely to the position where the peak occurs, but will exist also across a portion of the carpet, which might extend to the entire carpet width (Fig. 5). To comply with the sleep-disturbance and/or the hospital criterion (whichever is found to be critical), it seems possible, as mentioned above, that the highest acceptable mean value will be about 0.3 psf.

(*B*) The other principle is to consider *occasional severe sonic-boom effects* and apply a *boom safety factor* which should be chosen with due consideration of the normal scatter in boom intensities together with the probability, or expected frequency, of great magnifications due to the effect of focusing or "near-focusing." It must, in other words, be agreed upon how often occurrences of very severe sonic booms, capable of causing, for instance, window breakage or very severe shock to people, can be accepted when supersonic aviation has become a widely applied form of civil aviation. Continued research with regard both to normal scatter, focusing effects, and public acceptance in various countries might, for example, indicate that in order to avoid 1.0 psf from being exceeded more often than is deemed acceptable, a factor of 2 or 3 must be applied. This would imply limitation of the permissible mean value to 0.5 or even 0.33 psf.

The two principles might thus yield about the same result, but it might alternatively be found that one of them is usually more critical than the other. Both approaches must, however, be analyzed and considered, as *the reaction of the general public will undoubtedly depend upon the combined effect of every-day disturbances and occasional, extremely severe sonic bangs.*

With respect in particular to occurrences of damage to property, ICAO has taken a rather firm stand:[20]

> The (boom) intensity must obviously not be great enough to cause any damage
> to property and consideration would have to be given to its effects on animal life
> as well as to disturbance of or annoyance to humans.

There can be no doubt that SST operation, as it is at present conceived,
cannot by far comply with a requirement of limiting the mean value of the boom
pressure to the order of 0.3 psf; that would mean a gross weight of about 10,000
lb.[28] In this respect ICAO might again be quoted:[20]

> If the intensity is to be kept so low as not to awaken light sleepers in normal
> housing in areas being overflown, as has been suggested by some authorities, then
> the conclusion of these authorities that civil supersonic aviation, in its presently
> suggested form (see para. 86), will not be feasible, must be accepted.

As very few systematic investigations have been made, it is, of course, still
an open question whether such a low intensity as about 0.3 psf will be insisted
upon. In judging the feasibility of SST operation it should, however, be observed
that even if the limit of the peak overpressure is fixed to as high a value as 0.8,
the gross weight of the SST would still have to be reduced to less than 25,000 lb,
which would limit the payload to less than a dozen passengers.

In view of the observations made above it is, in fact, hard to understand how
introduction of supersonic aviation can be seriously contemplated

- before adequate research has been carried out to assess the scatter phenom-
  enon and the limits for public acceptance in various countries,
- before the governments of all countries likely to be overflown by SST's have
  been adequately informed about the probable implications of sonic booms,
  and
- before these governments, on the basis of such knowledge, have indicated
  the mean value of the sonic-boom overpressure that will be accepted both
  with regard to "everyday disturbances" and to the frequency with which
  magnifications causing severe shocks to people or damage to property are
  likely to occur.

It might be recalled here that ICAO has at an early stage very clearly indicated
the possible consequences of disturbances due to the sonic boom. In its Report
of 1960[6] ICAO states that SST's

> . . . must not cause serious trouble to the public living in the vicinity of air routes
> owing to the impact of the sonic boom.

No doubt will the millions of light sleepers that are likely to be awakened
consider this a "serious trouble," especially those who suffer from sickness.
ICAO also states that

> . . . if supersonic airliners not satisfying these conditions (*inter alia*, the one about
> sonic boom quoted above) are placed on the market . . . they would meet with such
> great resistance from government . . . authorities that it seems unlikely that they
> could be operated at all between ICAO Contracting States. ICAO States acting
> together could certainly prevent operation in or over their territories of aircraft
> that . . . created serious sonic-boom problems. . . .

To sum up it appears that, considering in particular sleep disturbances and the great scatter in sonic-boom intensities—implying a high frequency of great magnifications—supersonic aviation as it is at present conceived would cause extremely severe disturbances to and objections from people living in the wide areas affected. Supersonic flight is therefore likely to be subjected to so stringent restrictions in most countries (or even prohibitions) that it will be grossly uneconomic for this reason alone.

If, in spite of this, supersonic aviation is introduced and pressure is applied to ease the operational restrictions, it will cause a severe and ever-increasing strain between the general public on one hand and the SST operators and supporting governments on the other. The prospects are, obviously, such that it would be wise *not* to introduce supersonic aviation *until* sufficient research has been conducted to assess adequately the implications of sonic booms—in particular with regard to deviations from mean intensities—and *unless* this assessment clearly indicates that the impact of sonic boom does not cause "serious trouble to the public," as required by ICAO.

COSMIC RADIATION

Whereas the sonic-boom thunder will make itself known by its trail of awakened, frightened, and angry people, cosmic radiation will affect the SST passengers and crew without being felt at all at the time of exposure. The injury that it might lead to, or contribute to, may not appear until a long time after the exposure or in future generations.

In some previous papers I have expressed concern about the supersonic radiation hazard.[25,28,29] The discussion here will follow Table 1. It is based mainly on information obtained from three Swedish experts, Dr. E.-Å. Brunberg, Assistant Professor in Cosmic Ray Physics of the Royal Institute of Technology, Stockholm, Dr. Bengt Hultqvist, Associate Professor and Head of the Kiruna Geophysical Observatorium, and Dr. Bo Lindell of the Institute of Radiophysics, Karolinska Sjukhuset, Stockholm, former Secretary of the International Commission on Radiological Protection (ICRP).*

TABLE 1
PERTINENT QUESTIONS WITH REGARD TO COSMIC RADIATION AT SUPERSONIC FLIGHT ALTITUDES

1. What is known about the radiation risks today?
2. How will the present knowledge affect the operation of the SST's and their economy?
3. Will it ever be possible to fully assess the radiation hazards?
4. Is supersonic aviation important enough to justify the biological risks of cosmic radiation?
5. Will the passengers willingly take the personal radiation risks involved?

1. Our knowledge about the radiation risks is steadily increasing, but appears still to be inadequate for accurate quantitative assessment.[20] The uncertainties are particularly great with regard to the medical side of the problem, especially

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* The information checks very well with a paper received from the Air Registration Board in London, "Cosmic Radiation and Solar Particles at Aircraft Altitudes—Background Note," by Dr. P. H. Fowler and Dr. D. H. Perkins, Sept. 25, 1962.

the RBE (Relative Biological Effectiveness) factors that should be applied to the various components of the radiation in order to transfer the ionizing effect in rad* to "rem" (roentgen equivalent man), the common measure of the biological effect. The RBE factor can have values[42] from 1 to 20. It is, however, unlikely that the medical effects of radiation can in all cases be adequately represented by the simple way of using multiplying factors. Even the physical aspects of the radiation are subjected to considerable uncertainties. A special uncertainty is posed by the neutron component and its medical effect.[43-45] In particular, a source of error may lie in the fact that the walls of the measurement chambers used in the tests (which consist of high-atomic-number material) are not representative for the tissues in the human body (which to a large extent consist of low-atomic-number material). According to the Swedish experts, this uncertainty might correspond to a factor of 2 or more.

Both the galactic cosmic radiation and occasional occurrences of solar cosmic rays must be considered. The doses in rem due to the *galactic radiation* decrease rather moderately with altitude in the 60,000 to 80,000 ft altitude bracket, but below about 50,000 ft the doses fall off rapidly. In years of high solar activity (about 9 of the 11 years comprising a solar cycle) the galactic radiation produces full-time doses ranging from about 4 to 7 rem/year in altitudes from 60,000 to 80,000 ft considering commonly appreciated uncertainties in the RBE factor, but not the "neutron uncertainty." During solar minimum years the doses are higher; they range from about 6 to 15 rem/year within 60,000 to 80,000 ft.

The *solar cosmic rays* are associated with solar flares, but all severe flares do not produce significant solar cosmic rays hitting the atmosphere of the earth. The solar flares are associated with sunspots, but not all sunspots produce vigorous solar flares. This is important with regard to the predictability of solar cosmic rays penetrating to supersonic cruise altitudes. The galactic as well as the solar cosmic rays are most significant above about 50–55° geomagnetic latitude, north or south, whereas their effect is moderate to negligible at lower latitudes. The altitude dependence is much greater for the solar cosmic rays than for the galactic radiation. The overall RBE factor for these rays is believed to be close to 1.0, but the total uncertainty in the irradiation is nevertheless estimated to a factor of at least 2, perhaps 4 or 5. It might even be still greater due to the possible "neutron uncertainty."

