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ECONOMIC AND SOCIAL ASPECTS OF COMMERCIAL AVIATION AT SUPERSONIC SPEEDS

by

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ECONOMIC AND SOCIAL ASPECTS ON COMMERCIAL AVIATION AT SUPERSONIC SPEEDS [x]

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Abstract

Neither current nor greatly improved SST projects conceivable in the future will be able to compete with subsonic jets in the economy-class market without enormous losses or subsidies, even if no restrictions are imposed on overland flights. Operation at about first-class fares will also be grossly uneconomic, and at such fares SSTs, operating mainly over the oceans, can only take over at most half of the small long-haul oversea first-class market and a quite insignificant portion of the economy-class market. The main reason for the deficient economics is the much higher purchase price per seat. The exceedingly high cost/benefit ratio appears to make the SSTs unjustified even if they had no adverse environmental effects. Minimum requirements for their introduction are (a) that they are forbidden to fly supersonically over land, (b) that they comply with airport noise standards for subsonic aircraft, and (c) that it has been proved that no adverse effects result from sonic booms over sea, cosmic radiation or exhaust emission in the stratosphere.

1. Introduction

For any new and costly technological enterprise of international scope to be justified there must, in the first place, be a great real need for it, i.e. the benefits must be considerable in relation to the cost. Secondly, the operation economics of the enterprise must be beyond doubt. This is particularly important if the activity causes adverse environmental effects because then the profitability must be so good that the social "diseconomics" can be paid for out of the profit. The need for and operation economics of current and future SST projects will therefore be the main subjects of this paper.

The analysis are based on the presumption that civil supersonic flight is not inevitable. The opposite assumption - in particular that the "point of no return" has been reached because some Concorde aircraft have recently been ordered - would be biased and hence unscientific. Surely, an objective judgment of the justification of the SST, the social costs of which might be found either to be totally unacceptable per se or to more than outweigh its benefits, can only be made on the basic presumption that mankind has still a free choice to determine whether or not, or on what conditions, this means of transportation should be introduced.

II. The Need for the SST

All since the outset the SST proponents have maintained that the benefits of flying SSTs instead of subsonic jets would be about equally as great as the tremendous benefits of the transition from the piston aircraft to the jets. In both cases, it is alleged with little variation the "journey time is halved" and historically this causes "a great upsurge in trade" or has "a major positive influence on travelling habits".(1)

From the very beginning of my criticism of the SST I have opposed this allegation of proportionality between benefits and reduction in travel time(2-5) but apparently with no or little effect. Allegations that the travel time is halved and that therefore the SST is "enormously attractive" are still persistently repeated. (6-7) This makes it imperative to analyse these questions in even more detail than before because they are fundamental for the need for the SST.

Firstly, the door-to-door travel time is not halved. It is only reduced by 20 to 35 percent (depending upon trip distance) because of the long ground times. Secondly, and even more important, the human body and soul do not respond to percentage reductions in journey time; what is felt is the absolute travel time in hours! And the time gain by current SSTs would be only 3 to 3 1/2 hours on the longest distances they can fly, some 3,500 miles, see Fig. 1. As this gain is merely half of the 6 to

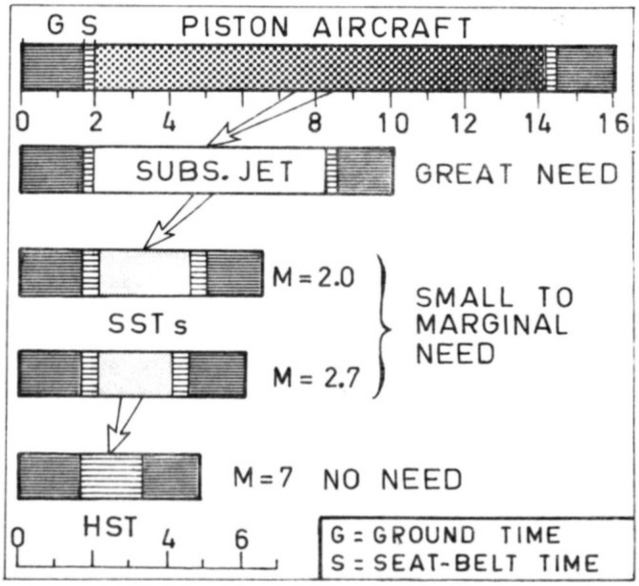

Fig. 1. Illustration of the impairment in "comfort per hour" and the rapidly decreasing time gains with flight speeds exceeding Mach 1.

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7 hours saved by the jets over the pistons, the benefit of the SST, measured in hours, is only half of the benefit of the previous large increase in cruise speed.

In reality, however, the SST/subsonic-jet benefit is, in fact, for many additional reasons rather insignificant, even on long flights:

1. It was, of course, the last about 6 hours of a 3,500-mile piston flight of some 13 hours that were the most tiresome because of the long duration, and the unpleasantness and tiring effect was enhanced by the high vibration and noise in the cabin of piston aircraft and, still further, by frequent occasions of bumpy weather at the low cruise altitude of these aircraft. Consequently, the elimination by the jet of these 6 last "piston hours", e.g. over the Atlantic, was an enormous improvement which would have no equivalence whatsoever if SSTs are to replace subsonic jets.

2. Next we should compare the smoothness of flights in SSTs, subsonic jets and piston aircraft. Also in this respect remarkable allegations are still being made. A spokesman for Boeing states:

> "This same load-factor preference for the SST, as compared to subsonic jets, has been used in the economic assessment (for the SST) because we see the same factors present (as for the transition from pistons to jets). Half the flight time, the airplane flying at very high altitude, out of the weather, and a much smoother ride." (8)

Disregarding the fallacy of implied benefits due to percentage reductions in journey time the two further points are also erroneous. Both the subsonic and the SST fly above most of the "weather", providing very smooth rides [x], also because they are both relieved from the high vibration and cabin noise in piston aircraft.

3. The fact that subsonic flights, thanks to the jets, have become quiet, smooth and reasonably short in duration can hardly be overemphasized. It means that the time on board is no longer a "loss" to the average passenger - as the SST proponents will have us to believe - because it can be pleasantly used for eating, reading, taking a nap or enjoying a movie, etc., occupations that are considered a plus in life when performed on the ground.

The time gain of a couple of hours by the SST might, of course, nevertheless be attractive to some hurried businessmen, but so is the spaciousness of the wide-bodied jets to the majority of passengers. And quite a few businessmen use the flight for effective work with no interference by phone calls, etc.

The "thrill of flying faster than sound" has been advertised as a plus but many passengers will certainly be more content with the less exciting subsonic speeds.

4. The speed advantage of the SST will also be questioned for a further reason, namely the great difference in local time between the two ends of most longhaul routes, e.g. over the Atlantic where 5 or more one-hour time zones are crossed. Most passengers will undoubtedly find the time gain by the SST of a few HOURS rather pointless as it normally takes several DAYS to adjust to the new local time, in particular as regards sleep, and be fully fit again for work or tourism. As a result the spaciousness and other advantages of the wide-bodied jets will to an increased extent be regarded as a greater plus than the time gain by the SST.

For all these reasons the passengers' SST-or-subsonic choice at equal fares has to a great extent been reduced to a matter of taste.

That this is so was clearly confirmed by the Gallup poll with nearly 200,000 passengers made by TWA. (9) No less than 20 percent "favored the 747" over the SST - and 14 percent "made no choice or answer" - because they considered the jumbo jet "more comfortable", "saw no need of getting to destination any faster", "enjoy longer flight time" or "prefer slower speed". Another set of replies indicated a 747/SST preference split at equal fares of about 40/60.

It should be observed that the time-difference nuisance was apparently not taken into account in this TWA poll. If it had been, the preference splits would likely have been more favorable for the subsonics. The important matter is, however, not the accuracy of the preference splits - all Gallup polls are subjected to uncertainties - but the highly significant revelation that increased speed is no longer taken for granted as the number one consideration.

To sum up, we are facing an entirely new situation. For the first time in the history of aviation there is no longer a great need for a further big increase in speed. SST proponents use to tell me that it is not the need but the demand that is important for the economics of the SST. I disagree. Admittedly, the SST/subsonic preference at equal fares might be as high as, say, 70/30, on some long routes, yielding a considerable demand. But it might also be much lower, say, 30/70. The pendulum could swing either way. The important fact is that whenever the need is insignificant or marginal there is no longer a sound concrete basis for good and reliable economics. It has, in fact, been a terrific gamble - with billions of dollars - to rely, in the prediction for SST economics, on speculative extrapolations of experience in the past that "passengers always flock to the fastest aircraft".

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[x] There might be a slight difference in cruise smoothness one way or the other: As the SST flies higher than the subsonic jet its encounters with "weather" (cumulonimbus clouds, clear air gusts, etc.) are probably even more rare but they might instead result in greater accelerations and thus be more upsetting than are such encounters for subsonic passengers. More important, however, the SST will likely be subjected to much greater "weather bumpiness" at low altitudes where turbulence is far more frequent: Because the SST is more sensitive to the increases in fuel consumption and flight time that would be caused by circumnavigating turbulence (e.g. thunderstorms) in the regions of the normal subsonic climb and descent flight paths, SSTs will have to fly through regions of considerable turbulence more often than subsonics.

One thing should be obvious: The need being marginal at equal fares, the demand for the SST can only be great and reliable in the long run if its operation costs are lower than for competing subsonics so that the SST fares can be set below subsonic economy-class fares. This was, in fact, what was expected some 10 to 12 years ago, as ever since 1945 each new generation of aircraft has proved to be significantly cheaper to operate, resulting in continous reductions in fares at constant money value.(10) IATA demanded in one of its "Ten Requirements" for the SST that "SST seat mile costs must be equal to or better than those of subsonic jets...".(11)

III. Operation Economics of the SST

Theoretical Analyses

In commonly used methods for calculating operation costs for subsonic and supersonic transport aircraft a great number of parameters are included which are all given absolute values. A new method for comparing the economics of supersonic and competing subsonic jets was developed in (12). The basic idea is that it is preferable, because it yields greater reliability and accuracy, to study the ratios between the values of the most significant parameters governing the economics, the SST parameters being related to a representative subsonic "comparison aircraft".

Even though this method is relatively simple it would be impossible to describe it in sufficient detail in a brief paper. Therefore only the highlights of the method will be presented. The reasons for the detailed assumptions are found in (12).

The yearly return on investment resulting from operation of one aircraft, subsonic or SST, is defined as the difference between revenue and costs divided by the purchase price, thus

$$R = (M\ S\ L\ F_n D - M\ S\ C)/I \qquad (1)$$

R = Yearly return on investment

M = Effective aircraft mileage per year computed as the sum of great-circle distances flown between city pairs

S = Number of seats per aircraft, in particular number of "effective" seats, see below

L = Load factor, i.e. proportion occupied seats

F_n = Nominal (non-discount) fare rate, cents per seat mile

D = Fare decrease factor (= 1 - discount)

C = Total operation cost, cents per seat mile

I = Aircraft purchase price

The relative economics for the two kinds of aircraft can be studied in many ways. For reasons that will be explained below the concept "Surcharge Number" appears to be significant. Introducing subscript s for SST the Surcharge Number is in general defined as

$$f \cdot l = \frac{F_{ns}}{F_{ne}} \cdot \frac{L_s}{L} \qquad (2)$$

$f = F_{ns}/F_{ne}$ = Nominal SST fare surcharge ratio

F_{ne} = Nominal subsonic economy-class fare rate

$l = L_s/L$ = Load factor ratio

Two specific Surcharge Number concepts are introduced: The Required Surcharge Number

$$(f \cdot l)_{req} = \left(\frac{F_{ns}}{F_{ne}} \cdot \frac{L_s}{L}\right)_{req} \qquad (2a)$$

and the Obtained Surcharge Number

$$(f \cdot l)_{obt} = \frac{F_{nas}}{F_{ne}} \cdot \frac{L_{s\ obt}}{L} \qquad (2b)$$

F_{nas} = Applied nominal SST fare rate

$L_{s\ obt}$ = SST load factor obtained at F_{nas}

Eqs. (1) and (2b) yield the following equation for the Obtained Return on Investment Ratio:

$$\left(\frac{R_s}{R}\right)_{obt} = \frac{M_s/M}{P_s/P} \cdot \frac{(f \cdot l)_{obt} \cdot y/(D/D_s) - C_s/C}{y - 1} \qquad (3)$$

$P = I/S$ = Aircraft purchase price per seat

P_s/P = Price per seat ratio, in particular on the basis of number of "effective" seats, see below

M_s/M = Effective aircraft mileage ratio, or "productivity ratio", for one seat in the two types of aircraft

$y = D\ F_{ne} L/C$ = Subsonic revenue to operation cost ratio

D/D_s = Fare decrease factor ratio

C_s/C = Operation cost ratio

For a new-technology enterprise involving many uncertainties and hence financial risks (such as the SST) it would be desirable to achieve a higher return on investment than for competing well-established activities (subsonic operations), a minimum requirement being equal return on investment. The concept Required Return on Investment Ratio is therefore introduced. The surcharge number required for achieving a certain $(R_s/R)_{req}$ is derived from eqs. (1) and (2a)

$$(f \cdot l)_{req} = \frac{D/D_s}{y}\left(\left(\frac{R_s}{R}\right)_{req} \cdot \frac{(P_s/P)(y - 1)}{M_s/M} + \frac{C_s}{C}\right) \qquad (4)$$

The Required Surcharge Number - see definition eq. (2a) - can be said to be the nominal SST fare surcharge ratio necessary for achieving, at a load factor ratio $L_s/L = 1.0$, the Required Return on Investment Ratio without the (possibly very high) SST surcharge resulting in a change of the load factor ratio.

Obviously, the lower the $(f \cdot 1)_{req}$ the better the SST economics. In general it has to be close to 1.0 for making it possible to apply nominal SST fares about as low as the nominal subsonic economy fares and still achieve the required return on investment.

Whatever the level of $(f \cdot 1)_{req}$, as computed by eq. (4), it should be compared with the Obtained Surcharge Number, $(f \cdot 1)_{obt}$, and in particular with its highest achievable value. To determine this is obviously an optimisation problem as the applied SST fare rate, F_{nas}, has to be set so that the product $F_{nas} \cdot L_{s\ obt}$ is maximum, see eq. (2b). If $(f \cdot 1)_{req} > (f \cdot 1)_{obt}$ SST operation will result in a deficit in relation to $(R_s/R)_{req}$.