The most severe solar cosmic ray event recognized up to now occurred on February 23, 1956. The dose during the first hour of the event has been estimated to 15–50 rads (considering the uncertainties) at 80,000 ft and to 3–5 rads at 60,000 ft. According to Foelsche, two such high-energy events *may* occur in short succession every four years.[42]

Most other flares known today have been of much less severity usually corresponding to 1 rad per hr or less, but their duration is usually rather long, one or several days.[43] The total number of significant solar flares during the five years 1956–1960 was about 30, thus on the average six per year. The most important thing to observe is, however, that *a flare of about the same, or of an*

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* 1 rad = 100 ergs/g of absorbed energy, practically the same as 1 roentgen.

even higher, severity than that of the February, 1956 event can be expected to occur once, or more than once, at almost any time during solar active years.

On the basis of this sketchy review the following conclusions about the radiation effect on SST crew and passengers seem justified.

With regard to the crew, the most important question is *whether or not crew members must be classified as radiation workers.* According to ICRP, personnel who *could* obtain radiation doses exceeding *1.5 rem/year* should be classified as radiation workers. If the crew spends about 500 hr/year at supersonic cruise altitudes, above about 50° geomagnetic latitude, it follows from the data mentioned above that *the "galactic" dose* obtained might be about 0.4 rem/year at 60,000 ft and 0.6 to 0.8 at 80,000 ft (during solar minimum years), thus less than the ICRP limit. These dose values are, however, subjected to the uncertainty regarding the effect of neutrons. If this corresponds to a factor of 2 or more, the crew of SST's would have to be classified as radiation workers considering merely the galactic radiation. It might be added that Foelsche[42] estimates the maximum possible galactic dose rate to about 2 rem/year for 480 hr/year at 75,000 ft, apparently without considering any extra neutron effect.

Considering *solar cosmic rays* in solar activity years there remains, however, no doubt that the SST crew must be classified as radiation workers, in view of the risk of obtaining doses of the order of 1 rad/hour or more, at almost any time. The dose can possibly be considerably reduced by diving to lower altitude (see below), but as long as this possibility cannot be guaranteed to give a sufficient reduction in the total dose obtainable in one year, the crew must still be classified as radiation workers.

In view of this it seems probable that the advisability of employing stewardesses on SST's will be taken into serious consideration. ICRP has been particularly concerned with the question of employing women as radiation workers, for instance in hospitals, and whether more stringent dose limits should be applied. To quote ICRP,[46] the reason for this is the following:

> It is especially in respect of somatic damage in fetal tissues that pregnant women present a "special risk problem" in case of occupational exposure.

ICRP also states:

> Any special recommendations for pregnant women must in practice apply to all women of reproductive age.

It should furthermore be observed that the solar-flare events make the problem of female crew members more accentuated than for the case of, for example, personnel in hospitals, where the radiation occurs at a fairly regular rate over the year. The reason for this is that the sensitivity of the foetus to even moderate radiation is particularly high during the beginning of pregnancy[43] and that the solar-flare event causes a concentrated dose.

The next significant question is *whether or not the crew can obtain higher doses than the limits set for radiation workers,* i.e., a maximum accumulated dose of 5 rem/year or a maximum of 3 rem in 13 consecutive weeks.[47] It has been suggested[42] that the dose could be appreciably reduced by exchange with crews

on "equatorial routes" and thus limiting the flight time of the crews at magnetic latitudes above 50° to six months per year. In practice this seems hardly feasible for most airlines, because at least 50 percent of all traffic on routes over 1,000 miles (including the North Atlantic routes) is above 50° magnetic latitude, and also because the radiation at lower latitudes is not negligible excepting, perhaps, routes below 30° latitude.

The other possibility of preventing too high doses for the crew is that of evasive actions. As, however, this is probably even more important for the passengers, it will be discussed below.

Considering next the exposure of *passengers* to *galactic cosmic radiation*, the extent to which the radiation doses will encroach upon, or be permitted to encroach upon, the limit recommended by ICRP (0.5 rem/year)[47] for other individuals than radiation workers is, of course, dependent upon how often the passengers fly. With special reference to genetic effects it would also be necessary to assess the contribution to the total genetic burden of the population, which would depend upon the total volume of supersonic aviation in terms of passenger-hours per year.[45,47] It should also be observed that the recommended maximum dose is intended to cover a number of radiation sources and therefore must not be reserved entirely for the new radiation source of supersonic aviation. For these reasons further studies of the problem are important.

The potential risk for the passengers to be subjected to irradiation by *solar cosmic rays* appears to be the most important medical aspect of the whole SST radiation problem. In this respect pregnant women again pose the most significant case. Medical experts seem to agree that doses exceeding such a comparatively low value as *one rem* should advisably be avoided. There is a potential risk that this dose will be approached or exceeded at any time during solar active years.

At the present state of knowledge one cannot either exclude the possibility of harmful effects of solar cosmic rays also to the passengers themselves, considering in particular the fact that the rays comprise components, energies, and velocities with which one has not yet made any experiments with animals.

With regard both to the maximum recommended dose for the crew and to occasional peak exposures of the passengers, it seems thus necessary that the SST's will have to dive down to low "subsonic" altitudes (below 40,000 to 50,000 ft) upon receiving warning that there is an imminent danger that solar cosmic rays will penetrate to supersonic altitudes. A warning system for such events can be expected to be developed in the near future. The decision to dive must, however, be made very quickly, in a matter of minutes, because of the exceedingly short time in which the dose usually builds up to the peak intensity on occasions of solar-flare events. Such a rapid decision to change altitude might conflict with ATC demands and thus with flight safety. Furthermore, it may not be possible to avoid receiving an appreciable dose before the SST has come down to a safe altitude, even if the dive is commenced a few minutes after the warning, considering also the time for descent.

2. With regard to the effects of cosmic radiation on the operation and economy of the SST's one must in the first place take into account *the need for carrying enough surplus fuel* to be able, after a dive caused by a solar-flare warning, to

cruise at subsonic speed to the destination or another airport. Considering, in particular, long overwater flights, e.g., across the Atlantic, and polar routes, such an extra fuel reserve might be incompatible with an economic payload for the case of fixed-wing SST's. The situation will probably be better for a variable-geometry SST, but still an extra fuel reserve must probably be carried.

Over and above the need for extra fuel, the significance of solar flares for the operation of SST's depends, of course, upon how often the aircraft will have to interrupt the supersonic flight and how often SST flights must be cancelled due to such events. With regard to the frequency of required deviations from the flight plan, it must be observed that at the present state of the art it seems difficult to develop a warning device that can with certainty discriminate between the few serious solar flares and the comparatively many flares which do not produce cosmic rays causing high radiation doses. The reasons for this are that the initial appearance on the recording instruments of serious and non-serious events might be the same and that the diving maneuver must be commenced and executed in the very beginning of the occurrence in order to avoid too high a dose, should the event develop into a serious one. Thus "false alarms" appear to be inevitable.

According to information obtained from Swedish sources, *solar flares of such an initial appearance that they would call for descents to lower altitude might occur at a frequency of once per month or more.* Interruptions of SST flights so often (assuming that discrimination between serious and nonserious events cannot be made) seem incompatible with public demand for reliability and regularity of the services. Passengers who prefer to fly supersonic, do this in order to save time. They are, therefore, probably even less tolerant than subsonic passengers to cancellation of flights, to delays in arrival time, or to landing at a different airport from the intended one.

I therefore cannot agree with the opinion that has been expressed that solar flares are just "another environmental factor similar to bad storms for aircraft flight planning."[42] For one thing, bad storms are usually rather local occurrences which nowadays very seldom affect the regularity, whereas solar flares cover quite considerable portions of the earth.

With regard to the effect of solar flares on the operation of SST's, I wish to make the following suggestion. Our knowledge of the galactic cosmic radiation and radiation due to solar flares for past years and, in particular, for the last few years, is fairly good, if not complete. Instead of treating the risk of the crew and passengers being subjected to intense solar flares as a probability problem, a more direct and practical approach would be to calculate as accurately as possible the radiation doses that occupants of SST's would have been subjected to *if* we had had supersonic aviation in the past, assuming both high and low limits with regard to all uncertainties such as the magnitude of the neutron flux and its effect and the RBE factors. In the first place, such calculations should be made for the case of unrestricted operation and for normal duty time of the flight crew. Then the same calculation should be carried through for various degrees of operational restrictions on occasions of solar flares. This should be done under various assumptions with regard to "false alarms" and

doses obtained before the dives were completed. Such studies would result in diagrams showing the radiation dose for crew members and passengers as a function of the percentage of the number of flights that have to be interrupted or cancelled.

3. Medical experts seem to question whether it will ever be possible to fully assess the radiation hazards for the following main reasons:

- Available information about the effects of radiation on human beings is quite insufficient for reliable statistical evaluation both with regard to somatic and genetic effects and we cannot, for obvious reasons, make special radiation tests with human beings.
- It is unlikely that radiation tests with animals can be proved to be fully representative of the effect on man.
- The cosmic radiation comprises a much wider range of different particles, partly with exceedingly high energies, than the radiation used for medical purposes and produced by atomic powerplants, and some parts of the cosmic-radiation spectrum cannot so far be reproduced in laboratories.

It might be objected that the two first points apply for all kinds of radiation. This is correct and implies that the main question also with regard to "supersonic" radiation is whether or not the, to a large extent unknown, risks are worth taking.

4. With regard to any increase of the radiation exposure levels it should suffice to refer to ICRP which emphasizes[47] "that the maximum permissible doses recommended . . . are maximum values," and recommends "that all doses be kept as low as practicable, and that any unnecessary exposure be avoided." ICRP also points out that "it is of the utmost importance . . . to make sure that nothing is done now that may prove to be a serious hazard later, which cannot be corrected at all or will be very expensive to correct."

It appears that for supersonic aviation to be justified to increase, even to a small extent, the total burden of radiation effects on mankind, it would have to be of an importance to man comparable with that of medical procedures or atomic power.

This, I think, can be questioned; the "saving" of merely a few hours by flying supersonic cannot possibly justify even rare cases in future generations of diseases caused by the cosmic radiation.

5. The question whether the passengers, in particular pregnant females, will take personal radiation risks, is perhaps the decisive one. The answer is to a great extent dependent upon whether or not it will be possible to make evasive dives, sufficiently rapidly, for all cases of solar-flare events which might result in serious solar rays. If this is proven to be technically feasible, a doubt may still remain on behalf of the passengers whether such deviations from the flight plan (for reasons of economy and regularity as well as flight safety) will in reality be conducted in all cases of solar-flare warnings. There might be cases of marginal fuel reserves, where the pilot deems that the risk of a high radiation dose is less serious than the risk of proceeding to the intended or another airport at subsonic speed.

However, even if it can be assumed that almost all harmful effects of solar flares will be avoided by evasive actions, it must be observed that people are becoming more and more "radiation-minded" these days as a consequence of nuclear explosions and atomic powerplants. Fear of radiation might, therefore, adversely affect the public appeal of supersonic flying as long as the risks are not fully assessed and proven to be negligible.

To sum up:

● Present knowledge about cosmic radiation at supersonic cruise altitudes indicates that the risks are not negligible either to the crew or to the passengers, in particular if they are subjected to cosmic rays of the highest severity that can occur above some 55,000 to 60,000 ft.

● SST's should therefore carry enough surplus fuel to be able to cruise at subsonic speed and altitude after a solar-flare warning, which will reduce the payload that can be carried.

● The economy of SST operation will be adversely affected also by the high number of "false alarms" that might be inevitable.

● The advisability of employing stewardesses on SST's seems questionable.

● Evasive actions for reasons of "radiation safety" will conflict with demands on regularity and might conflict also with flight safety.

● It might not ever be possible fully to assess the hazards due to cosmic radiation at supersonic flight altitudes.

● It seems doubtful that the radiation risks involved are worth taking.

● Fear of radiation is likely to affect adversely the public appeal of supersonic flying as long as the risks are not fully assessed and proven to be negligible.

CONCLUDING REMARKS

I will now stress some of the most important conclusions of this lecture and try to put the issue of speed and safety in civil aviation in a long-term and broad perspective with respect to the security and welfare of man.

Civil aviation has potentially the prospects of a most brilliant future. To achieve this, a great many prerequisites must, however, be satisfied. Aviation will always find itself in competition with commercial surface transportation and traveling by car, and the competition is, and will always be, harder the shorter the distance. The travelers will be more and more demanding; their preference for flying will be motivated less and less merely by the sensation of taking to the air. Generally, people will increasingly prefer flying only *if* there is a net gain in the combined time-comfort-cost aspect, *if* the reliability is comparable with that of surface transportation, *if* availability is steadily improved, and, above all, *if* the *safety* in civil aviation is unquestionable.

Among these prerequisites, *safety in aviation* is in a class by itself in importance. If the goal of the Flight Safety Foundation to make aviation "the safest means of transportation" can be met, so as to compensate for the natural human fear of leaving the ground, there would be no limits whatever to the expansion and prosperity of civil aviation.

If, on the other hand, the safety standard remains at the present unsatisfactory level, the ever-increasing death toll—growing in pace with the expansion of aviation—will be the most effective means conceivable to retard the growth of aviation. Thus, safety in aviation must not be compromised; we are—in a long-term perspective—much too far below any "economical optimum" of the safety level.

Safety in civil aviation is the "number-one challenge" to aviation.

To solve adequately the safety problem—and by this I mean to prevent any appreciable increase in the *absolute* number of air fatalities per year in spite of the growth of aviation—is, however, an exceedingly difficult task. It calls for long-term national and international planning, intense efforts, and great expenditures on behalf of the whole aviation community.

Increased *flight speed* is, of course, also important for the future development of civil aviation, but we should not go overboard by the sensational aspect of high speed as such. I repeat the observation by the Guggenheim Aviation Safety Center made eight years before the modern jets appeared:

> Speed is now assured beyond the most enthusiastic expectation.

This certainly was not meant to imply that further speed increases should not be made. But, having attained near-sonic speed, it must be admitted that flying still faster is less urgently needed today than it was ten years ago.

The only rational reason for moving fast is to decrease the total traveling time, door to door. We should therefore concentrate our efforts to *reduce traveling time*—not necessarily by increasing flight speed—*where it is most needed*. This means, first, that with the flight speeds already obtained, a reduction by an hour in the ground times to and from airports is, in general, much more important

than saving another hour in the air, for the simple reason that the ground time is pronouncedly inconvenient, whereas the flight time nowadays usually is rather comfortable.

Second, it means that it is more important to increase the flight speed on short routes which are at present flown by aircraft types whose speed is far below near-sonic speed than on medium and even long routes, where such speeds are, to a great extent, already applied. Thus the emphasis should be put on creating faster short-haul aircraft, in particular V/STOL aircraft. Concentration on V/STOL developments would at the same time open the only effective way for substantial reductions in ground time, important not only for short-haul but also for medium and long routes.

The really crucial question of today with regard to further speed increases is whether or not *supersonic aviation* should be introduced. No doubt it would be a considerable advantage for many travelers to fly two to three times faster than the speed of sound on distances above about 2000 miles *if* this can be achieved safely and at the same or nearly the same cost as for near-sonic speed. It must be observed, however, that we are facing a case of rapidly diminishing returns as flight speed is increased above the speed of sound and approaches the "worthwhile cut-off speed." Secondly, the need for such a tremendous jump in speed is much less than it was for the jet/propeller speed increase. Furthermore, the gain in time by SST's would, in contrast to the jet/propeller case, be counteracted by an appreciable reduction in comfort.

With regard to speed increases both below and above the speed of sound I am sure there is general agreement on one point: *developments towards higher speeds must not endanger flight safety* and, to be more specific, must not hamper the urgently needed improvement of safety.

With adequate regulations based upon a scientific approach to the safety problem and with due cautiousness, there is, in my opinion, no doubt that the substantial speed increases in the subsonic regime, which still remain to be made for many applications, can be achieved without endangering safety and the prospects of improving it.

However, for supersonic aviation, the situation is different. I have become convinced that the SST's if developed within the next 10 to 20 years will be appreciably less safe than contemporary subsonic aviation and that it will not be possible to assess their safety level in advance. Briefly, the reason for this is the combined effect of (a) the unprecedentedly great multitude of radically new design features that are inevitable for the SST's, (b) the kinetic heating, and (c) the hazards of the "ballistic" speed as such with regard to collision with other aircraft, as well as with regions of hail, heavy rain, severe gusts, and similar atmospheric conditions.

Considering also the indirect adverse effects that an all-out effort to launch the SST's will have on safety in subsonic aviation, *to introduce supersonic aviation within the next 10 to 20 years appears to be incompatible with the urgent need for concentrated efforts to improve flight safety.*

Regarding *public safety*, unrestricted supersonic aviation will subject hundreds of millions of people on the ground to disturbances, sufferings, and damage due

to *sonic booms*, ever-increasing in frequency as well as in severity (due to the normal trend towards higher gross weight). To my mind it is incomprehensible—in particular in view of the explicit warnings by ICAO and IATA—that commercial supersonic aviation would be introduced without prior knowledge about the extent of the sonic-boom disturbances that will be accepted by the countries intended to be overflown by SST's.

Finally, the effects of cosmic radiation on passenger safety—and on public safety in a long-term perspective—must be observed. It might prove possible to reduce the problem (by adequate solar-warning and avoidance procedures) to having mainly economic implications. Yet, it remains to prove that the risks due even to these reduced radiation doses are negligible.