One of the main features of this method for assessing SST economics is the way in which the operation cost ratio, C_s/C, is determined. This is done firstly by considering the percentages of the various cost items that contribute to the operation cost, C, for the subsonic comparison aircraft, and, secondly, by multiplying each percentage item cost with a factor indicating the known or estimated increase or decrease for SST operation of the cost of the item in question. The following equation is derived:

$$C_s/C = \underbrace{0.54}_{\text{Const.}} + \underbrace{\frac{0.11}{A_s/A} \cdot \frac{P_s/P}{M_s/M}}_{\text{Depreciation}} + \underbrace{0.09\ k_m\ P_s/P}_{\text{Maintenance}} + \underbrace{0.03\ k_i\ P_s/P}_{\text{Insurance}} + \underbrace{0.10\ k_b\ B_s/B}_{\text{Burnt fuel}} + \underbrace{0.05\ k_c\ S/S_s}_{\text{Crew}} + \underbrace{0.04\ k_a}_{\text{Cabin attendants}} + \underbrace{0.04\ k_f}_{\text{Food}} \tag{5}$$

The cost item percentages 0.54, 0.11, etc. apply for the Boeing 747.(8) Furthermore

A_s/A = Depreciation period ratio

B_s/B = Ratio of the average amount per year of fuel burnt per seat mile

S/S_s = Number of seats ratio, subsonic to supersonic

As is seen C_s/C is above all dependent upon the important parameters P_s/P and M_s/M and this applies also to the Surcharge Number equation (4). Eq. (5) may therefore be written

$$C_s/C = \alpha \frac{P_s/P}{M_s/M} + \beta P_s/P + \gamma \tag{5a}$$

(The expressions for α, β and γ are obtained from eq. (5).)

The price per seat ratio, P_s/P, will be analysed in the following Section.

As regards the effective mileage per aircraft ratio, M_s/M, leading SST proponents (8, 13-16) have alleged that the productivity (per seat) of SSTs is superior to that of subsonics in proportion to the cruise speeds of the two types.

This is incorrect as it neglects (a) that the ratio between average block speed and cruise speed is substantially smaller for the SST than for the subsonic, (b) that each flight is burdened by a turn-around time for reloading and refuelling and (c) that the total maintenance time per year (e.g. for daily inspections and major overhauls) is also roughly proportional to number of flights, not to hours of flight. In particular the aspects (b) and (c) imply that the increase in productivity of an SST due to its increased speed is greatly offset by the increased number of flights (e.g. on a given route) made possible by the speed increase. (4)

The correct expression for the increase in productivity per seat by the SST is, of course, M_s/M, which is much smaller than the ratio between the cruise speeds of the SST and the subsonic jet. I submit that the concept "productive speed" be introduced and defined as

$$V_{prod} = M/(365 \cdot 24) \tag{6}$$

As will be exemplified in the following V_{prod} for SSTs is rather modest and definitely subsonic.

Reverting to the possible deficit in SST operation, this should be related to the Required Return on Investment. Furthermore one should, of course, compute the deficit on the basis of the same magnitude of investment in subsonic aircraft as in SSTs thus preferably on I_s (for one SST). The yearly deficit is obviously

$$Z = \left(\frac{R_s}{R}\right)_{req} \cdot R\ I_s - R_{s\ obt} \cdot I_s \tag{7}$$

Z = Deficit per year and SST related to $(R_s/R)_{req}$

From eqs. (1), (2a), (2b) and (7) is obtained

$$Z = M_s\ S_s\ D_s\ F_{ne}\ L\ \ \Delta(f \cdot 1) \tag{8}$$

$$\Delta(f \cdot 1) = (f \cdot 1)_{req} - (f \cdot 1)_{obt} \tag{9}$$

Eq. (8) is convenient to use when $(f \cdot 1)_{req}$ has been computed on the basis of eq. (4) and $(f \cdot 1)_{obt}$ is estimated according to eq. (2b) for a known applied SST fare surcharge ratio, F_{nas}/F_{ne}, and an estimated resulting load factor ratio, $L_{s\ obt}/L$.

For studying Z as function of the main significant "relative parameters" the following equation, derived from eqs. (1) and (2b), could be used

$$Z = \frac{M\ S\ C}{S/S_s}\left[\left(\frac{R_s}{R}\right)_{req} \cdot (y - 1)\ P_s/P - M_s/M\left(y \cdot \frac{(f \cdot 1)_{obt}}{D/D_s} - \frac{C_s}{C}\right)\right] \tag{10}$$

For the purpose of studying the prospects of improving the operation economics of future generation SSTs it is advantageous to split P_s/P into two significant components:

$$P_s/P = \frac{(I_s/W_{es}) \; / \; (I/W_e)}{(S_s/W_{es}) \; / \; (S/W_e)} = \frac{i_s/i}{x_s/x}$$

$i = \bar{\imath}/W_e$ = Purchase price per ton empty weight

i_s/i = Purchase price per ton empty weight ratio

$x = S/W_e$ = Number of "effective" seats per unit empty weight, being proportional to W_p/W_e

W_p/W_e = Payload to empty weight ratio, payload being defined as a full load of "effective" passengers

$$x_s/x = \frac{S_s/W_{es}}{S/W_e} = \frac{W_{ps}/W_{es}}{W_p/W_e} = \text{Ratio between the payload ratios}$$

S and S_s are the numbers of "effective" seats, i.e. the sum of real passenger seats and "cargo seats". The latter concept is introduced in order to account for the extra revenue that is obtained for cargo carried in excess of passenger baggage. Due consideration should be taken to the fact that the revenue per ton cargo is smaller than the revenue per ton passengers.

From eqs. (4) and (5) is obtained

$$(f \cdot l)_{req} = \left(\frac{F_{ns}}{F} \cdot \frac{L_s}{L}\right)_{req} = \frac{D/D_s}{y}\left[\frac{i_s/i}{x_s/x}\left(\frac{K_1}{M_s/M} + K_2\right) + K_3 \frac{1}{x_s/x} + K_4\right] \qquad (11)$$

$K_1 = (\frac{R_s}{R})_{req} \cdot (y - 1) + \frac{0.11}{A_s/A}$

$K_2 = 0.09\ k_m + 0.03\ k_i$

$K_3 = 0.10\ b_s/b$

$K_4 = 0.54 + 0.05\ k_c\ S/S_s + 0.04\ k_a + 0.04\ k_f$

$b = B \cdot x$

b = Burnt fuel per unit empty weight and mile

Applications, especially to Concorde/747

a. Parameter Values

The assumed values of the various parameters in the equations above are listed below with but a few explanations in some important cases. Detailed reasons for the assumptions are found in (12).

Number of Seats Ratio, S/S_s. Most of the evaluations are based on the 128-seat Concorde and the 440-seat Boeing 747. Whereas the former can take no cargo, the latter can take a substantial load of cargo, corresponding to 105 "cargo seats", assuming that on a weight basis the revenue for cargo is half of that for passengers. The number of "effective" seats in the 747 is thus 545 and $S/S_s = 4.25$. This corresponds to an appreciably lower maximum payload in lbs for the 747 than is quoted in Jane´s (22) because the available cargo compartment volume rather than weight is limiting when having a low density load. Comparing Concorde with the 490-seat 747, i.e. 590 "effective" seats, S/S_s is 4.6. BOAC´s all-first-class 104-seat Concorde compared with a 350-seat 747, carrying about 465 "effective" seats yields $S/S_s = 4.5$.

Price per Seat Ratio, P_s/P. The price for Concorde, except spares, has for some time been estimated at about \$ 34 m, which is to be compared with \$ 26 m for 747. This yields a range of P_s/P from 5.5 ($S/S_s = 4.25$) to 6.0 ($S/S_s = 4.6$). According to Pan Am (17) the 104-seat Concorde would at \$ 60 m with spare parts cost "more than twice as much" as a 350-seat 747 thus yielding P_s/P at least 9.0. It could be objected that there are no all-first-class, 350-seat 747 flying today, but what is significant is that it is potentially possible to apply a first-class comfort standard to 747s of this or "stretched" capacity. It seems therefore realistic to extend the possible P_s/P range to 9.0.

Effective Aircraft Mileage Ratio, M_s/M. As follows from the text to Fig. 2 Concorde can hardly average more than 3 single Atlantic flights per 24-hour day during longer service periods if it is to have the same average time per flight available for inspection and maintenance (about 3.5 hours) as a subsonic jet making 2 single flights per day. This means that M_s/M can hardly exceed 1.5 assuming the same total number of service days per year. Because of its greater complexity and the kinetic heating at each flight, etc., the SST will, however, likely require a longer total off-service time per year for major overhauls and repairs and this reduces M_s/M.

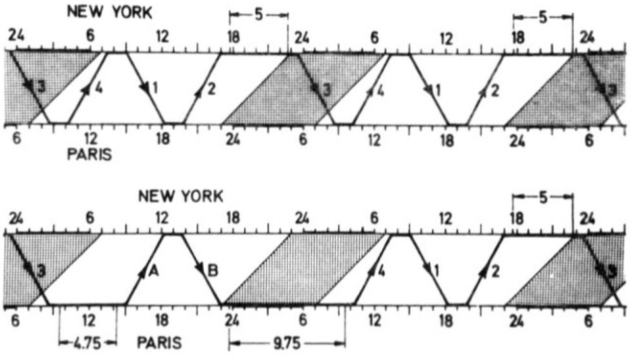

Fig. 2. Assuming 3.25 hrs flight time and 1.5 hrs turn-around time, 4 single flights per 24 hrs allow a daily maintenance time of only 5 hrs, i.e. 1.25 hrs/flight. For a subsonic jet making 2 flights in 24 hrs of 7 hrs each the daily time for maintenance is 7 hrs, i.e. 3.5 hrs/flight. Three daily SST flights yield an average daily maintenance time of 9.75 hrs, i.e. 3.25 hrs/flight.

A still further reduction will be caused by the fact that the subsonic jet often produces a greater mileage per 24-hour day than is obtained by 2 single flights between, for example, New York and Paris, e.g. by longer direct flights, such as Frankfurt to New York, or by "tag-end" flights to or from the coastal cities before or after the flights over the Atlantic. Even if there are no boom restrictions the SST is much inferior as regards this "range flexibility", because short supersonic "tag-end" flights are uneconomic and usually pointless to the passengers.

For these reasons the lower limit for the possible range in M_s/M is in the no-boom-restriction case assumed to 1.25 whereas the upper limit is optimistically set at 1.5. The latter value, however, presupposes a Mach number close to 3.0 and/or extreme measures and costs to reduce overhaul, daily maintenance and turn-around times. Note that the "productive speed" of a Mach 2+ SST averaging for example 2.8 Atlantic crossings per day (which might correspond to $M_s/M = 1.4$) during 320 days/year is only 360 mph.

For the "sea-limited" SST - forbidden to fly supersonically over inhabited land, except, perhaps, over some sparsely populated areas - the achievable Mileage Ratio will be greatly reduced, in particular because of the necessity to circumnavigate islands and mainland areas located on the great circle routes, and also because of the practically non-existent possibilities to supplement the main oversea operations, e.g. over the Atlantic, with supersonic "tag-end" flights, (SST operation at subsonic speed will usually be out of the question for economic reasons). Detailed studies indicate that it will be very difficult for the sea-limited SST to attain $M_s/M = 1.25$ and that a realistic productivity ratio falls rather close to 1.0.

BOAC intends initially "to operate two Concorde services each day from London to New York, three each week on the routes to Sydney and Johannesburg, and two a week across the Soviet Union to Japan".(18) Assuming that these services are all roundtrips the great-circle distances flown per week would total 218,000 miles. This is to be achieved by 5 Concordes, but let us conservatively assume that one serves as reserve, thus that the schedule can be carried out by 4 aircraft. A typical mileage per week achievable by 4 subsonic jets (each making for example one New York - Paris roundtrip per day) is of the order 196,000 miles. The Concorde mileage is thus only 10 % better, i.e. $M_s/M = 1.1$. It should be noted, however, that although the BOAC schedule could possibly be improved later on, the corresponding weekly mileage assumed for 4 subsonic jets is probably unduly small. Furthermore, SST operation will likely require a higher proportion reserve aircraft and a longer total off-service time for overhauls. The net effect of all this could well be $M_s/M = 1.0$, or even smaller.

Fare Decrease Factor Ratio, D_s/D. As is well-known considerable discounts are often applied on the nominal subsonic economy-class fares whereas discounts are comparatively rare on first-class services. As the SSTs will be catering largely for business and first-class passengers they would also have rather small revenue reductions due to discounts. A spokesman for the Concorde enterprise (19) has suggested that realistic values would be $D_s = 0.95$ and $D = 0.71$, thus $D/D_s = 0.75$.

Subsonic Revenue to Operation Cost Ratio, y, is obtained on the assumptions $D = 0.71$, $F_{ne} = 6.5$, $L = 0.55$ and $C = 1.7$, yielding $y = 1.5$.

Remaining Parameters. Most of the remaining factors in eq. (5) for C_s/C are assumed to have "optimistic" and "realistic" values, thus $A_s/A = 0.9, 0.8$; $B_s/B = 3.4, 3.6$; $k_c = 0.6, 0.75$; $k_a = k_f = 0.7, 0.8$. The factors k_m, k_i and k_b are all assumed to have the value 1.0. These assumptions yield $\alpha = 0.12, 0.14$; $\beta = 0.12$ (jointly) and $\gamma = 1.07, 1.12$.

b. Evaluations

The Operation Cost Ratio, C_s/C, is shown in Fig. 3 as a function of M_s/M and P_s/P, and the indicated values for α and β. As is seen P_s/P is by far the most important factor for C_s/C which might obtain values roughly from 2.2 up to 3.5 when M_s/M varies from 1.0 to 1.5.

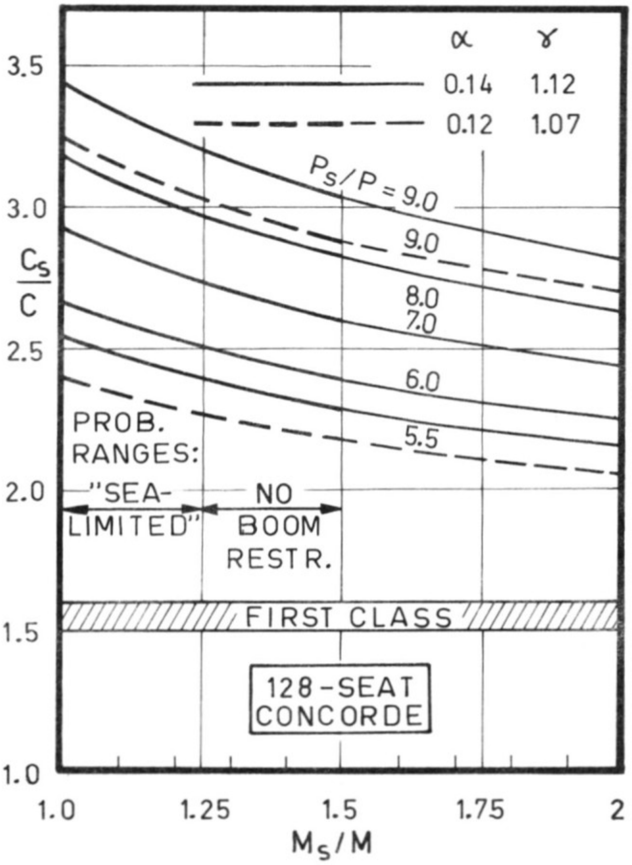

Fig. 3. Operation cost ratio as function of productivity (great-circle mileage) ratio, M_s/M, and price per seat ratio, P_s/P.

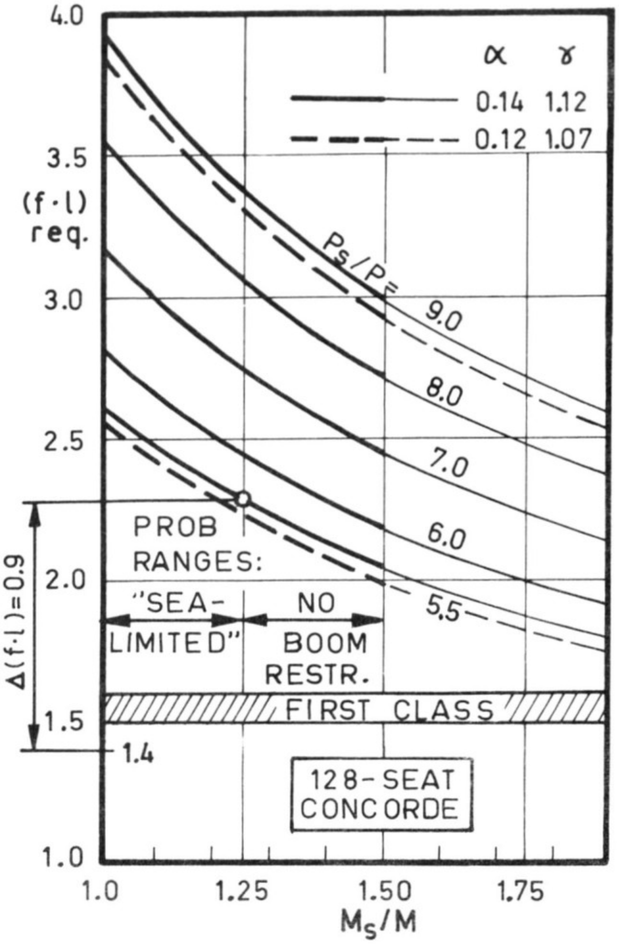

Fig. 4. Required Surcharge Number, $(f \cdot l)_{req}$, as function of productivity ratio and price per seat ratio.

Surcharge Number. In Fig. 4 $(f \cdot l)_{req}$ for $R_s/R = 1.0$, is shown as function of the same parameters as for C_s/C in Fig. 3. P_s/P is obviously the most significant factor, followed next by M_s/M, whereas α and γ have relatively little importance. Within the realistic range of M_s/M (1.0 to 1.5) the Required Surcharge Number varies from 2.0 to 3.9. In view of recent information about the price for Concorde, see above and (7, 23), it seems unrealistic to assume P_s/P lower than 6 to 8 at the time when Concorde is expected to enter service. Thus $(f \cdot l)_{req}$ would have to be of the order 2.5 to 3.5 in the "sea-limited" case. However, even if as low a value as 2.3 is assumed this would apparently far exceed the Obtainable Surcharge Number. It has been indicated (1) that for the 128-seat model the surcharge should preferable be 40 % over the subsonic economy-class fare level. Assuming the same load factor for SST as for subsonic, $(f \cdot l)_{obt}$ would thus be 1.4.

Deficit per year and SST, Z. For the values $\Delta(f \cdot l) = 2.3 - 1.4 = 0.9$, $S_s = 128$, $F_{ne} = 6{,}5$, $D_s = 0.95$, $L = 0.55$, $M_s/M = 1.25$ and assuming $M = 2{,}100{,}000$ miles for the subsonic aircraft (e.g. an average of 7,000 miles per day during 300 days of the year) eq. (8) yields Z = \$ 10.3 million per Concorde and year.

In Fig. 5 the yearly deficit as a function of M_s/M is computed on the basis of eq. (10) for a few selected combinations of the Surcharge Ratio and the Load Factor Ratio, using the realistic set of values for the other parameters. The curve 1.4/1.0 is believed to represent the lowest achievable deficit because an SST surcharge of 40 % probably yields about maximum revenue for the 128-seat Concorde (see above) and because it seems overly optimistic to assume $L_{s\ obt}/L$ significantly above 1.0 for several reasons: Firstly, also SSTs will suffer from seasonal variations, secondly, their inferiority with respect to making "tag-end" flights will tend to reduce the overall load factor and, thirdly, the SST night flights, e.g. over the Atlantic, will be particularly unpopular because the passengers will be practically deprived of sleep for one night (see Fig. 2). The two latter factors are believed to about outweigh the definite advantage with the SST with respect to "schedule flexibility": An SST can, for example, make popular daylight flights from North America to Europe whereas most subsonics fly at night on this route direction.

Let us, however, optimistically assume that the SST/subsonic Load Factor Ratio could be as high as 1.2. Fig. 5 shows that the yearly deficit per 128-seat Concorde would nevertheless be \$ 7 m to \$ 8 m.

The arrows in Fig. 5 illustrate in principle the optimisation problem involved when determining the SST surcharge: If the surcharge is increased from 40 % to 60 % with the hope of increasing $(f \cdot l)_{obt}$ from 1.4 to 1.6 the SST load factor might instead be reduced by 20 % yielding an $(f \cdot l)_{obt}$ of only 1.28 and an increase in the yearly deficit of over one million dollars.

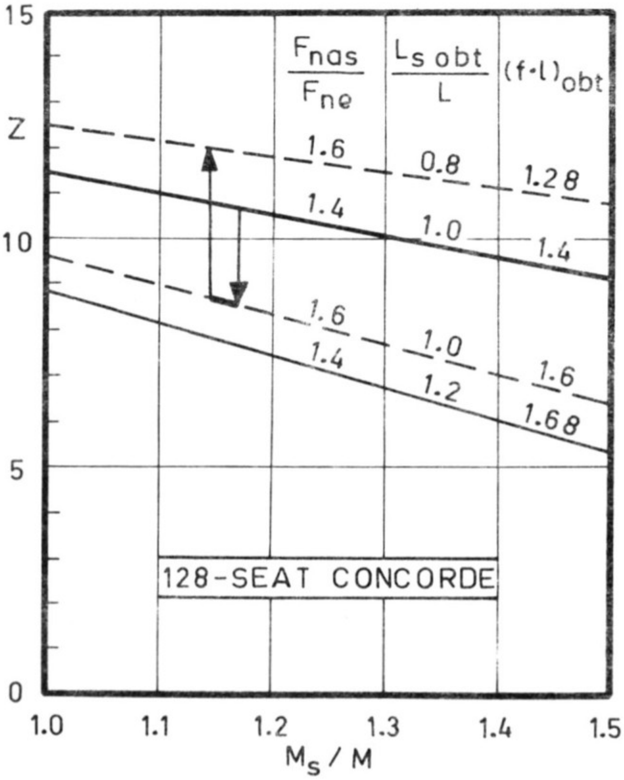

Fig. 5. Yearly deficit in million dollars per 128-seat Concorde (costing \$ 34 m).

Prospects of Future Improvements

a. Second Generation SSTs

It seems now to be widely accepted that Concorde´s economics is doubtful, but the magnitude of the deficiency is apparently not recognized. The general belief seems to be that it is a marginal case and that consequently a "stretched" version of the Concorde, having a moderate increase in payload, could be designed and be an economic success. The Concorde Consortium is in fact said to study such a project.

There are also many indications of strong beliefs in the USA that it is possible to design a profitable SST and that therefore a new American SST project will likely be initiated in a few years.(20.21)

In view of these ambitions it is highly important to find out in quantitative terms the aeronautical and other constraints that must be overcome for making SSTs economically viable.

Fig. 6 is prepared for studying this problem in particular with respect to a Concorde successor, or, in general, a "second generation" SST defined as a Mach 2 to 2.2 aircraft based on evolutionary rather than revolutionary advances in supersonic technology. The figure is based on eq. (11) and shows $(f \cdot 1)_{req}$ as function of the two most important parameters i.e. the ratio between the payload/empty-weight ratios, x_s/x, and the relative purchase price/empty-weight ratio, i_s/i. The productivity ratio, M_s/M, has been chosen to range from 1.0 to 1.3 assuming that the sonic boom still limits supersonic operation almost exclusively to oversea routes. For the other parameters the realistic set of values indicated above has been applied.

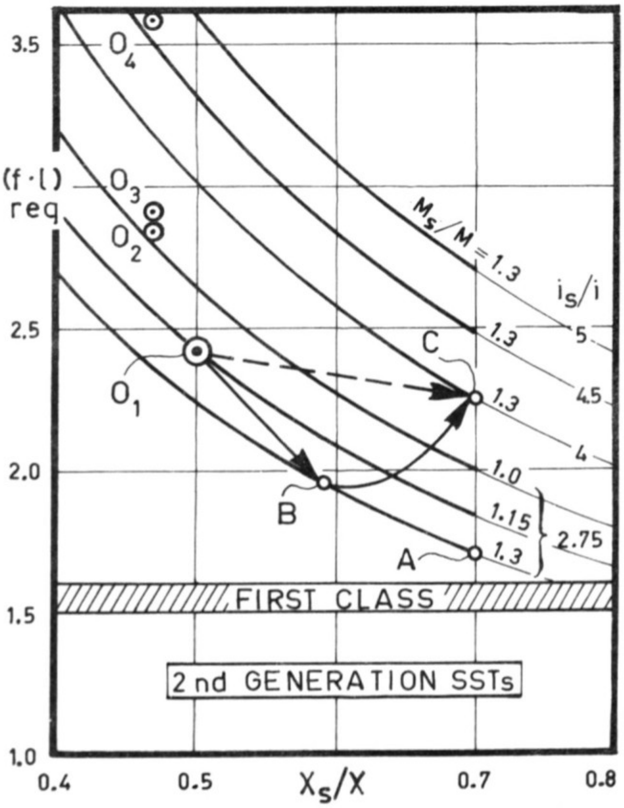

Fig. 6. Required Surcharge Number for second generation SSTs as function of the relative payload to empty weight ratio, x_s/x, and the relative price to empty weight ratio, i_s/i.

The 128-seat Concorde is taken as the basis for possible improvements. Its x_s/x is about 0.5 based on $S/S_s = 4.25$ and empty weights 170,000 lbs for Concorde and 356,000 lbs for 747.(22) Further assumptions for this Concorde version, marked 0_1, at $(f \cdot 1)_{req} = 2.4$, are $M_s/M = 1.15$ and $i_s/i = 2.75$ based on the earlier price estimates I_s = \$ 34 m for Concorde and I = \$ 26 m for 747 ($I_s/I = 1.31$).

It may be emphasized here that this i_s/i level, which corresponds to the lowest P_s/P level indicated above, namely 5.5 (= 2.75/0.5), now appears to be based on a too low Concorde/747 price ratio. According to recent information (23) the prices without spares are \$ 36 m for the 104-seat Concorde and \$ 23.85 m for 747, yielding $I_s/I = 1.51$. The prices with spares are \$ 44.345 m and \$ 28.345 m respectively, i.e. $I_s/I = 1.56$. The relative price/weight ratio i_s/i would thus be 3.16 without and 3.28 with spares. On the basis of $M_s/M = 1.15$ and the other detailed assumptions above (e.g. 350 seats and 465 "effective" seats for 747) P_s/P would be 6.7 without and 7.0 with spares, and $(f \cdot 1)_{req}$ would be 2.84 and 2.91, respectively. The corresponding points 0_2 and 0_3 are marked in Fig. 6 at the approximate relative "effective" passenger load ratio 0.47 that applies for the seating capacities in question.

It may furthermore be noted that for the 104-seat Concorde i_s/i would be 4.2 on the basis of Pan Am´s statement that Concorde (with spares) would cost twice as much as 747. This estimate might be realistic anticipating rises in Concorde prices for later deliveries. It corresponds to $P_s/P = 9.0$ (see above) and $x_s/x = 0.47$, these data being marked as point 0_4 in Fig. 6. Finally, all the points $0_1 - 0_4$ are based on purchase prices which do not cover the high R&D costs for the Concorde. Considering the total economics of the Concorde enterprise the points are therefore located on too low i_s/i levels.

In spite of all this $i_s/i = 2.75$ and point 0_1 will, very conservatively, be retained as the basis for the following analysis.

A substantial improvement in SST economics, i.e. reduction in $(f \cdot 1)_{req}$, can only be achieved by great increase of the ratio between the payload to empty weight ratios (thus increase in x_s/x); the possibilities of increasing M_s/M are very limited and the other parameters have a relatively minor significance. In order for the SST to be reasonably competitive in the first-class market the necessary reduction in $(f \cdot 1)_{req}$ is at least from 2.4 to 1.7. Assuming that M_s/M can be improved from 1.15 to 1.3, by extreme efforts to reduce maintenance and overhaul times, it follows from Fig. 6 that x_s/x must be increased from 0.5 to 0.7, i.e. by 40 %, for point "A" to be attained.