Proponents of the SST's might state that the risks are small compared with many other risks in daily life. I cannot agree with this outlook. Just as for the case of flight safety, it is not the statistical risk as such that counts; it is the *absolute* number of individual tragedies that is significant. This, I think, is the only way to look at activities that involve risks of fatalities or injuries, which conforms with ethical principles.

Regarding the *economics* of supersonic aviation, prospective SST manufacturers have produced many reports indicating that the seat-mile cost (based upon the standard method for its computation) would be no higher than for present jets and that the attractiveness of supersonic speed would induce most travelers on long and "long-medium" ranges to prefer the SST's. However, even if these two conclusions were right, they are not nearly sufficient proof that the SST's will be able to compete successfully with long-range subsonic aviation. One must not forget

- that the SST's will have greater difficulties than subsonic aircraft to achieve high passenger load factors on the inconveniently scheduled flights required for a reasonably high annual utilization,
- that the maximum utilization of the SST's cannot, for scheduling and other reasons, amount to more than about ⅔ of that of long-range jets,
- that the maintenance and overhaul costs for the SST's will be higher due to design complexity and aerodynamic heating, and, above all,
- that new subsonic types of aircraft will be developed at a much faster rate than new types of SST's, implying that the subsonic operating costs will be successively reduced and that subsonic aircraft will be increasingly able to use airports closer to city centers than the airports required for SST's, thus reducing the time gain by flying supersonic.

Considering the hard facts emphasized in this analysis, I have come to the conclusion that supersonic aviation, as it is at present conceived, will be economically unfeasible if judged by normal commercial criteria of profitability, even without taking into account the serious economical consequences of the sonic boom and cosmic radiation.

I do believe that most of the views I have expressed here are shared by the majority of people who have thoroughly studied the problem of supersonic aviation. No wonder, then, that the reason why many nevertheless insist upon early introduction of SST's has been explicitly stated to be noncommercial

considerations, in particular to keep the aircraft industry occupied and to increase prestige.

With regard to the first motive, I fail to see why the industry could not instead devote its capacity, much more than at present—and, if needed, by financial support of governments—to solving the problems of efficient high-speed V/STOL aircraft, of engine noise, and of laminar-flow control for achieving really low operating costs, and to the manufacture of aircraft resulting from such advances. Such developments would open up tremendous passenger—and thus aircraft—markets, whereas the SST's, even if successful, will contribute little, if anything, to the expansion of aviation.

I do not want in any way to belittle the importance of prestige in the world today. I do feel, however, that there is a danger in mixing prestige into a purely commercial undertaking such as supersonic aviation must be, where ticket-paying passengers are, after all, the most important ingredient. The first successful supersonic flights would undoubtedly add to prestige, but, more important, a subsequent commercial failure of supersonic aviation would mean a loss in prestige.

However, even if a gain in prestige could be obtained for an SST-manufacturing country, one may well ask: Is it worth itz At first sight the question should be of no concern to anyone outside the SST-manufacturing countries. But the issue is of international scope. Unless supersonic flying is prohibited over many countries, the sonic booms will strike all over the world. Furthermore, premature introduction of the SST's would lead to an increasingly severe internal struggle and tension in international aviation, with regard to fares as well as to aviation trade agreements. And, still more important, supersonic aviation, launched on the basis of present knowledge, will inevitably hamper the promising prospects for subsonic aviation to become a really cheap and safe means of mass transportation.

It is often said that one must not try to oppose progress in technology. This is true, but let us first attempt to define what is progress and what is not.

I am convinced that the SST, as it is at present conceived, will be a cripple in the family of civil aircraft. From the time of the Wright brothers the beauty of aviation has been that one can fly day and night, on straight courses, over water as well as land, regardless of terrain or density of the population below. The cost to fly commercially has been steadily reduced and the safety has, until recently, been steadily improved. What kind of progress would it be to create a new type of flying vehicle, the SST,

- which due to the sonic boom might not be allowed to fly at night,
- which also in daytime might be forced to circumvent populated areas, or be prohibited to fly at all over many countries, and
- which in a great many ways will counteract the really significant goal of civil aviation, safe and cheap transportation of as many people as possible?

Aviation has, in fact, come to a crossroads in its development (Fig. 6).

Should we choose the avenue of maximum effort for improving safety, reduction in fares and noise, development of V/STOL aircraft, and for improving reliability, comfort, and availability?

Or, should we detract from these efforts and launch supersonic aviation before its basic problems are solved?

This is, in fact, not only a crossroads; it is also a "point-of-no-return." Once it is passed by introduction of SST's, there seems to be no way to escape, without tremendous cost and turmoil, from the detrimental effects on civil aviation as well as on people.

One of the greatest worries of our time is the fact, often resulting in tragedy, that the splendid progress achieved by science and technology is sometimes accompanied by serious harmful effects, which usually do not appear until after the advances have been made. The medal has not only a bright obverse but often also a dark reverse. Well-known examples are the use of roentgen techniques for medical purposes before its harmful effects were discovered, the contamination of the air by the exhaust gases of motor vehicles, the spoiling of lakes and rivers by disposal of refuse, the spraying of crops with chemicals having toxic effects on humans, and the harmful effects caused by some medicines, such as neurosedyne (thalidomide).
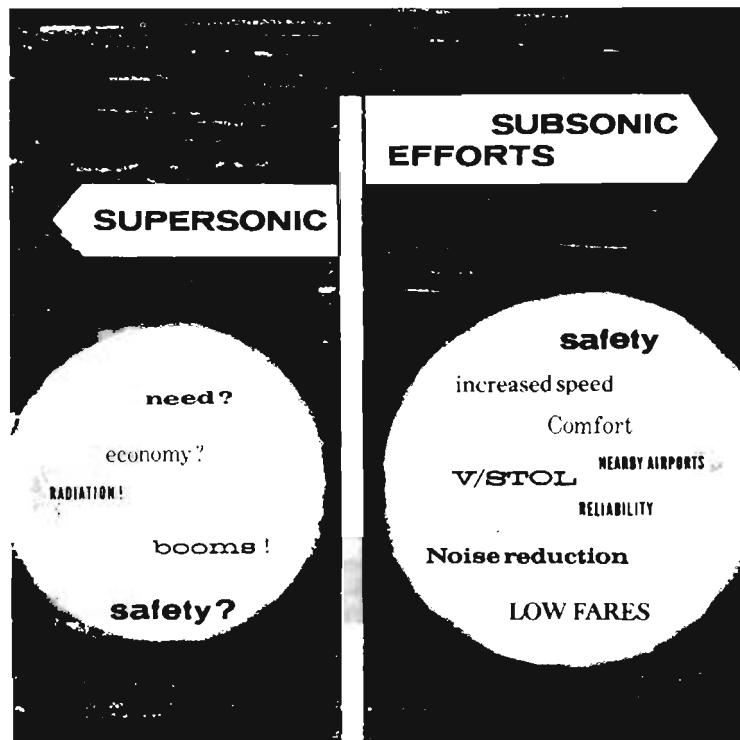

Fig. 6.

Introduction of the SST's would, however, differ in two respects from such occurrences in the past:

● Whereas it was not possible to foresee the detrimental effects of such developments, we do know sufficient about SST's to foresee the harmful consequences, and

● Whereas the scientific and technological advances made up to now have usually been of great importance to the welfare of man, the need for supersonic speeds cannot be regarded as very significant.

In conclusion, I wish to say that it is not only aviation that is facing a crossroads at this time. It is the whole of mankind, because we are confronting an issue of paramount importance which calls for balancing the demands of Ethics against the possibilities of Technology. Whenever there is a conflict between the two, I am sure most people would agree that Ethics should rule over Technology and, indeed, govern it. This is the only solution compatible with democratic and humanitarian principles.

It has often been said that if a difficult technical problem *can* be solved at all, someone *will* solve it. That is possible, but I think we should ask: *Should* it be solved?

It might be greater to refrain than to achieve.

The crossroads mankind has reached implies that we more and more often must make a choice between achieving spectacular technological progress or refraining from it on ethical grounds.

The fact that aeronautics is perhaps the first branch of technology that has progressed to a point where such a decisive choice must be made—with sufficient knowledge about the serious consequences of proceeding—burdens us with great responsibility.

How splendid it would be if aviation took the lead in proving that spectacular technological advances could and should be balanced against the harms and hazards they might inflict, and that the balance should be guided by ethical rules and standards. Such an example would, indeed, be an even greater service by aviation to Mankind than the safe transportation of people.

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Discussor: T. Foelsche, NASA, Langley Research Center, Langley Field, Va.