It follows, however, from eq. (11) and Fig. 6 that this great increase in x_s/x must not be appreciably offset by a consequential increase in the relative price per ton empty weight, i_s/i. We shall therefore in the first place discuss the possibilities and implications of bringing about a 40 % increase in x_s/x under the assumption that there are no appreciable advances neither in supersonic technology, as represented by Concorde, nor in subsonic technology, implying an approximately unchanged ratio between the cost/weight ratios, i_s/i (= 2.75). The necessary improvement in x_s/x would thus have to be achieved mainly by building the new SST very much larger than Concorde. The development and manufacture of such a large Concorde successor would, however, take considerable time, during which also enlarged subsonic jets will be developed either by "stretching" existing types or by new designs. It is conservatively assumed that the subsonic payload/empty weight ratio is improved by only 10% over the current 747 and that this can be achieved at a retained cost/weight ratio, i.

This improvement in the subsonic x means that the new SST would need to have a payload/empty weight ratio = $(1.4 \cdot 1.1 - 1) = 54\%$ better than the 128-seat Concorde. For achieving such an improvement the payload of a Concorde successor would have to be increased from 128 to 197, i.e. by 69 passengers or $69 \cdot 210 = 14{,}500$ lbs. This primary weight increase causes in the first place an additional direct weight increase for seats and such equipment which would grow roughly in proportion to number of passengers, e.g. galleys, toilets, cabin attendants, part of the air conditioning system and a portion of the fuselage (for holding the additional passengers). This addition is estimated to fall between 50 and 100% of the increase in payload.

As is well-known to aircraft designers an initial weight increase inevitably causes secondary or indirect weight increases if the performance of the aircraft project, in particular its range and cruise and landing speeds, are to be retained at original levels. The ratio between the resulting total weight increase and a primary weight increase is commonly called the Weight Growth Factor, or WGF. In a paper to the R.Ae.S. in 1963 (5) I pointed out that WGF is much greater for SSTs than for subsonic jets (about 9 vs 5) "because of the higher relative fuel weight" and warned that "This impairs the possibilities of "stretching" an SST of a given basic type even if there were no sonic-boom limitations".

This warning will now be repeated and explained in greater detail because of the tremendous significance of the WGF with respect to the possibility of improving the economics of SSTs. In support of the statement the following equation (derived earlier (24)) was presented using here somewhat modified symbols. Furthermore the primary weight increase is defined as comprising only the increase in payload, thus including in the WGF concept the direct increases in empty weight (seats, etc.) due to the increase in payload.

$$g_p = \frac{\Delta W_t}{\Delta W_p} = \frac{k}{1 - \frac{W_{ewo}}{W_{to}} - \frac{W_{fo}}{W_{to}}} = \frac{k}{\frac{W_{uo}}{W_{to}}} \qquad (12)$$

The symbols and the underlying concepts in eq. (12) are the following:

g_p = Weight Growth Factor referred to the increase in payload

W_t = Gross weight

W_p = Payload. Note that W_p in this WGF analysis is the total payload which, if also cargo can be carried, is greater than a full load of "effective" passengers.

ΔW_t = Resulting total weight increase

ΔW_p = Increase in payload

k = Increase factor, 1.5 to 2.0, see above

$k \cdot \Delta W_p = \Delta W_i$ = Initial weight increase

W_f = Fuel weight

W_u = "Useful load", this somewhat inadequate name being retained from (24)

W_e = Operating weight empty

$W_{ep} = (k - 1)\, W_p$ = The portion of W_e that is roughly proportional to payload

W_{ew} = The portion of W_e that is roughly proportional to gross weight, e.g. weight of wings (at retained landing speed, i.e. wing loading) tail surfaces and landing gear, as well as of a considerable portion of the fuselage (the one not included in W_{ep}) and also of the major portion of the power plant assuming an unchanged thrust to engine weight ratio

W_c = The portion of W_e that is roughly constant, i.e. independent of changes in gross weight, such as crew and cockpit, or the like, and minor portions of the weight of the power plant and the hull (e.g. wing tanks)

$$W_t = \overbrace{W_{ew} + \rlap{$\underbrace{\phantom{W_c + W_{ep} + W_p}}_{W_u}$}W_c + W_{ep}}^{W_e} + W_p + W_f \qquad (13)$$

Index o is used for a basic or original aircraft, e.g. the current Concorde, and index 1 is used for a "final" project resulting from a primary weight increase. Index s is deleted in this analysis until SST/subsonic comparisons are made. It follows from the definitions that

$$\Delta W_t = k \cdot \Delta W_p + \Delta W_{ew} + \Delta W_f$$

$\Delta W_{ew} = \Delta W_t \cdot (W_{ewo}/W_{to})$ = The increase in empty weight required for retained wing loading and speed, thus including also the increase in power-plant weight

$\Delta W_f = \Delta W_t \cdot (W_{fo}/W_{to})$ = Increase in fuel weight required for retained range at unchanged fuel consumption

It may be emphasized that the dependence of the weight of different portions of the aircraft on the gross weight and other design parameters is a highly complex matter. It is believed, however, that the simple linear approach applied here is adequate for the purpose of broad studies of this kind.

Introducing W_u from eq. (13) eq. (12) can be written

$$g_p = \frac{1}{W_{po}/W_{to} + \sigma} \qquad (12a)$$

W_{po}/W_{to} = Original payload to gross weight ratio

$$\sigma = \frac{W_c/W_{to}}{k} \qquad (15)$$

W_c/W_{to} = Original constant weight to gross weight ratio

σ = Original "effective" constant weight to gross weight ratio

The weight growth factor, g_p, is shown in Fig. 7 as function of σ for the W_{po}/W_{to} levels that apply for Concorde and 747 (0.07 and 0.21 resp.). An estimate is also made for an advanced future SST project discussed later. For reasons indicated below, σ will normally be about 0.03 yielding g_p = 10 for Concorde-technology SSTs and about 4 for subsonic jets like 747.

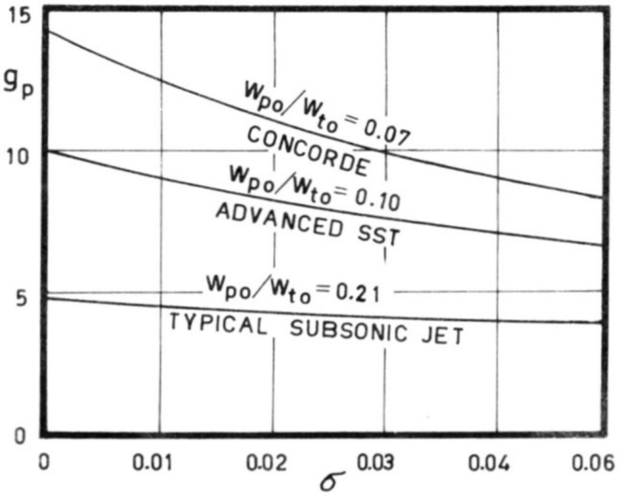

Fig. 7. The Weight Growth Factor, g_p, as function of σ, the original "effective" constant weight to gross weight ratio.

It may be noted here that a relative increase in W_p will result in the same relative increase in "effective" passenger load. It follows that for enlarged aircraft carrying cargo

$$\frac{W_{p1}/W_{e1}}{W_{po}/W_{eo}} = \frac{S_1/W_{e1}}{S_o/W_{eo}} = \frac{x_1}{x_o} \qquad (16)$$

Let us now investigate the possiblities and implications of increasing the payload to empty weight ratios for enlarged subsonic jets and SSTs. It is in particular of interest to find out the increases in payload, gross weight and empty weight that are required in order to attain a desired increase in the payload to empty weight ratio. For these purposes the following equations are derived:

$$\frac{W_{p1}}{W_{po}} = \frac{(1 - \xi)\,(x_1/x_o)}{1 - \xi x_1/x_o} \qquad (17)$$

$$\xi = \frac{W_{po}/W_{to} - \sigma\, W_{po}/W_{eo}}{W_{po}/W_{to} + \sigma} \qquad (18)$$

$$\frac{W_{t1}}{W_{to}} = 1 + \frac{W_{p1}/W_{po} - 1}{1 + \sigma/(W_{po}/W_{to})} \qquad (19)$$

$$\frac{W_{e1}}{W_{eo}} = \frac{W_{p1}/W_{po}}{x_1/x_o} \qquad (20)$$

W_{p1}/W_{po} is shown in Fig. 8 for an enlarged subsonic jet based on 747 and in Fig. 9 for a second generation SST based on "Concorde technology". Fig. 10 shows W_{t1}/W_{to} as function of W_{p1}/W_{po} for the two categories of aircraft. As is apparent from Fig. 8 and 9 the magnitude of σ is of decisive importance for the possibility of attaining great improvements in x and x_s. From eq. (15) follows:

$$W_c/W_{eo} = k\,\sigma/(W_{eo}/W_{to}) \qquad (21)$$

which yields the following table for W_c/W_{eo} in percent:

	Concorde			747		
σ \ k	1.5	1.75	2.0	1.5	1.75	2.0
0.05	17.0	19.8	22.6	16.3	19.1	21.8
0.045	15.3	17.8	20.3	14.7	17.2	19.6
0.04	13.6	15.8	18.1	13.0	15.2	17.4
0.03	10.2	11.9	13.6	9.8	11.4	13.1

It seems obvious that the "constant weight", W_c, which comprises the weights of cockpit and crew, and other empty weight items which are not affected by the weight growth factor, can hardly appreciably exceed about 10 % of the empty weight; this percentage would for Concorde mean W_c= 17,000 lbs and for 747 about 35,000 lbs. For a large aircraft (747) W_c/W_{eo} can in principle be expected to be somewhat smaller than for a lighter aircraft, but

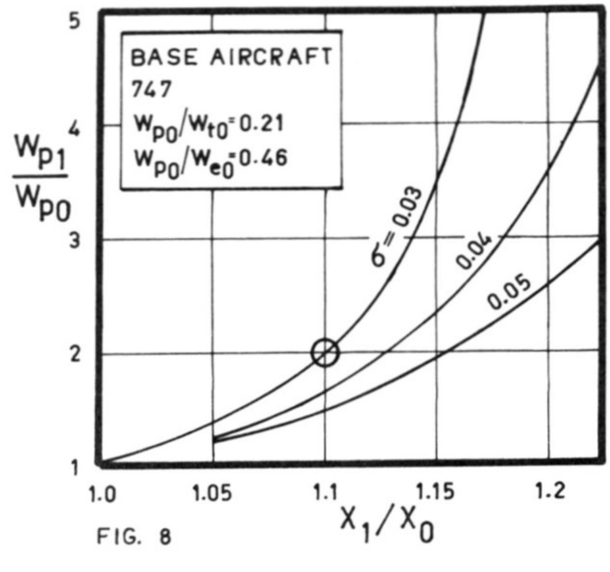

FIG. 8

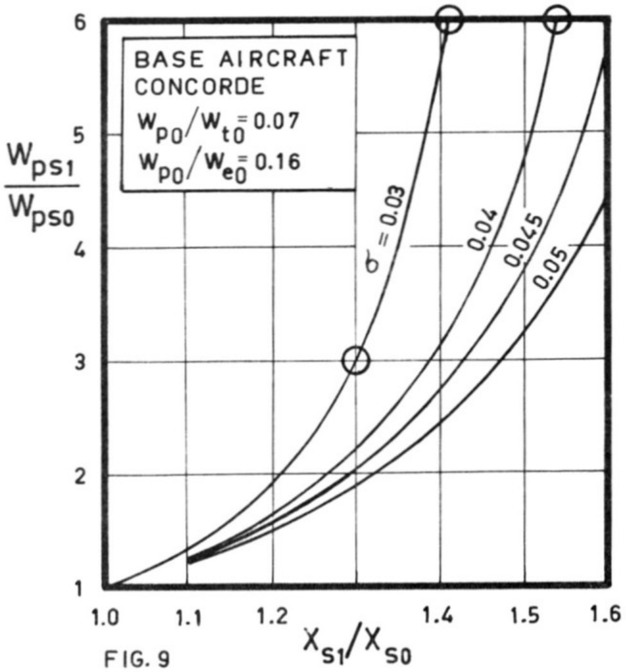

FIG. 9

Fig. 8 and 9. Required increase in payload for achieving a desired increase (x_1/x_o) of the payload/empty-weight ratio, for enlarged subsonics and SSTs based on 747 and Concorde, respectively.

for an SST/subsonic comparison, this is counteracted by the facts (a) that the factor k, catering, *inter alia*, for part of the weights of air conditioning equipment and fuselage skin, is likely to be greater for SSTs and (b) that the "built-in-stretch" capability normally (and more easily) provided for in designs of subsonic jets implies that a greater portion of the empty weight is exempted from the "weight carrousel". It is therefore maintained that for both SSTs and subsonics σ is about 0.03.

Fig. 8 shows that for new subsonic jets and for σ = 0.03 an increase in x by 10 % requires an increase in payload by 100 %. Fig. 10 shows that the corresponding increase in gross weight would be 87 %, and eq. (20) indicates that the empty weight would be increased by 82 %. Using 747 as the base aircraft the gross weight would be increased from 775,000 to 1,450,000 lbs. Such a large subsonic jet appears to be fully feasible.

As stated above the second generation SST would have to increase the payload to empty weight ratio by 54 % over the Concorde in order to improve x_s/x by 40 % (point A in Fig. 6) over a 747-based subsonic for which x has been improved by 10 %. Fig. 9 indicates that x_{s1}/x_{so} = 1.54 would, for σ = = 0.03, require an infinitely large SST, and that the payload would have to be increased by a factor of 6 (770 passengers) even at the probably unrealistically high σ value of 0.04. It is therefore altogether impossible to reach the point A on the basis of current supersonic technology.

The greatest realistic enlargement over the 128-seat Concorde is probably by a factor of 3 in payload (nearly 400 passengers). For σ = 0.03 this would mean x_{s1}/x_{so} = 1.3 (Fig. 9). W_{t1}/W_{to} would be 2.35 (Fig. 10) and thus the gross weight about 900,000 lbs. Disregarding the great increase in sonic boom level, the *size* of such an SST cannot be regarded as unrealistic. It should be noted, however, that although the relative cost/weight ratio, i_s/i, would be retained at about 2.75, the relative increase in purchase price would be greater for the new SST than for the new subsonic: $I_1/I_o = (i_1/i_o)(W_{e1}/W_{eo})$ would be 1.82 for the subsonic and 2.31 for the SST, eq. (20). The price of the latter would then increase from the (probably too low) value of \$ 34 m to nearly \$ 80 m.

The increases in x_s by 1.3 and in x by 1.1, on the basis of current technology, would mean an increase in x_s/x by 1.3/1.1 = 1.18, thus to 0.59. This yields the point B in Fig. 6 at $(f \cdot 1)_{req}$ = = 1.95, thus far too high for competition even in the first-class market.

It follows from the above that an increase in x_s/x to a value higher than about 0.6 cannot be achieved without advances in supersonic technology. And these have to be quite dramatic because they must be much greater than the considerable advances that are continuously made in subsonic technology. The reason for this is, of course, that the advances during the time it takes to develop a new SST will result in appreciable improvements in the subsonic payload/weight ratio and that the supersonic advances must be so much greater that the ratio between the payload ratios, x_s/x, is substantially increased.

There is no denying that advances in supersonic technology greater than the subsonic advances are conceivable in view of the fact that Concorde and TU-144 are the first SSTs ever built. But the big crux is that advances in SST technology appreciably greater than in subsonic technology will in general also result in a higher price/empty weight ratio, i.e. a greater i_s/i. The simpliest way to make this clear is perhaps to consider the structural

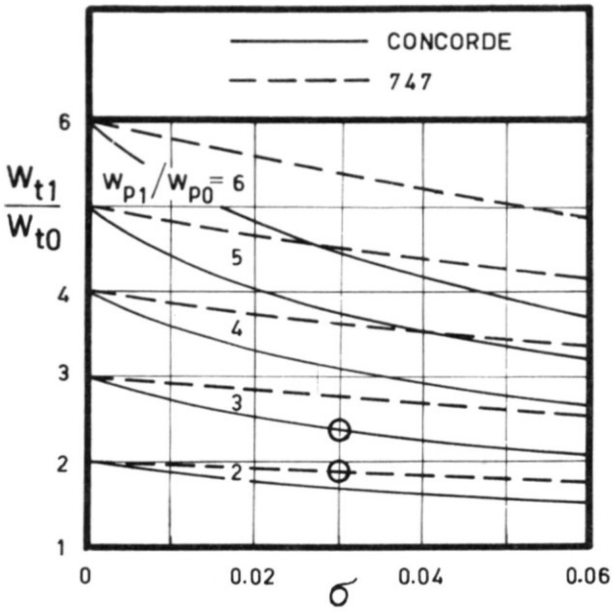

Fig. 10. Resulting increase in aircraft gross weight due to increase in payload (W_{p1}/W_{po}).

field - i.e. advances in light-weight materials and design - which is probably the most promising area for great improvements to appear within the relatively near future both for subsonic aircraft and for a second generation SST.

CORTRIGHT (Director, Langley Research Center) believes (25) that "Composite structures can reduce structural weight by 20 percent". This statement apparently refers to subsonic aircraft. To make a similar reduction in a new SST is perhaps conceivable, but will likely be much more expensive because of the kinetic heating at supersonic speeds: The cycles of very high and low temperatures will make it much more difficult not only to develop reliable bonding in the composite materials but also to ensure a sufficiently long fatigue life of the structural assemblies.

It seems therefore safe to state that one and the same percentage reduction in empty weight, i.e. unchanged x_s/x, used to accomodate more passengers will result in a higher cost/empty weight ratio for SSTs than for subsonics, thus an increase in i_s/i without an appreciable increase in x_s/x. This would increase $(f \cdot 1)_{req}$, thus impair instead of improve SST economics.

Obviously then, if the supersonic structural technology is "pressed" so very hard that the ratio between the payload ratios, x_s/x, is greatly increased, this would result in a very considerable increase in i_s/i. It is also evident that the increase in i_s/i rapidly grows with the increase in x_s/x. In Fig. 6 the bent arrow reaching point C (on the curve for $i_s/i = 4.0$ and for $x_s/x = 0.7$) is intended to illustrate the nature of this continous dependency of i_s/i on x_s/x. The $(f \cdot 1)_{req}$ at this point is a very slight improvement over the original level in point 0_1.

It may be emphasized that neither the shape of the bent arrow nor the location of point C is based on quantitative analysis, accurate calculations being exceedingly difficult to make. I do believe, however, that at least with respect to structural improvements, it is fully realistic to assume that an increase in x_s that exceeds the increase in the subsonic x by as much as 0.7/0.59, i.e. about 20 %, would increase the relative cost/weight ratio, i_s/i, by 40 to 50 % (4.0/2.75 = 1.46).

It follows that the great efforts that might be made with the purpose of improving SST economics substantially by means of increasing its payload/empty weight ratio will inevitably be counteracted, and might be completely offset, by the high costs of the very same efforts.

There are two reasons why the location of the arrows in Fig. 6 give a too favourable picture (too low $(f \cdot 1)_{req}$) of the economics of a second generation SST (even disregarding the much too low location of the base point 0_1, see above).

(1) In the first place one must assume that future SSTs will have to comply with the international airport noise standards for new contemporary subsonic aircraft. To base a new SST project on a hope that it would be exempted from the subsonic noise standards would be exceedingly hazardous. On entering service the production version of Concorde is expected to be some 15 to 20 PNdB noisier than current DC-10s and L-1011s. This discrepancy is probably representative of the improvement in SST jet noise that must be achieved for second generation SSTs ^{x}: Such a very great improvement is bound to affect adversely the payload ratio for the SST not only because of the direct increases in engine weight resulting from the silencing measures but probably also because of increased fuel consumption and hence fuel weight. The weight growth factor will multiply these primary weight increases, yielding a substantial total increase in empty weight and hence reduction in payload/empty weight ratio. Furthermore, the extreme silencing measures required are likely to increase the cost/empty weight ratio i_s.

(2) Secondly, the attainment of $M_s/M = 1.3$ for a "sea-limited" SST, assumed in Fig. 6, probably calls for extreme and costly measures to reduce turnaround, maintenance and overhaul times by means of special equipment and shift work. The costs would increase the maintenance coefficient k_m in the factor K_2 in eq, (11). This means that the point B cannot be reached; $(f \cdot 1)_{req}$ will likely be about 2.0 even disregarding the increase due to airport noise.

To sum up - and considering also that the base point for the analysis, 0_1, represents a too low Concorde/747 price ratio - it appears impossible to design a new engine-noise acceptable SST having

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^{x} CORTRIGHT (25), for example, has indicated a "subsonic transport goal" of 90 PNdB for 1985 (the current level is 108), i.e. at least 25 dB lower than the expected level for the first Concorde version.

a Required Surcharge Number low enough for competing economically in the first-class market (it would, of course, be even less competitive in the economy-class market) without such a drastic "break-through" in supersonic technology that it would have no counter-part in subsonic developments.

b. Third Generation SSTs

Radical supersonic advances will, however, inevitably take long time. Let us therefore call an SST that is based on more or less revolutionary developments, and having a likely Mach Number of about 2.7 or 3.0, the "third generation" SST (thus disregarding the fact that it might be found wise to refrain from developing a second generation SST in the meaning of a Concorde successor based on less spectacular supersonic advances).

Before discussing the prospects of economic viability for such an SST it seems prudent to review briefly the reasons for the apparent great difficulties to design a supersonic aircraft that is economically competitive with subsonic jets. The main reasons are:

(1) An SST must fly in two different aerodynamic environments, subsonic and supersonic, with different "aerodynamic laws" with respect to stability and optimum configurations etc. Solutions must be found which satisfy minimum requirements for both environments. The necessary compromises (e.g. with respect to wing aspect ratio) can usually not be ideal for either ends of the tremendous speed range from landing speed to supersonic cruise speed.

(2) Over and above this general drawback, the SST has a drag component, the wave drag, which does not exist for subsonic aircraft. For current SST projects the wave drag is one third to half of the total drag, which includes also friction and induced (lift) drag. The wave drag is the primary reason for the poor lift/drag ratio of SSTs. L/D is about 7 for Concorde and about 18 for subsonic transports.

(3) The aerodynamic heating at each supersonic flight necessitates (a) lower stress levels in order to obtain the same fatigue life and safety of the primary structure as for subsonics and/or more sophisticated materials and detail design, (b) a more complicated and heavier air conditioning system and (c) more complicated and/or robust design of such systems that are not cooled.

(4) The higher cruise altitude of the SSTs necessitates a heavier skin of the fuselage in order to withstand the greater pressure differential.

(5) In general it is more difficult with SSTs than with subsonic jets to comply with a given airport noise standard, e.g. because high by-pass, large diameter engines are rather incompatible with supersonic speed. For an SST to comply with the noise standard of the future - which are expected to be much more stringent than the present - will therefore result in extra weight penalties due to impaired specific fuel consumption and thrust.

All these five "hard facts of life" are inevitable and bound to imply increased structural weight (i.e. less payload/empty weight than for subsonics) and more complex designs (i.e. higher cost/weight). In particular the wave drag (due to the shock waves which also cause the sonic boom) is a "law of nature". So far no one has put forward a well-founded hope that the wave drag can ever be reduced substantially. MORGAN, for example states (26):

"The total wave drag term is large, and forms the major obstacle to economical supersonic flight", and observes that the resulting "Poor lift/drag ratios are only tolerable at supersonic speeds because their adverse effect on range, direct operating costs - or any of the parameters denoting efficiency - may be counter-balanced by a very marked increase in the propulsive efficiency of jet engines as we sweep through the Mach Number range between 1.0 and 3.0".

So far, however, such a counter-balance has not been achieved. The general consensus, expressed for example by LOFTIN (27), seems to be that "flight values of the lift-drag ratio of the order of 10 appears to be possible with configurations which, though perhaps not practical today, may be practical in the future".

In view of these observations it seems to be a research area of great importance to make a general study of the improvement in the propulsive efficiency of SST engines, over the improvements that can be expected to be made in the propulsive efficiency of subsonic jets in the same time period, in order to offset not only the poor basic L/D of the SST but also the additional penalties (again over the subsonics) that will burden the SST, due to the factors (1), (3) and (4) listed above with respect in particular to structure weight. In such a study the following "percentage equation" based on eq. (13) has to be observed.

$$\frac{W_f}{W_t} + \frac{W_{eng}}{W_t} + \frac{W_{hull}}{W_t} + \frac{W_c}{W_t} + k\,\frac{W_p}{W_t} = 1 \qquad (22)$$

W_{eng} = the major portion (the one varying with the size of the aircraft) of the engine weight

$W_{hull} = W_{ew} - W_{eng}$

It follows from the foregoing that an SST for economic viability must attain roughly the same payload/gross-weight ratio, W_p/W_t, as competing subsonic jets (or, in fact, an even higher ratio in order to offset the higher cost/weight ratio of the SST which can hardly be compensated by the productivity ratio, M_s/M, and other factors that might be favourable to the SST). Let us furthermore assume the same values for W_c/W and k for SSTs and subsonics. Considering also that the high fuel consumption of SSTs has hitherto been the greatest obstacle for attaining a good payload the issue at stake is elucidated by the following self-explanatory approximate condition:

$$\left(\frac{W_f}{W_t}\right)_{subs} - \left(\frac{W_f}{W_t}\right)_s = \overbrace{\left(\frac{W_{eng}}{W_t}\right)_s - \left(\frac{W_{eng}}{W_t}\right)_{subs}}^{(a)} + \underbrace{\left(\frac{W_{hull}}{W_t}\right)_s - \left(\frac{W_{hull}}{W_t}\right)_{subs}}_{(b)} \qquad (23)$$

We can thus draw the important conclusion that a necessary but probably not sufficient condition for economic SST operation is that the "supersonic" fuel consumption must be so low that the relative fuel weight of an SST is so much smaller than the relative fuel weight of contemporary subsonic jets that the difference equals the sum of the difference (also in relation to improved subsonic jets) in (a) the relative engine weight (caused, in part, by the likely requirement of equally low engine noise) and (b) the relative hull weight (caused in particular by the kinetic heating of SSTs, their higher flight altitudes and more complex design).

At the face of these observations the prospects that a future SST project can ever comply with this minimum condition appear to be very slim indeed. The question is, however, worthy of a quantitative study. Whereas the relative fuel weight, for a certain range, is rather well-known for current subsonics and can be estimated for future jets with reasonable accuracy, estimation of the relative fuel weight for SSTs - for any given or assumed basic specific fuel consumption, e.g. in cruise - is a much more complicated matter. It is dependent in a complex way on the specific fuel consumption and L/D throughout the whole flight path. For the cruise segment the fuel consumption can be estimated on the basis of Breguet´s range formula and a similar approach would have to be used for the subsonic and supersonic climb and descent segments, the high fuel consumption in climb being particularly important.

It seems fully possible to assess the relationships between a "basic" specific fuel consumption and L/D that are required for compliance with eq. (23) assuming realistic values for the relative subsonic fuel weight and the differences (a) and (b). Furthermore it is certainly possible to make a more general study - by applying eq. (22) both for SST and subsonics but without assuming equal payload ratios - for assessing overall relationships between all the most significant parameters governing the relative SST/subsonic economics, in particular payload/empty-weight, specific fuel consumption, M_s/M and resulting cost/weight ratios.

Pending research of this kind, the only way to get further in judging the prospects of improved operation economics of a third generation SST is to analyze information about performance of advanced SST projects believed by their proposers to be attainable. CORTRIGHT $^{(25)}$ indicates as design goals for an advanced SST (apparently believed attainable during the 1980´s) an "L/D near 10", a payload/gross-weight ratio of 0.1, a noise level of 108 EPNdB and a range of 5000 nautical miles, to be achieved by a Mach 2.7 to 3.0 aircraft with a gross weight of 800,000 lbs. As

$$\frac{W_p}{W_e} = \frac{W_p/W_t}{1 - W_p/W_t - W_f/W_t} \qquad (24)$$

and if we assume that this SST project would have a relative fuel weight, W_f/W_t of from 50 to 55 %, its payload/empty-weight ratio would range from 25 to 29 %. This might be compared with a subsonic jet of the 1980´s whose payload/empty-weight ratio is improved over the current 747 by 20 %. If we furthermore conservatively define the payload of the subsonic aircraft as the weight of merely a full load of "effective" passengers this ratio would be $1.2 \cdot 545 \cdot 210/356{,}000 = 0.385$.