Since Dr. Lundberg in his comprehensive survey mentioned the discussion on radiation exposure in supersonic transports at the 14th IATA Conference, Montreal, April 1961, I feel obliged to comment that on the basis of the derivation of the numbers in the paper presented in Montreal I am not in agreement with Dr. Lundberg's conclusions. May I recall the mentioned dose rates: As conservative upper limits of exposure by galactic cosmic rays (G.C.R.) and solar cosmic rays (S.C.R.) were given for the crew (80 hours flight time per month, 40 hours in 75,000 ft altitude, in geomagnetic latitudes $> 50°$)

<center>

Without any Precautions

</center>

during minimum years (2)   in certain activity years (9)

<center>

42%   200%

</center>

of the maximum permissible dose rate (MPD) of 5 rem/year, 0.1 rem/week for radiation workers.

160 percent of the 200 percent during solar activity years are attributed to certain rare solar proton events, when the particles have sufficient energy and flux, to penetrate to supersonic flight altitudes with significant intensity. Such events occurred during the last solar cycle, which was the most active cycle since 80–100 years, 3 to 4 times (Feb. 23, 1956; Nov. 12 and 15, 1960 and probably July 16, 1959). Distributed over the 11-year cycle the average dose rate would be only $\approx 75\%$ of the MPD.

There remains still a high safety factor in these numbers, as high as 2–3, as well for the G.C.R. as for S.C.R. dose rates, which I mention later on and which result probably in a real exposure of 25 percent of the MPD only.

<center>

With Precautions

(such as diving down to 45,000 ft and continuing in this altitude and exchange of the crew on polar with that on equatorial routes the following upper limits were obtained)

</center>

minimum years   activity years

<center>

23%   25%

</center>

These dose rates are mainly due to G.C.R. In deriving these numbers a factor 4 is attributed to the buildup of secondaries presumably produced beneath several centimeters of lead in highest altitudes according to balloon measurements of Van Allen in comparison to the intensity without lead. The roof of an SST airplane is presumably only few millimeters thick and of lower Z number material also the effect of heavy primaries seems lower than assumed in these estimates. For an airplane at 75,000 ft it is therefore more realistic to cut the above number by 2, thus arriving at about 12 percent of the MPD.

All numbers also those without precautions contain still another safety factor. The MPD is defined for 50 years professional duty. The regular flight duty time of the crew should, however, only in rare cases surpass 25–30 years. This would reduce the exposure to about 6 percent in the case that precautions are taken. Since, according to Dr. Sowby (ICRP), the definition "radiation worker" and his obligations are attributed to persons who receive with high probability 25 percent of the MPD, the crew would not fall in this category probably also if no precautions are taken.

With respect to the general population, the MPD is by a factor 10 lower (0.5 rem/year) from genetic reasons. The exposure in SST flights depends on the average number of

flights. At 1 flight/week with precautions the exposure would be only 6–12 percent of this MPD. Since pregnant female persons will fly with much lower frequency (e.g., 1–2/year) the exposure would be correspondingly by a factor 25–50 lower and possibly insignificant in its effects in comparison to similar effects of other agents in modern civilization.

These considerations suggest, in my opinion, the conclusion that the probability of a radiation risk is rather low. The mentioned precaution measure of diving down on indication of the flight dosimeter, if an intense high energy event occurs would for my opinion not impair the economy of SST flights, since these events occurred only with a very low frequency.

Author's reply to discussion:

I have not been able to follow all phases of Dr. Foelsche's reasoning, whereby the radiation dose to the crew has been reduced from 200 to 6 percent of the maximum permissible dose. In view of this I wish to emphasize the fact that the conclusions in my paper are not based upon Dr. Foelsche's original paper.[42] I do think, however, that the factor of about 4 that Foelsche has originally applied on the galactic radiation is rather appropriate in view of the great uncertainties.

In my opinion, Dr. Foelsche is far too optimistic about the feasibility of exchanging crews between SST's flying above and below about 50° magnetic latitude. In particular, the dose rates on routes in the two vast regions between 30° and 50° latitude cannot be neglected. Furthermore, exchanging crews will meet with economic and other difficulties for airlines operating mainly on routes above about 50° latitude.

With regard to the radiation dose to the crew in solar activity years, the reduction by Dr. Foelsche to 25 percent of the maximum permissible dose of 5 rem/year, i.e., to 1.25 rem/year, is also based on the assumption that evasive dives can be performed without obtaining any dose at all except the moderate one during the continued subsonic flight at 45,000 ft. Considering the very high rate of increase of the dose in the beginning of a solar cosmic-ray event, it does not seem likely that the occupants of an SST can escape receiving a relatively appreciable dose during the minimum time that it will take for the pilot to decide on (which might require permission from ATC) and conduct a dive.

With regard to pregnant female passengers, Dr. Foelsche indicates that the dose per year would only be 1/25 to 1/50 of the average for passengers flying about once a week, and that this would yield a correspondingly very high safety factor. This way of treating occasional doses cannot be correct. It is only with regard to genetic effects that the obtained doses can be averaged, over the year. For somatic effects, in particular for the case of pregnant women, it is, rather, the risk of obtaining single high doses that is significant.

Finally, I cannot agree that cosmic radiation would not impair the economy of the SST. If the doses that the crew and passengers can be subjected to is to be kept below acceptable limits on the basis of preparedness to conduct evasive dives at occasions of solar-flare events, it follows that *an extra fuel reserve must be carried at all flights* in order to enable the pilot to proceed at subsonic speed and altitude— e.g., from mid-Atlantic to any of the continents. With regard to this penalty it is,

of course, immaterial whether serious cases of solar events occur very seldom or rather frequently. If "false alarms" cannot be avoided, the economy as well as the attractiveness of supersonic aviation will, however, suffer also because of a second reason, the correspondingly rather unsatisfactory irregularity.

Discussor: J. J. Green

Mr. Chairman, I would like to make a few general comments. It seems to me that in the discussion so far sufficient emphasis has not been given to the real significance of Dr. Lundberg's paper which is that he has pointed out the factors which absolutely must be considered if the SST is to be socially acceptable. It is no doubt possible to criticize some of the points made in the paper, to take issue with the author on some of the details thereof, but the fact remains that he has put his finger on a number of major issues which must be faced squarely before we can expect to see the SST introduced into commercial service on the world's air routes.

In the early days of commercial aircraft the designer was faced with the problems of airworthiness and reliability and the ever present desire for improved performance and economy. He coped with these problems by the application of refined engineering principles based on the rapidly expanding knowledge in the aeronautical sciences. He was aided in his work by carefully developed airworthiness codes and the international exchange of operating experience and knowledge. In those days, generally speaking, the airport was a good neighbor and the social acceptability of the airplane was scarcely ever in question. If power failures occurred during takeoff, this did not necessarily entail a highly spectacular crash involving great loss of life. Over the years we have seen this happy situation gradually deteriorate. First the high-powered piston engine and later the jet engine introduced a noise factor which rendered the airport area a bad residential district and the commercial airplane became endowed with a certain nuisance value. Low approach and climb-out paths drew increasingly frequent complaints from nearby residents, while the occasional accident during landing or takeoff produced disasters of great magnitude. There was not much the aircraft designer could do about these things. The application of improved engineering skill and knowledge had led, as was intended, to greatly increased performance and passenger carrying ability but the silencing of large engines and propellers and later the jet engines to an acceptable noise level without too great a sacrifice of performance has been no easy engineering task. And while reliability has accompanied design refinement a flock of birds in a jet intake or for that matter the sudden failure under takeoff power of a small but vital component must always be considered as a possibility.

The social acceptability of the airplane has now become, with the SST, something which the designer must seriously concern himself about, perhaps for the first time. I believe that Dr. Lundberg's paper will become a classic, the first paper to deal in so detailed a fashion and so exhaustively with these important factors affecting the acceptability of the SST. There will doubtless be other papers which will follow which might dot the i's and cross the t's, as it were, extending and refining the studies begun by Dr. Lundberg. I would compare Dr. Lundberg's paper, however, with the classic paper by Mentzer and Nourse in which they introduced for the first time the concept of a set of formulae for calculating the direct operating costs of transport aircraft.

Dr. Lundberg has drawn attention to the fact that the SST would cater to the needs of the minority of the air traveling public. I have always understood that studies of the transportation market have indicated that the great traffic potential lies in the really short haul but that to reach this untapped market will require the development of the VTOL or STOL aircraft. It might be that with the existence of supersonic military aircraft the SST presents an easier technological task than the development of an efficient V/STOL commercial aircraft. Here in any case is a challenge where the pay-off and market returns are most attractive and where the development path is not strewn with the type of problem so forcefully brought to our attention in Dr. Lundberg's paper.

Author's reply to discussion:

I wish to thank Dr. Green for his kind remarks.

Discussor: F. C. Haus

I do not want to discuss here which would be the passenger choice if speed increases in the future; I want only to comment on the present situation because I think it is a pity that the safety level has not improved during the last ten years.