The relative payload/empty-weight ratio, x_s/x, would thus be from about 0.65 to 0.74. On the assumption that the coefficients $K_1 - K_4$ in eq. (11) for $(f \cdot l)_{req}$ are roughly the same as indicated above the curves in Fig. 11 would apply. If we furthermore believe that this Mach 2.7+ SST could achieve a productivity ratio of 1.5 its $(f \cdot l)_{req}$ would fall between the heavy-drawn vertical lines marked, assuming that the cost/empty-weight ratio, i_s/i, would be at least 4.

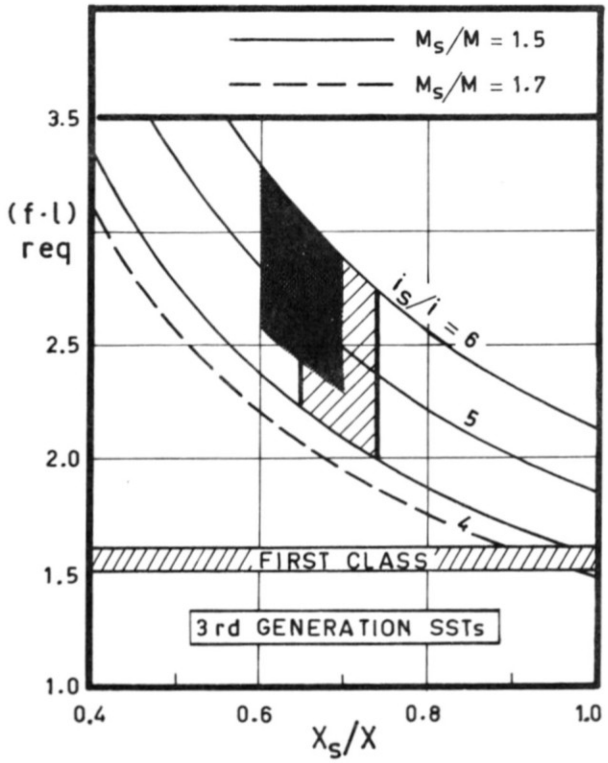

Fig. 11. The Required Surcharge Number for a Mach 2.7+ SST project suggested by CORTRIGHT will likely fall within the dark area if the SST is to conform with the 1985 airport-noise design goal of 90 EPNdB, indicated by C. for subsonic jets.

In the light of the foregoing analyses regarding second generation SSTs and considering the extreme complexity and sophisticated design of a Mach 2.7+ SST with a high L/D (e.g. with "semi-integrated" wing-body configurations and lengthwise varying cross section of the fuselage with a warped center line) using also "exotic" composite, heat-resistant materials, i_s/i will in all likelihood be considerably higher than 4, perhaps 5 or 6. The Required Surcharge Number would thus fall somewhere within the hatched area between the two heavy lines in Fig. 11. The whole of the area falls above $(f \cdot l)_{req} = 2$.

In envisaging this advanced SST project CORTRIGHT has, however, assumed a noise level of 108 EPNdB, whereas he predicts that 90 EPNdB will be attained by new large subsonic jets by 1985. The modern trend is that what is achievable as regards low airport noise should also be prescribed in noise requirements for new aircraft. One must therefore assume that SST projects appearing at the end of the 1980´s, or later, will have to comply with a 90 EPNdB noise level. The reason why CORTRIGHT has not set this noise level as a goal for his SST project is probably that he believes that such a quiet SST either is impossible to design or would suffer from unacceptable weight and fuel consumption penalties.

Whatever the reason, we can conclude from CORTRIGHT´s prognostication that, if compliance for SSTs with the 90 EPNdB level is achievable at all, it will be very costly indeed in terms of both reduced payload/weight (x_s/x) and increased cost/weight (i_s/i). It therefore appears that the Required Surcharge Number for a third generation noise-acceptable SST will likely fall within the dark area in Fig. 11. This would yield an $(f \cdot l)_{req}$ anywhere from about 2.5 to about 3.

Conclusions about SST economics

The analyses above yield three main conclusions:

1. Concorde cannot compete in the economy-class market without enormous losses or subsidies. It cannot either compete in the first-class market without a great deficit in relation to the requirement of equal return on investment as for competing subsonics. This applies for a purchase price per aircraft, without spares, of the order \$35 m which, however, does not cover the R&D costs. At a purchase price covering the R&D costs Concorde would be still more uneconomic.

2. Provided that one does not base the judgments on speculations about advances in supersonic technology far beyond what is conceivable today, it appears impossible ever to develop an SST which - without great subsidies for covering considerable portions of the development, manufacturing and/or operation costs - could be economically competitive even in the first-class market. (Still less could it compete in the economy-class market).

3. The second conclusion applies even if boom-alleviating SST configurations would lead to abandoning all overland boom restrictions. Disregarding that such an advancement seems impossible, and also that near-boomless SST configurations would increase substantially the purchase-price/weight ratio and/or decrease the payload/weight ratio (thus increase the purchase-price/payload ratio), the improvement in mileage productivity that could be achieved at full freedom to fly supersonically over land would be far from sufficient to make the SST economically viable.

Market Penetration

In view of these conclusions it would seem wise not only to terminate the Concorde enterprise - in order to avoid great losses that will increase with number of Concordes built and put into service - but also to abandon the plans to develop Concorde successors or third generation SSTs until and unless analyses of the kind presented above, clearly indicate that the level of the art permits the design of an SST that is economically competitive in the contemporary "subsonic-jet environment".

It must be feared, however, that such decisions will not readily be made mainly because of the vast investments in the Concorde already made and because of the rather common belief in the aviation community, and hence also on governmental levels, that it is possible to develop economically viable SSTs in the future and that such developments therefore should be undertaken considering also alleged social benefits with respect to employment and the like (see below). One must therefore count with the possiblities that Concordes will be put into service and second and/or third generation SSTs will be developed and introduced later on. The great losses, or deficits, that will be incurred might then come, more or less, as a surprise, but will likely be covered, as long as possible, by hidden subsidies, e.g. in the form of increased subsonic fares for compensating deficits in SST operation. It seems therefore important to make an approximate assessment of the likely or possible encroachment by SSTs on the subsonic market.

Operation, also of future SST projects, at fares close to subsonic economy-class market would clearly incur altogether unacceptable losses. About first-class fares will therefore probably be applied in SST operation, at least to begin with. It must then in the first place be observed that the first-class market is quite a small fraction, some 10 percent, of the total scheduled market. A second limitation of the available market is caused by the fact that the time gains by SSTs are normally pointless on distances below about 2000 miles. A third limitation is that the overland boom restrictions, that in all likelihood will be applied also for future SST projects, will drastically reduce the number of feasible supersonic routes.

Furthermore, and most important, the SSTs will only be able to take over a portion of the resulting small potential market. The magnitude of this portion can hardly be accurately assessed, but it follows from Chapter II that at about equal (first-class) fares the SST/subsonic preference split can, on the average, hardly be better than 50/50 because of the marginal net benefit to the passengers of flying the SST, in particular on oversea routes crossing 5 or more one-hour time zones. The average preference split will be further reduced because of another factor, not mentioned in Chapter II:

Overland sonic-boom restrictions will often necessitate considerable detours around mainland areas and inhabited islands which will increase SST flight times and thus reduce the time gains.

It has been alleged (1) that some businessmen who fly subsonic today might prefer SSTs even at first-class fares because "historically people are willing to pay extra for higher speeds". Honestly I think that such an extrapolation from the piston-to-jet advance is entirely unsupported. It is true that a moderate surcharge was applied for a limited time on jet fares partly in order to protect fully serviceable but not yet amortized piston aircraft. The decisively important difference compared to the SST/subsonic jet situation is, however, that whereas the benefits to the passengers of flying jets instead of pistons were tremendous and could well justify even a considerable surcharge, the benefits of the SST over the subsonic is at best moderate. It therefore appears that the portion of economy-class passengers that would pay first-class fares will be almost negligible.

It follows that current and future SST projects can at best take over half of the, rather small, potential market, (long-haul, first-class and mainly oversea), provided that economic considerations are to govern the fare setting. One cannot be sure, however, that this proviso will apply in the long run. The required number of SSTs will be so small - resulting in great losses also in production, even if the R&D costs are written off - that the whole concept of civil supersonic aviation would appear to be a failure. The billions of dollars that have already been spent on the Concorde and other SST developments and the further billions of dollars that development of new generation SSTs would require, and also the political prestige that has gone into the various enterprises will, however, make the SST sponsors very reluctant to admit a failure of the SST concept.

In other words, the sheer inertia of the billion-dollar spending might well override normal airline economy considerations. Thus the motto may well be: "As we have already entered the Supersonic Age, wisely or not, we have to see it through, if not by Concorde so by second or third generation SSTs". And the consequential ambition - although not spelled out - will logically be to generate, litterally at any cost, a great appeal and demand for supersonic travel.

A great demand for SST services can, however, only be attained by considerable enchroachment on the economy-class market, and for achieving this it is necessary to apply about economy-class fares. By doing this the operation losses will greatly escalate but the goal, a large SST market, might well be reached.

To sum up, in the event that SSTs, in particular Concorde successors, are developed and introduced at all, strong economic reasons speak for applying about first-class fares, implying a very small SST market. For mainly political reasons the SST fares might, however, be set so low that the total fleet of SSTs becomes quite large.

In this context it may be observed that Boeing (8, 28) founded its estimates of the SST market on the presumption of economy-class fares (yielding a demand for over 500 298-seat US SSTs), that ZIEGLER, Chairman, SNIAS (6), foresees a demand for over 900 Concordes by 1989 (if there are second generation SSTs) and that EDWARDS (29) foresees "1500 Concorde and Concorde development aircraft to be in service by the end of the century".

It follows that, in spite of the inevitable great losses that will be incurred by SST operation at about economy-class fares, the assessment of the environmental effects should be based on the assumption of a total SST market penetration corresponding to the order of 1000 to 2000 SSTs, including USSR aircraft.

IV. Social Aspects

Cost/Benefit of the SST, Disregarding Social Costs

Let us now apply the modern cost/benefit concept for judging the justification of major technological enterprises. It stands to reason that in the field of aviation the cost/benefit ratio has continously decreased in the past; in particular the piston-to-jet transition implied reduced transportation costs and greatly increased benefits in the form of really important time savings and much smoother flights.

This trend would, however, be drastically changed by SSTs, even if one disregards their social "diseconomics": Firstly, the SST transportation cost per passenger mile is much higher than for subsonics. Secondly, and even more important, the real benefit to (or need for) passengers to fly at supersonic speed can at best be considered moderate and will, in the opinions of many, be marginal, i.e. approach zero. The denominator being quite small the cost/benefit ratio for the SST would clearly be extraordinarily high.

In a world of limited resources and great poverty this fact would appear sufficient for abandoning the plans on supersonic travel, and thus there would be no need to investigate the social aspects of the SST, be they positive or negative. But the ambitions to launch large-scale supersonic aviation prevail almost intact. It is therefore necessary to consider also the social implications of the SST. For the purpose of this paper, i.e. to see the SST in a total and global perspective, it is sufficient, however, to make a rather brief survey of the social effects.

Social Aspects Alleged in Favour of the SST

We may define here the social aspects as all factors, significant for the justification of the SST, other than operation economics including demand (the demand for SST being related to the need as pointed out in Ch. II).

The main "social" arguments put forward for the Concorde and for the (abandoned) US SST are employment, preventing loss of investments made (or profits in production), improved balance of payment, technical "spin-offs", aeronautical leadership and national prestige. The four first of these arguments have economic implications.

Employment. Development and manufacture of SSTs require very considerable numbers of scientists, engineers and workmen. This would be an important argument for SST production if such aircraft were greatly needed and economic in use. If this is not the case, however, the employment aspect appears to be invalid; most economists would agree that production of goods the use of which would be an economic burden to taxpayers and/or the users is not a sound way to fight unemployment.

Preventing loss of investments made and/or profits in production. These two arguments, which are closely related, have been strongly advocated in favour of SST production, in particular of continuing production of Concorde (and before also of the US SST). Both arguments can, however, be questioned. It has been officially declared that most or all of the R&D costs that have gone into the Concorde Project (about 650 million pounds) cannot be recovered. With respect, for example to Concorde, there is also reason to doubt that, even if the R&D costs are written off, the price that airlines would be willing to pay for "sea-limited" SSTs could yield a normal profit to the SST manufacturers over the production cost per aircraft at the limited number of "boom-restricted" SSTs that can be expected to be sold. (30)

Improved balance of payments. This argument was the subject of intense debate with respect to the US SST project. The general consensus among leading economists in the U.S. was that the net effect of an SST enterprise on the balance of payments - considering also outflow of money due to the alleged increase in travels abroad - would be small even if, as was assumed, the SSTs could be sold at a profit. (31) I will not venture an opinion on this subject except that, if SSTs can only be sold abroad at a loss (taking also the R&D costs into account) then such sales appear to be a dubious method of strengthening the economy of a country, including the balance of payments aspect.

Technical "spin-offs". A certain amount of by-products in the form of new knowledge, usable in other fields, does normally result from any major technological effort. It appears, however, that the value of "spin-offs" can be regarded as an argument for an enterprise only if this is profitable or otherwise desirable on its own merits.

Aeronautical leadership. The justification of this argument, too, depends upon the need and economic viability of an SST enterprise. Surely, if the SST is bound to be an economic failure it would be better to ascertain leadership by more sound and important aeronautical developments, e.g. in the V/STOL, noise-alleviation and safety areas.

National prestige. It seems that the prestige that could lie in "showing the flag" on faster-than-sound aircraft is no longer advocated as a strong argument for the SST. By contrast, however, the loss in national prestige that might lie in termination of, say, the Concorde enterprise - to which so much pride, hope and enthusiasm has been attached and on which so much money and efforts have been spent - appears to be felt by the sponsors as a very strong argument "to see it through", as was indicated above.