I know there are many agencies involved in safety work, they are doing their job quite well, but the result appears nevertheless not to be completely satisfactory because one should expect that progress of science, technics and organization would have improved the overall safety.

It may be argued about the value of the number of passengers killed per 100 millions of passenger miles as a criterion of safety, but the criterion exists and there is no other available so we must accept it and use it as a basis for studies of safety.

The title of the lecture suggests that safety could be studied in terms of speed—or as a function of speed considered as an independent variable. May I suggest that safety should be studied as a function of a lot of variables.

The overall safety level for all ICAO countries is worse than the level for American domestic airlines alone. They provide a big share of the total amount of passenger miles flown. This means that the non-American lines have a higher fatality rate than the American domestic transport. This was still more the case in 1947 than it is now, and I remember I was nearly shot in 1948 for having made such a remark.

The fatality rate for chartered flights is certainly worse than the rate for scheduled transport. In general the chartered transport planes are slower. This proves that the increase of speed is not the only variable that could be blamed.

I think that a fundamental study of the causes of accidents—that is past or accumulated experience—should allow us to evaluate better the probability of occurrence of every possible cause of accident, and it is only when accumulated experience has shown the importance of every possible cause of accident—or combination of causes—in the now existing conditions that it may be possible to evaluate the improvement that may

be brought to the probability of each cause of accident. This information is necessary before it could be possible to discuss about allotted probability share.

I do not know how that will be done, nor who will do it, but I think Mr. Lundberg was right to ring the alarm bell.

Author's reply to discussion:

I quite agree, and have emphasized in the paper, that speed is only one of a host of factors that influence safety. I wish to repeat (a) that speed increases in the subsonic regime have been made in the past and can be made in the future without impairing safety, and (b) that it seems extremely difficult, if at all possible, to introduce supersonic speeds, on the basis of present knowledge, without adverse effects on safety, both directly with regard to SST operation itself and, indirectly, considering repercussions on subsonic aviation.

Professor Haus indicates, rather pessimistically, that we have to wait for a sufficient amount of experience about accidents in order to be able to evaluate the improvements that can be made, and that we only then can adopt the principle of Allotment of Probability Shares. I cannot share this pessimistic view. The philosophy behind the APS-Method is the opposite to the method of basing actions and regulations merely upon accumulated experience. I do believe that it is high time to introduce new thinking on this point and to agree on an international safety policy. Such a policy must be based upon statistical principles, and I do think it is necessary to share into subdivisions or "slices," the total "probability cake" (corresponding to the total risk of accidents according to an overall safety goal), and allot the slices to various accident causes in order to prevent the sum of all the probabilities of accidents from exceeding an acceptable magnitude, the safety goal.

Discussor: N. J. Hoff

I consider as one of the major contributions of the paper the statement that the present rate of fatalities per passenger mile must be significantly reduced as the total passenger miles flown increase in order to retain or to gain public confidence in the safety of air transportation. On the other hand, I find the departure and arrival times unimportant on really long flights. I simply cannot shift my bedtime nine hours when I travel from San Francisco to Stockholm; hence it does not matter at what hour I arrive. Anyway, few people sleep more than an hour or two between New York and Paris with the present evening departure times on the jet transports. Thus Mr. Lundberg's ideas on the poor utilization of the capabilities of supersonic transports should be revised. What counts with the passenger is whether he has to spend two hours sitting in the plane or six hours to complete the trip.

Author's reply to discussion:

I agree to some extent with Dr. Hoff that the departure and arrival times might be less important on really long flights, such as an Atlantic flight. In particular, accustomed travelers may wish to get the flight over with as soon as possible, mainly in order to use the remainder of the day for resting. This agrees with the statement in my paper that most passengers might prefer the SST to the subsonic aircraft as long as the departure and arrival times do not encroach appreciably upon the normal sleeping hours. The main point I have made in this respect is that I find it unlikely that most people would prefer to rise at, say, three or four o'clock in the morning in order to catch a very early SST flight to taking a subsonic flight at a decent departure time later in the morning.

Thus the problem of "feeding" the SST's with passengers around the clock is indeed a serious one. It seems most difficult to solve as the fare reductions required for obtaining reasonable load factors on the inconveniently scheduled SST flights are likely to imply losses on those flights.

Discussor: E. D. Keen

In my opinion the practice of fixing the same fares for all types of aircraft operating on the same route is wrong and will seriously prejudice the future of the airline business if attempts are made to use present day fare levels to judge the efficiency of operation. Differential fares should be charged for the benefits of speed that these new and expensive aircraft at least in the early stages of introduction. I should be grateful for any expressions of opinion of this view.

Author's reply to discussion:

The question of whether or not differential fares should be charged for different types of aircraft is both important and, as is well known, controversial. Personally, I do not think that a higher fare should be applied merely because of higher speed. High speed is one of the most attractive features of aviation, and the high-speed aircraft should, therefore, be "punished" by a higher fare only if its real total operating costs are higher than for competing slower aircraft. Thus, if the jet aircraft is cheaper to operate than the piston aircraft, the jet should not have to apply a higher fare only for the sake of keeping the piston aircraft in the market.

If, however, the SST, as is likely, will be more expensive to operate than near-sonic jets (if the operating costs are calculated on an objective basis, including any financial support by governments that might be applied), then this should reflect in a higher fare.

The surcharge that the SST passenger thus with all probability would have to pay would have a special, important, and interesting effect: The extent to which medium and long-range air passengers would prefer SST's to near-sonic jets in

spite of the surcharge—be it of the order of 10 or 50 percent—would be an indication about how close we have come to the "Worthwhile Cutoff Speed." Such information would be most valuable with regard also to any possible plans to develop hypersonic aircraft.

Discussor: B. P. Laight

I should like to say first that although there is much that everyone will agree with in this paper, particularly in the desire for more safety. I do feel that Mr. Lundberg overstates his case when he gets on to the subject of it being a matter of ethics that the SST should not be continued. I can think of no technological breakthrough that did not involve some risk and the SST can be no exception; so I think it is a wrong argument to condemn the SST because there may be some risk. Equally it would be wrong if engineers did not make every possible attempt, short of abandoning their work to make the SST as safe as possible, and I am sure that is what they will do.

It seems to me that a greater case against the SST can be made on economic grounds. Although there are those who say that in due course the supersonic aircraft will be cheaper to operate than the subsonic, they do not give figures and there is going to be a considerable investment needed before this is achieved. At least first generation SST's, as far as any figures I have seen show, will cost more to operate and this money has to be found from somewhere—higher fares or national resources. Either of these is a controversial subject but what happens will be of overwhelming importance to the business side of the SST.

Finally, I should like to suggest that the subject of reliability should be given more attention because it is very closely tied up with safety but is a much more manageable quantity to discuss. The reliability of each part of the airplane can be worked on and any improvements help economy as well as safety. Perhaps reliability of air transport in all its aspects would form a suitable topic for the next Congress.

Author's reply to discussion:

I have not condemned the SST's because they might involve "some risk." A certain amount of risk must admittedly be taken for every technological breakthrough, but when it comes to advances that will be applied for ticket-paying travelers I do maintain that the risks must not exceed a certain, very low level, and that the risks must be at least roughly assessible. I do not think that the SST will comply with these two demands. To "make the SST as safe as possible" will probably be far from satisfactory.

My view that technological advances should be balanced against ethical demands refers, however, in particular to the millions of people on the ground that will suffer from the sonic booms and to the unknown deleterious effects of cosmic radiation. It is in these two respects I consider the harms and hazards imposed by the SST's to be out of all proportion to the possible benefits.

I have noted with interest the observation made by Mr. Laight that statements to the effect that supersonic aircraft will be cheaper to apply than the subsonic, have not been adequately supported, and that anyhow considerable investments must be made before such a statement of affairs can be achieved. I agree on this, and I also agree to the suggestion that reliability should be given more attention. The reason why I have treated the reliability rather superficially lies, of course, in the title of the paper.

Discussor: G. H. Lee

This paper will give rise to much thought and discussion because it attempts to answer the question: "What type of transport airplanes should be produced?"

While many of the factors affecting the choice of airplane are mentioned, it strikes an engineer at once that, despite the many numbers given, many of the numerical data are missing. For example, it is agreed that high speed attracts passengers, but we do not know at present how load factor varies, numerically, with block speed.

What is needed is an engineering approach, market research perhaps, to the problem. The first step is to find the form in which to arrange the various parameters and then to determine numerical values.