Overall judgment. As indicated in these brief observations there is room for considerable differences in opinion about the justification and strength of all these (social) pro-SST arguments. But whatever strength is attached to these aspects there can be no denying firstly that they have nothing to do with the main purpose of aviation, which is to provide safe, cheap and reasonably rapid transportation, and, secondly that they are all of a national character, promoting (at best) the interests of a few nations. Commercial aviation is, however, fundamentally of international scope and aim, serving the whole mankind. National arguments are therefore hardly a relevant aspect for judging the justification of international supersonic aviation.

Social Disadvantages and Hazards of the SST

a. Sonic Boom Over Land

As of August 1972 ten ICAO Member States - Canada, Denmark, Ireland, Japan, the Netherlands, Norway, Sweden, Switzerland, the U.S. and West Germany - have imposed restrictions on civil supersonic flights, or plan to do so in the near future. The restrictions of Denmark, Norway, Sweden and Switzerland are in the form of laws that prohibit supersonic overflight, and the same will probably apply to Japan. In the U.S. a regulation is about to be promulgated which prohibits overflight of SSTs generating a sonic boom "which will touch the surface in the United States" including the territorial waters. This is equivalent to prohibition of civil supersonic flight at speeds above about Mach 1.15, thus at speeds commonly called supersonic. Also the "conditional" restrictions of the remaining four States are *de facto* equivalent to prohibition of supersonic overflight because they stipulate that the boom must not cause damage to health which SST booms are certain to do (see below).

Furthermore, the Government of the United Kingdom has declared that in its view "commercial supersonic flights which could cause a boom to be heard on the ground should be banned". (32)

The Council of Europe "urges" in its Resolution 512 (1972) "on repercussions of supersonic civil flights on human and natural environment" that

> "civil flights at supersonic speeds over land should be banned",

and makes the following statement in its Resolution 511 (1972) "on the economic implications of the introduction of civil supersonic aircraft"

> "Recalling with approval that it is now commonly accepted at both governmental and professional level that supersonic flights will not be permitted over inhabited land".

This recognition was based on the Explanatory Memorandum (10) to the Council's Economic Committee which in turn was based on the deliberations of a Round Table organised "to discuss the Concorde Project" with representatives of the Aérospatiale/BAC Consortium and led by General Ziegler, Chairman and Managing Director of Aérospatiale. The Memorandum states twice

> "that nobody (including the Consortium construc-

ting Concorde) envisaged the operation of the aircraft at supersonic speeds over inhabited land areas".

These assertions of early 1972 seem very reassuring indeed but they appear to have been already negated: BOAC has made it known that they plan to fly Concorde at supersonic speed across the USSR and to apply for permissions to erect "supersonic corridors" over sparsely populated portions of many countries, e.g. Canada and in Africa and Central America, and on the planned route to Sydney (18, 33), see Fig. 12. In view of this it seems prudent to discuss briefly whether or not it would be morally defendable to subject people of <u>any</u> country, more or less sparsely populated, to disturbances and hazards[x] deemed unacceptable (and therefore banned) to the people of those 10 to 11 States which have studied the effects of SST sonic booms particularly thoroughly.

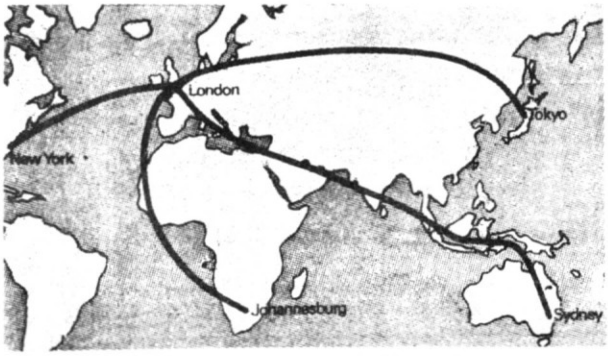

Fig. 12. Concorde routes as indicated by BOAC.

Understandably, in a way, the public interest in, and the research on, various effects of the SST sonic boom have until recently been focussed on the more spectacular effects of the boom, such as window breakage, house rattles, possible damage to churches and historical monuments and severe startle - possibly with disastrous results - to people and animals. I will not review here the mass of litterature on boom effects of this kind that has been written by a great many authors, e.g. (35-40).

May it suffice to state that there is abundant proof that startle effects, house rattle, window breakage, or the like, <u>begin</u> at a nominal, or calculated, boom overpressure of the order 0.7 to 1.0 psf, the inevitable atmospheric and/or topographic magnifications being the reason why such effects result from so low nominal boom intensities.

This overall result renders, of course, the boom of current and hitherto planned (e.g. the Boeing 2707) SST projects entirely unacceptable: As Fig. 13 (based on (41) and (42)) shows the nominal boom of such SSTs ranges from about 2 psf in cruise up to 2.5 to 4 psf in climb, after the "horseshoe", or "crescent", area, and up to some 6 to 15 psf in this area.(42) So, even if one could disregard the intense crescent boom, the SST boom in the first half of the vast <u>climb</u> carpet (over 4000 sq miles) would roughly be up to 4 times greater than the approximate threshold level for <u>beginning</u> startle effects and structural damage.

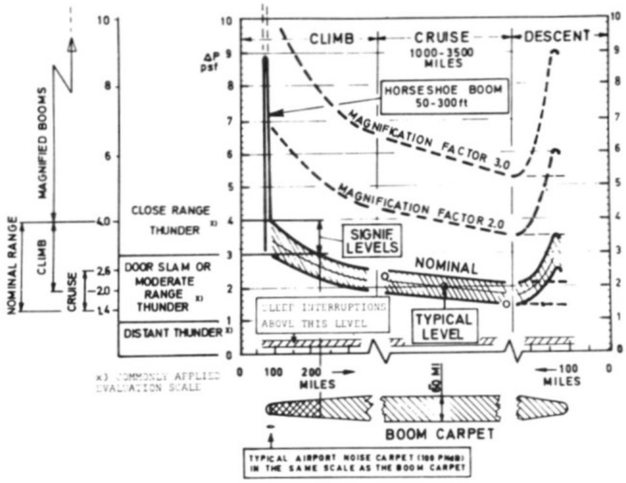

Fig. 13. Ranges of SST boom overpressures along the flight path.

Even worse, however, <u>the crescent boom</u>, see Fig. 14, cannot be disregarded. As I have pointed out in my dissenting Statement, published in (40), to the Report of the ICAO Sonic Boom Panel and also

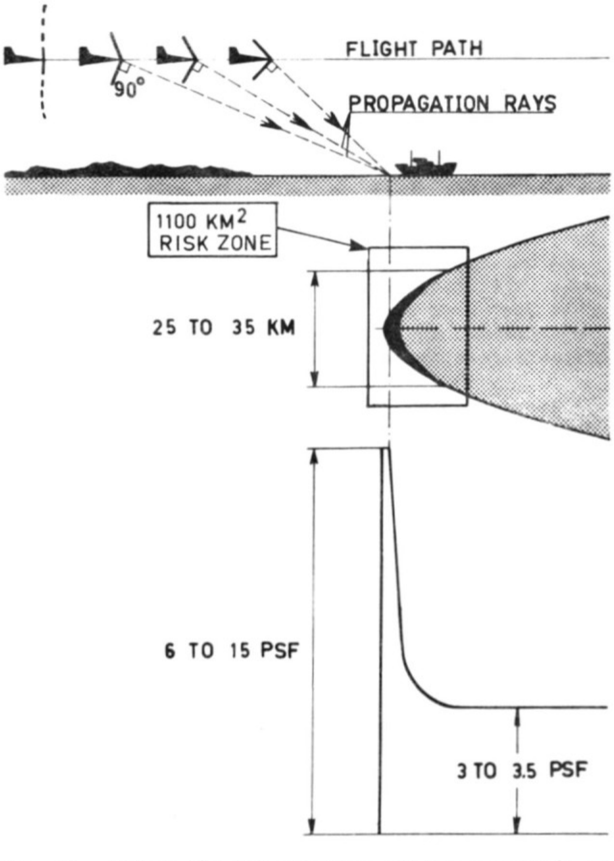

Fig. 14. Schematic illustration of the generation of the "crescent", or "horseshoe", boom.

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[x] This issue has recently been studied by ADAMS and HAIGH.(34)

in (43) and (44), to place the exceedingly frightening and potentially destructive crescent boom so that it with certainty does not hit people and buildings, is an unsolved and seemingly insoluble problem.

Strangely enough, practically all attention as regards the acceptability of the SST boom has been focussed on the intensity of the SST cruise boom. But even the cruise boom is some 2 to 3 times stronger than the threshold level for beginning startle effects and structural damage. This fact appears, in most cases, to be the main reason (and surely a sufficient one as has been clearly proved by the Concorde test flights over the west coast of the U.K. (45)) for the boom restrictions, imposed or intended, by the 10 to 11 States mentioned above.

The extensively applied policy of judging the acceptability of the SST boom mainly on comparison of the cruise boom intensity with the threshold intensity for startle and structural damage is, however, most deplorable for two reasons: In the first place the discrepancy between the two intensity levels might to SST sponsors not seem to be so great that it unquestionably outrules supersonic flight over sparsely populated areas, implying that they could hope that such operation would be acceptable to some countries located on planned SST routes. Secondly, this policy has given rise to a rather common belief that, if the nominal cruise boom of future SST projects could be reduced to about 0.6 psf, the effects of SST booms over land would probably be acceptable. This belief, maintained, for example by FERRI (46, 47), is apparently the very basis for the extensive current research programmes aiming at boom-alleviating SST configurations.

Both these hopes, or beliefs, are unfounded. The crescent and climb booms must, of course, be considered, and, even more important, it is not the more spectacular effects, such as window breakage and startle of people awake, that determine the limit for the acceptable boom intensity. As has been emphasized since 1961 (2-5) the acceptability limit is set by the "Sleep Disturbance Criterion" which is much more critical, i.e. yields a much lower acceptable boom intensity, than does a requirement that the SST must not cause window breakage, or the like. The Sleep Disturbance Criterion is suggested to be defined as follows (40)

> "Because of the exceptional vastness of the SST sonic boom carpets - making it virtually impossible to escape - the acceptable nominal SST boom must be so weak that it, taking due account to atmospheric and topographic magnifications, does not usually awake those people who are in the greatest need of undisturbed sleep, in particular the sick and old, and people with sleeping difficulties".

This condition is, in fact, a self-evident consequence of accepted humanitarian considerations in civilized countries for suffering citizens. Since this criterion was recognized at the OECD Conference on Sonic Boom Research (48) it is beginning to become more generally accepted. A most important, also self-evident, consequence of the criterion is that sonic booms, which are so weak that they do not usually awake light sleepers, or the like, cannot possibly cause appreciable or harmful startle to people awake in daytime, nor noticeable damage to structures or serious harm to animals.

As regards the value of the acceptable nominal boom as determined by this Criterion there is now clear evidence that the limit in all likelihood falls below 0.4 psf. Only one such evidence will be mentioned here, namely the Gallup polls in connection with the extensive daytime boom tests over Oklahoma City in 1964. Fig. 15 shows that very high proportions of the daytime sleepers were awakened by booms of about 1.0 psf, and the trend of the curve for sleep interruption indicates that some 10 to 15 percent of people asleep would be awakened by booms of the order 0.2 to 0.3 psf. As most people belonging to the Critical Group obviously (almost by definition) are to be found in the low percentage portion of sleep-interruption curves booms of this strength will awake a considerable proportion of such people.

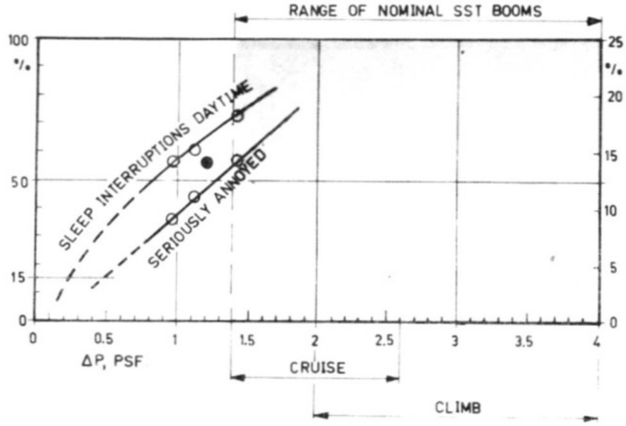


Fig. 15. Percentage - scale to the right - of Oklahomians polled who reported sleep interruption caused by 8 daytime booms per day and serious annoyance due to such disturbance. If the number of daytime sleepers is assumed to 25 %, the percentage of daytime sleepers who were awakened is to be read on the scale to the left. (The black dot represents roughly some recent Swedish tests.)

It is, of course, difficult to determine, and obtain general agreement on, an exact limit for the acceptable nominal boom intensity, but nor is it necessary: Even if the acceptable limit is set as relatively high as 0.4 psf, the SST climb boom would be some 7 to 10 times and the cruise boom about 5 times too strong for compliance with the Sleep Disturbance Criterion.

Considering the self-evident fact that the sufferings from sleep disturbance by people belonging to the Critical Group rapidly increase with boom strength, it would clearly be ruthless to subject any inhabited land (or island), however sparsely populated, to SST booms of current levels. In every community, also in sparsely populated countries, there are sick and old people, and people with sleeping difficulties.

In view of all this it seems imperative

(a) that all countries of the world as soon as possible ensure themselves protection against SST sonic booms by prohibiting civil supersonic overflights, and

(b) that, until this has been realized, SST operating airlines conform with the assertion of the Concorde Consortium to the Council of Europe that "operation of the aircraft of supersonic speeds over inhabited land areas" will not take place.

b. Sonic Boom Over Sea

As I have dealt extensively with this topic in the past (38-40, 43, 44) only a brief summary will be made of the most important observations.

As is well-known the Concorde manufacturers and sponsors take for granted that the sonic boom will cause no appreciable disturbance or hazard to people at sea, the alleged proof for this being that there has so far been no reported complaints from boats that have been overflown at supersonic speed by military aircraft or by the Concorde prototypes. By contrast I have persistently maintained that SST booms, which in the vast climb carpets are some 5 to 10 times too severe (disregarding the crescent boom) for being acceptable over land, in all likelihood will often cause considerable disturbance and fright to people on boats, in particular in calm weather.