The ideal solution would be to formulate an expression for, say, the profit that an airline should be able to make. Suppose one could write:

Profit to air line $=$ Function of $[N,$ (D.O.C.), (I.O.C.), $n,$ $R,$ $V,$ $V_B,$ (T.P.), (C.F.) etc. . . .

where N = number of airplanes

(D.O.C.) = direct operating cost

(I.O.C.) = indirect operating cost

n = passenger capacity

V = frequency of service

V_B = block speed

(T.P.) = ticket price

(C.F.) = "comfort factor"

Such an expression would enable an aircraft designer to assess on a sound basis how much various different types of airplane might appeal to possible purchasers.

The first step would be to find the form of the function, by general thought and consideration of the economic and practical aspects of Air (and other forms of) transport and then, by reference to existing data, to assign numerical values to the various constants. This type of study may be new, but could, I think, be of great value.

However, without waiting for the above magnum opus to be completed, one can see right away that today there is a good case for considering a short range transport to fly at just supersonic speeds, say $M = 1.15$.

For ranges up to 500 or 600 miles, the cruising L/D ratio is less important than for long ranges since the fuel load is small and the gain in block speed from the high cruising speed increases productivity and so reduces the nonfuel costs. Flight at $M = 1.15$ in the stratosphere will not give rise to sonic bangs on the ground, nor are there any problems with kinetic heating. At the cruising height of 30,000 ft–40,000 ft, there is no cosmic radiation risk. For the short ranges, the time saving by cruising at higher Mach number is negligible (compare Figs. 9 and 11). Current swept wing aerodynamics apply because

the sweep (say 50°) is enough to avoid wing shock waves; the body is area-ruled. Such an airplane would fit normal traffic patterns.

Calculations on a design study show that short-field performance (5,000 ft at ISA, S.L.) and direct operating costs similar to those achievable with high subsonic (M = 0.85) types, e.g., 1.3 pence per passenger mile for a 500-mile stage, can be expected with a 500-mph block speed (A.T.A. Method), for that range, which compares with 400 mph for the M = 0.85 subsonic airplanes.

The M = 1.15 airplane can, therefore, be operated on short to medium stages to give a 25 percent increase in block speed without any increase in D.O.C. or loss of field performance and without any of the disadvantages currently associated with the SST. Such a type merits serious consideration.

Author's reply to discussion:

I am a little doubtful whether it will ever be possible to treat the whole problem of optimum choice of aircraft by a sufficiently comprehensive parameter study. I do agree, and have actually emphasized in the paper, that market research is urgently needed in order to find out, for instance, the attractiveness of supersonic speeds. I do feel, however, that a complete study of the optimum development of aircraft, as well as of the whole of civil aviation, must and can be guided by a fair amount of common sense. By using this old tool, somewhat disreputed in our days of computing machines and operational analyses, it is often possible to make "short cuts" and arrive at the correct answers with a more reasonable amount of computations.

I entirely agree with Mr. Lee about the promising potentialities of a "just-supersonic" or transonic transport, as I have also briefly indicated in the paper.

Discussor: R. Legendre

The increase of flight altitude, connected with the use of high speeds, is favorable for the safety, and the supersonic flight is not disquieting. The developments of devices for short or vertical takeoff are more useful for the supersonic aircraft than for the subsonic aircraft, to eliminate the dangerous phases of flight at low speed and low altitude. The takeoff and landing speeds and distances should not increase.

The doctors do not wait to use new medicines until they know the effects of them on the descendants of their patients, and, in spite of some accidents, we ought to be grateful for that. There will be, and there are already, a sufficient number of volunteers to be exposed to cosmic rays to make the principal effects of such rays rapidly known.

Attention is drawn sufficiently to the noise of high-speed aircraft so that efficient limitations could be exempted without excessive optimism.

Finally, meeting places for very busy people could be arranged near the airports. I prefer this Congress to be held in Stockholm rather than at its airport, and yet I would take pleasure in traveling by supersonic aircraft.

Author's reply to discussion:

I understand that Mr. Legendre means to imply that supersonic flight might be safe, because there is less traffic at supersonic altitudes. I do not think that the SST safety problem is as simple as that.

In theory I agree that the SST, in order to be really competitive with subsonic aircraft, and also for safety reasons, should be a V/STOL aircraft. Eventually, such a vehicle might be developed. To make a V/STOL SST in the first and even second generation of supersonic aircraft would, however, add enormously to complexity, and thus to the risk of accidents. Furthermore, to comply with the maximum acceptable engine noise level for V/STOL SST's operating close to the cities, will pose a staggering problem.

I very much doubt that we can, in a reasonable time period, attain a sufficient, or even an appreciable, knowledge about the hazards of cosmic rays by sending great numbers of astronauts into space. For reliable statistical evaluations of the genetic and somatic effects the numbers of astronauts would be too small even if manned space flight were to grow very rapidly during many decades ahead. Finally, I question the ethical side of the method of subjecting even paid crew members of space ships to radiation, in order to assess the seriousness of somatic and genetic effects of cosmic radiation. In particular I doubt that this will ever be an accepted method for investigating the effects of radiation on the fetus of pregnant women.

Discussor: L. F. Nicholson

In this paper the case for and against supersonic transports is discussed in terms of passenger appeal. I would suggest that the most important case for the supersonic transport is that it is potentially the cheapest aircraft to operate at long ranges, and perhaps at medium ranges. One can argue about the attraction of speed to the traveler but there is little doubt about the attraction of cheaper fares. Laminar-flow control has been mentioned as a means of reducing costs and I would like to say that this promises to give about the same savings to supersonic as to subsonic aircraft. Other improvements, in engines, materials, etc., tend to improve the supersonic aircraft more than the subsonic, so that relative costs should move steadily in favor of the supersonic aircraft.

It has been suggested that the market for supersonic flight is very small since most passengers only want to travel a few hundred miles. I believe the market to be larger for two reasons. First, the supersonic transport can operate efficiently down to smaller ranges than has often been thought and second, my view is that the speed of travel will influence the length of the journeys made. The bulk of journeys will tend to be confined to that journey time which allows a passenger to go and return in the day. As speeds increase the distance between places fulfilling this criterion of going there and back in the day does increase very significantly.

With regard to the time wasted on the ground, I suggest that the combination of aircraft and hired car with the elimination of wasted time going to and waiting at the town terminal will be increasingly popular and have some effect on the conclusions in the paper.

It has been contended that the cheapness of supersonic flight is illusory because of the difficulty of fitting in enough flying hours at convenient times. The example used has been a Mach-3 aircraft crossing the Atlantic. This is, I believe, an unusually difficult case. A Mach-2 aircraft can fit in just as many journeys at convenient times and makes better economic sense. Moreover, most airlines operate a complex mixture of routes and this makes the problem of utilization more tractable. After all, what the supersonic aircraft is doing is giving the long range operator the utilization problems which the short range airlines has had to deal with already. Short-range airlines do not, I agree, use their aircraft for as many flying hours per year as long-range airlines but they don't fall so very far short.

Finally, supersonic aircraft must not be built which are not socially acceptable. I think a Mach-2 aircraft can be made which will be socially acceptable, but there is uncertainty and everything that can be done must be done to reduce this uncertainty.

Author's reply to discussion:

Mr. Nicholson's suggestion that the SST is potentially the cheapest aircraft to operate at long and possibly also at medium ranges is presumably based upon the common observation that as speed goes up, productivity increases. As explained in great detail in the paper, this "first approximation" is a much too inaccurate basis for conclusions about the operating costs. With reference to the paper, I wish to stress that there are a great many factors that must be considered. Such factors are, poor load factors (or great fare reductions) on the inconveniently scheduled flights required for reasonable utilization, the small maximum possible magnitude of this utilization for scheduling and other reasons, the high maintenance costs due to design complexity and aerodynamic heating, and, above all, the faster rate at which subsonic aircraft with decreasing operating cost and with ability to use centrally located airports will be developed. Due consideration to these and other factors is likely to very substantially alter the economic picture that can be obtained on the basis of the standard method for operating costs.

As stated in the paper, it might well be that the SST's give better hopes for future advances for the simple reason that, the SST represents a completely new category of flying machine. There will, however, be great difficulties, to say the least, in exploring its potentialities, under increasingly severe competition with new types of subsonic aircraft. The reason for this is that new types of SST's, employing radically new features (such as laminar-flow control, V/STOL properties, new engines and materials, etc.), cannot possibly be developed at short intervals, say every fifth year. For this the supersonic market is much too limited. The subsonic transport market, relevant with regard to aeronautical improvements of significance, for competition with SST's, is about an order of magnitude bigger than the supersonic market. This means much better possibilities for the subsonic case with regard to rapid developments, which at the same time can and will be much safer (with regard both to technical/economical shortcomings and to flight safety) as only one radically new feature has to be introduced for each development step.

Furthermore, I think that Mr. Nicholson exaggerates the need for air passengers to go and return in the day. This certainly does not apply to tourists. It applies

only for a limited part of the businessmen category, and mainly for fairly short "supersonic" ranges. Very few businessmen will make return trips over the Atlantic in one day.

Finally, I do not believe, for reasons explained in the paper, that the utilization problem of the SST's will be even nearly the same as for present short-range operation; the difficulties to keep the SST's in the air will be much more severe.

Discussor: B. S. Shenstone

Although I agree with Mr. Lundberg's conclusions to a considerable extent, I feel that it might be worthwhile to mention a couple of points because my reasons for coming to Mr. Lundberg's conclusions are not always the same as Mr. Lundberg's.

I think the two main unknowns about the SST are today the costs and the annoyance. At present the calculated costs, calculated by airlines are high, too high, and the annoyances are noises. Civil airlines should be civilized and annoying people is not civilized.

I agree with Littlewood that there is a danger that we may all be victims of his eager beavers. Although the beaver is Canada's national animal, he is no more civilized than von Doblhoff's status seekers.

Indeed, the wheels are beginning to turn and the airlines are looking over their shoulders. My God, if we are forced by pressures and our own human weaknesses to embark too early on the SST, airlines will fall down like ninepins and I hate to think of Lundberg's safety predictions.

Let us not forget that when supersonics come, all airlines will be short-haul airlines, and believe me, even with good airplanes it is not easy for short-haul airlines to break even.

Author's reply to discussion:

I very much appreciate Mr. Shenstone's warning that we should not let ourselves be forced by pressures, and our own human weaknesses to embark too early on the SST.

Discussor: B. R. Stanojlovic

I wish to thank Mr. Lundberg for his admirable study on the problem of aviation safety which will remain a classic reference on the subject. Until not so long time ago "air safety" was not considered a decent word to be uttered in public. Mr. Lundberg has put an end to this.

He rightly disagrees with those who "are expected to employ more psychology and less statistics in future campaigns against one of the industry's greatest handicaps to building a mass market of air travel—the fear of flying, which Gallup investigations have indicated is often regarded as the major disadvantage of aviation."

This policy of "more psychology and less statistics" leads to no briefing of passengers on emergency procedures, on location of oxygen masks; to almost invisible markings of emergency exits; to calling sonic boom "sound of freedom," etc. It is obvious that this is an ostrich's policy. I agree, therefore, with Mr. Lundberg's remark: "I don't think that such campaigns will ever be an efficient remedy. There are no other efficient means of fighting cleancut of fear than by making aviation safer."

This policy of "more psychology—less statistics" is, it seems to me, a defeatist policy, an unscientific approach, an acknowledgment that critics are right, that the fear of flying is justified. This policy is in sharp contrast with that adopted by military aviations in both Europe and America. I quote from the 1962 issue of "Survey of Research Projects in the Field of Aviation Safety" published by the Cornell-Guggenheim Aviation Safety Center:

> In view of the high performance aircraft introduced by the military services in recent years, their safety record has been spectacular. The military services have active aviation safety organizations, which conduct accident investigations, make special studies, publish safety magazines, posters, and flight safety material, organize safety programs at base and fleet activities and assign flying safety officers trained for special duties. Results of this are apparent in a decreasing accident rate, particularly in training activities. Aside from humanitarian aspects, the value of such programs is obvious, since a crashed airplane represents many thousands or even millions of dollars, in addition to the loss of highly skilled pilots and crewmen.

It is my considered opinion, based on twenty years of experience in the field of aviation safety, that this is the only realistic and successful way for dispelling "the fear of flying"— the way of *making* aviation really safer, as suggested by Mr. Bo Lundberg.

As an argument against such an effective and aggressive policy for improving aviation safety one is told that it will be costly in terms of money. I shall comment on this by quoting again from our Center's "Survey of Research Projects in the Field of Aviation Safety":

> ECONOMICS OF SAFETY. A decision as to whether to adapt a safety device technique or system is inevitably related to its costs. This may consist of reduced payload, loss of performance, delays caused by malfunctions of added equipment, additional maintenance requirements. With the safety of air transport operations being well within the normal risks of living, a question arises as to whether the flying public is willing to pay more for small increases in safety, above the additional sums necessary to place the airlines on a sound financial basis.
>
> A thorough study of the economics of safety has never been undertaken, to assist the industry in deciding on the tangible and intangible merits of fewer losses and greater public confidence. For example:
>
> (a) Development in all-weather landings would improve schedule reliability as well as safety, and attract many short-trip passengers who now take alternate transportation or cancel their trips because of adverse weather.
>
> (b) Airport improvements should stimulate both long range jet and short range traffic.
>
> (c) Weather Forecasting improvement is closely related to all-weather landings, and has the added feature of benefitting many other industries, such as agriculture, communications, and ground transportation.
>
> (d) Monitoring Systems, properly applied and analyzed, should result in less unscheduled maintenance and more accurate flight paths, requiring less fuel and flight time.

(e) Crash Fire Protection, if made effective, might save millions of dollars in personnel, equipment, and insurance losses, if only a single large transport were involved in an accident in which fire was prevented from occurring.

The Center therefore feels that one of the greatest gaps in safety is the lack of information on the economics of safety.

Finally, I am using this opportunity to thank Mr. Lundberg for his kind words about the work of Mr. Jerome Lederer, Director, Cornell-Guggenheim Aviation Safety Center and Flight Safety Foundation, who has dedicated his life "to make flying the safest form of transportation."

Author's reply to discussion:

I thank Mr. Stanojlovic for his kind remark, and I wholeheartedly agree with his opinion that, although measures for improving safety might often be expensive, they will pay richly in the long run.

Author's concluding remarks to the discussion:

When I started to study the problems involved in supersonic aviation, about two years ago, I was under the impression that the situation would be very much the same as when the jetliners were introduced a few years ago, in that if one major airline bought SST's and put them into operation, most other airlines would have to follow suit to stay in the market. That this will happen, seems to be generally contended even today.

Having completed the study, on which my paper is based, I have now come to the conviction that this repetition of history, will not come about. As opposed to the situation when the new jetliners were introduced and made most piston aircraft rather obsolete, the SST's will not be able to outmode the subsonic aircraft to an even remotely comparable extent; the airlines, which stay in the pure subsonic market, will be in an excellent, not to say improved, competitive position. For this reason, the market for the SST's will be very much smaller than present predictions; this will (unless great subsidies are given) adversely affect the purchase price and thus also the operating cost of the SST's, with the result that the competitiveness of the subsonic airlines will be still more strengthened.

With this conclusion, it would, at first sight, appear that the possible introduction of SST's would not be much to worry about, at least not for those airlines which upon closer investigation will find that they do not need to follow the examples of one or two "supersonic" airlines.

I do think, however, that the introduction of SST's would nevertheless be a most serious event for aviation as a whole. The reason for this is that once SST's have been manufactured and put on the market with the support of some governments, these governments will undoubtedly make every effort to favor supersonic

operation, not only by subsidies but also in other ways. This would lead to intense stresses within the aviation community, as well as between countries. I do fear that aviation will then face a really severe crisis, compared with which the present financial difficulties will seem rather trivial. We are, therefore, virtually confronting the "point of no return" in the history of aviation, as emphasized in the paper.

One thing that has almost shocked me during the course of the discussion, is the opinion that, in spite of the fact that neither the passengers, nor the operators, nor most of the aircraft manufacturers want the SST's, this development is inevitable. This, I think, is nothing less than sheer defeatism.

However, I personally am not that pessimistic. I do think that all that is needed to prevent our being involved in something that no one really wants, is adequate information about all its implications to all the countries—the general public as well as the governments—which will be affected by supersonic aviation. And I am convinced that with all the thorough investigations that are being made in the U.S., the U.K. and France, such complete information will be given also to all the other countries, so that they are not taken by surprise, for instance by sonic booms. Such information lies, of course, not least in the interest of the "supersonic" airlines so as to prevent their being subjected to unexpected prohibitions, or restrictions, with regard to flying over countries which have no direct interest in this kind of operation.

Most of the discussion has centered around the issue of supersonic speed, whereas the most important theme of the paper is safety. I am, indeed, glad that there have been practically no differences in opinion expressed with regard to my thoughts and proposals on safety. I only hope that this issue, which is the real and all-important challenge to aviation, will not be obscured by the present controversy about supersonic aviation.

With regard both to speed and safety, there is a great need for international planning, cooperation and action, so that aviation will master the course of development rather than becoming a victim of uncontrolled occurrences. Once more, I wish to emphasize that in this international planning and action the real needs of mankind must be considered, and this, I think, is also of primary interest for aviation itself. In the long run, aviation can have no other interest than that of the general public.

Finally, I wish to express my sincere thanks for your very kind interest in my paper. The fact that so many different opinions have been expressed, will, I hope, cause further intense discussions. If this is so, I will be richly rewarded, because exchange of views usually leads to further studies, and that is of great importance in the present situation.