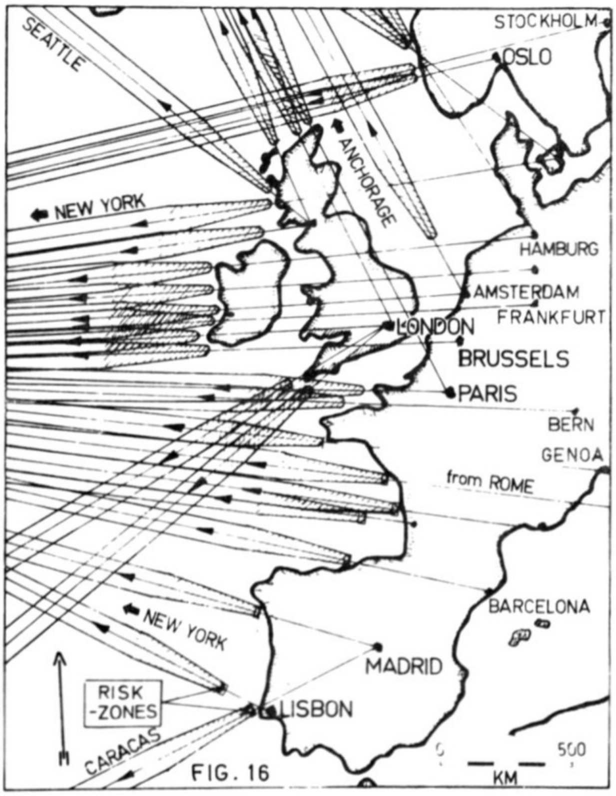
The figures 16-18, reprinted from (43), indicate the approximate coverage of the coastal waters of the North Atlantic by SST climb boom carpets.

The waters southeast of New York constitute the most "critical area" on the globe because they, for any given total fleet of SSTs, will be subjected to a far greater number of supersonic climb-outs than could conceivably occur anywhere else, and also because the boat traffic in these waters is relatively dense.

The allegation that the absence of complaints from boats is sufficient proof of the harmlessness of the booms must be objected both on statistical grounds - large-scale SST operation will cause a much higher daily frequency of occurrences where boats are struck by booms than has ever occurred up to now - and because the SST climb and crescent booms are much stronger than most of the booms that so far have been imposed on boats. In particular with respect to the intense crescent booms it must be observed that, whereas the probability that the rather thin crescent (some 200 ft) would have hit boats in the supersonic oversea flights so far conducted has been quite small, the risk that SST crescent booms - produced, for example, with a frequency of many dozens per day (on the "critical" waters off New York) - will hit boats is so high that such events can be expected to occur many times per year, perhaps per month.

This conclusion applies, of course, only if adequate measures are not taken to warn ships not to enter the crescent-boom risk zones which will have a minimum extension of some 1100 km^2. (44) To do this, however, appears to be very difficult and expensive.

An indication about the unlikelihood that SST booms will be acceptable to people at sea was pro-



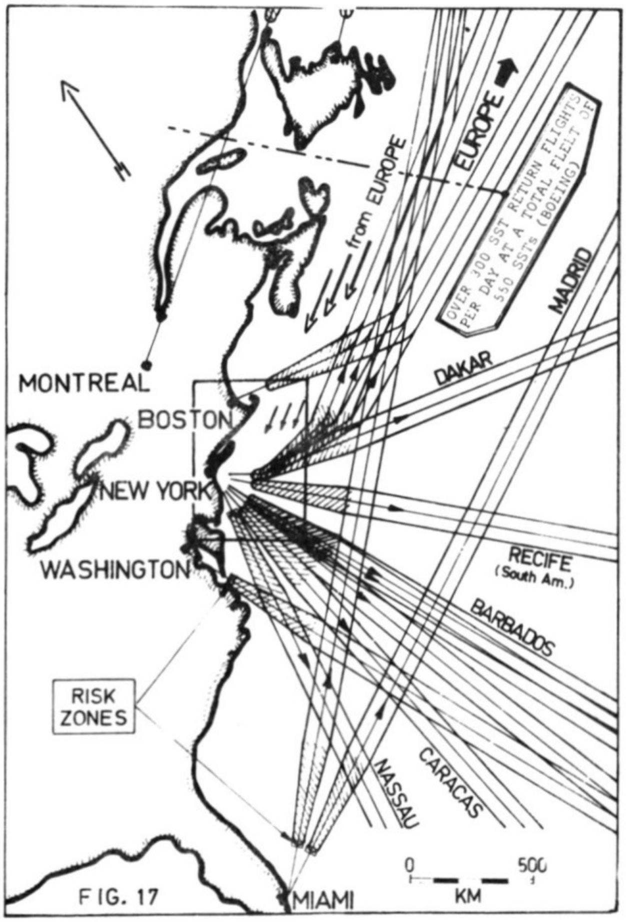


Fig. 16 and 17. Approximate locations of SST boom carpets west of Europe and east of U.S. assuming prohibition of supersonic flight over land. The hatched areas indicate the vast climb carpets with nominal overpressures of 2.5 to 4.0 psf, see Fig. 13. The intense crescent booms (Fig. 14) occur in the beginning of each climb carpet.

vided by the boom tests carried out by the Swedish Air Force over the Baltic in 1969. The purpose of the tests was to find out whether or not the current lowest permissible supersonic flight altitude over sea of 5000 m could be appreciably reduced without creating undue disturbance and hazards to people at sea due to the boom. As a result of the tests the Air Force decided that this altitude limit, which for the military aircraft in question yields a nominal overpressure of about 2.7 psf, should not be lowered, it being maintained that booms exceeding this level could be too frightening to passengers and crew members on boat decks. The level 2.7 psf is to be compared with the nominal SST boom intensity of up to 4 psf in the climb boom carpets and 6 to 15 psf in the crescents.

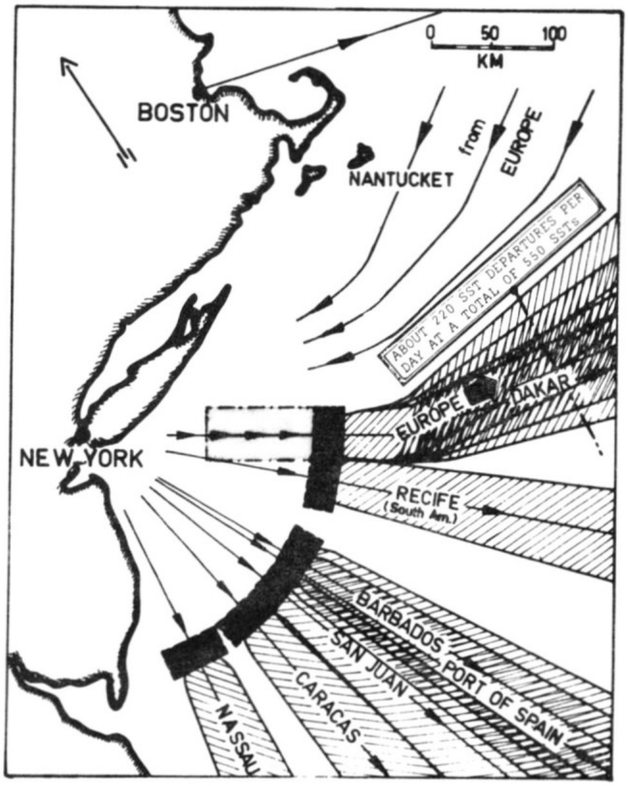


Fig. 18. Possible locations of crescent boom risk zones off New York. The vast light zone illustrates the area within which the crescents would fall if transonic speed is applied as soon as possible. The dark areas, of about 1100 km^2, are the risk zones within which most crescents would likely fall if efforts are made to locate them within an as small area as possible; some crescents will inevitably fall outside the risk zones. (57)

These observations should be sufficient to show that there is an urgent need for boom tests, and other research, in order to assess the SST boom intensities and daily frequencies that can be deemed acceptable to people at sea for various kinds of boats and weather conditions, etc. Such tests have been recommended by the Nordic Council in a Resolution of early 1971, and also in the Memorandum that supported the Resolution 512 (1972) of the Council of Europe, from which may be quoted

> "Sonic boom effects upon man at sea are still relatively unknown. As boom effects on man at sea is still a matter on which diverging views exist it seems necessary to conduct adequate boom tests on boats of various kinds, in order to find out the acceptable maximum limit of the civil supersonic boom over sea."

Needless to say it appears to be in the best interest also of SST sponsors and operating airlines that such tests - which should, of course, be made in co-operation with representatives of various categories of people at sea - be carried out without further delay in order not to risk unexpected severe opposition against SST booms over sea at a later stage.

c. Airport Noise

The take-off and landing noise of the first version of Concorde will far exceed current international standards (106 EPNdB for aircraft of Concorde´s weight) and still more exceed the noise levels of the latest wide-bodied jets, DC-10 and L-1011. As was also pointed out above, it is inherently much more difficult to achieve the same low future noise levels (of the order 90-95 EPNdB) that are achievable with future large subsonics which levels will be guiding for future standards. Most likely, however, these difficulties will not be taken as a justification for exempting SSTs from contemporary future noise standards for subsonics. Moderately higher noise levels of SSTs could possibly be defendable if it could be asserted that supersonic travel is much more important and more economic than subsonic transportation, but the opposite applies.

In view of this it seems highly desirable that an international agreement be reached that SSTs should comply with the noise standards for contemporary new subsonic jets. If such an agreement is not realized and SSTs do produce appreciably more noise at airports than the subsonic standards permit, this would weigh heavily against the SST as regards social acceptability.

d. Effects on Climate

As a result mainly of recent reports by JOHNSTON, e.g. (49), there has been much concern lately about the possibility of serious depletion of the ozone shield by exhaust emission of SSTs in the stratosphere. The ozone shield protects the earth from dangerous ultra-violet radiation. After thorough discussion of this possible danger the Symposium on Inadvertent Climate Modification held in Stockholm in 1971 (as a preparation for the UN Conference on the Human Environment) stated (50)

> "We consider that answers of these questions (regarding ozone depletion) should be produced before large-scale aircraft operation in the stratosphere becomes commonplace, and we believe that solutions might be produced by concentrated research."

Recent work by CRUTZEN (51, 52), a leading expert in this field, support this recommendation. Research programmes with the indicated aim have already been initiated.

e. Ionizing Cosmic Radiation

In a recent Memorandum (53) written upon consultation with Professor Bo Lindell, Director of the

Swedish National Institute of Radiation Protection,[x] I made the following main observations:

(1) The International Commission of Radiobiological Protection, ICRP, concluded in 1966 that the radiation at SST altitudes would be within permissible limits only *if exposure to major solar flares can be avoided*. (54)

(2) According to the Airworthiness Standards for Concorde (55) solar flares will, however, *not* be avoided: In such events the aircraft will reduce altitude only if the radiation dose rate, according to the radiometer, amounts to the rather high "Action Level" of 100 millirem per hour, and then it will only dive as much as is necessary for preventing the dose rate from exceeding this level.

(3) The SST occupants could thus receive up to 200 mrem in a 2-hour supersonic flight. Such a dose and possibly even smaller ones, e.g. 20 mrem, can conceivably cause foetal damage, such as malformation, or childhood leukaemia.

(4) In spite of the low frequency (probability) of solar flares producing 20 to 100 mrem per hour female air passenger of child-bearing age might prefer flying at subsonic heights where the risks due to solar flares are negligible.

In its aforementioned Resolution 512 the Council of Europe invited ICRP to study the SST cosmic radiation problem. This was done in a Statement of April 5, 1972, from which may be quoted

> "The Commission recognizes that the latter radiation (from solar flares) may on rare occasions increase in intensity so rapidly that early planning will not suffice as a measure of keeping exposures to an appropriately low level. The only way of avoiding high exposures would then be to descent to lower altitudes. In the exceptional situations when this is necessary, radiation risks would have to be weighed against any hazards related to the remedial action".

This recommendation, however, does not solve the problem at issue. The risk connected with "the remedial action", i.e. un-planned simultaneous diving by perhaps a great number of SSTs to a lower altitude (where there might be dense subsonic traffic) is one that many SST pilots are likely to consider greater than the statistically small combined risk that some SST occupants are pregnant and that their foetus could be harmed.

It follows that, at the present level of the art and planned measures for avoiding solar flare radiation, female passengers cannot be certain that they will not be subjected to unadvisably high radiation doses. Thus there is a need for further research in this area before SSTs are put into service.

f. Flight Safety

The Concorde and TU-144 are undoutbtedly the most thoroughly tested aircraft ever built. In particular the full-scale fatigue tests with realistic heat/load cycles are most impressing. In my opinion, however, this is not enough for ensuring the same very high safety level as that of commercial subsonic aircraft. On the basis of extensive studies (4, 56) I have concluded that SSTs will inevitably be less safe, both with respect to the aircraft itself and its operation, than contemporary subsonics. Briefly, the main reasons for my conviction are

(1) The imcomparably greater complexity of the SST.

(2) The simultaneous introduction of an unprecedented multitude of radically new design features; subsonic developments are characterized by few and usually "small-step" design novelties for each new model.

(3) The supersonic speed as such which, *inter alia*, increases the risks of collision with unforeseen "weather", e.g. hail, jet streams and cumulonimbus clouds which could contain destructive turbulence.

(4) The severe aerodynamic heating (and subsequent cooling) of the structures, and some of the systems, of the SST at each supersonic flight which is bound to imply increased risks of unpredictable failures due to creep, distortions and metal fatigue. These risks cannot be eliminated by only one full-scale fatigue test because the heat/load history in real operation will always differ from the heat/load schedules applied in the test.

Over and above the safety aspect as such, the SST buyers will get no proof about the safe fatigue life of the structures until many years after the purchases because of the exceptionally long times required for fatigue testing when a heating cycle - which should be of nearly the same duration as in actual flight - must be applied for each simulated flight.

V. Conclusions

The transition from piston aircraft to subsonic jets implied substantially reduced operation costs and greatly increased benefits in the form of really important time savings and much smoother and less tiring flights. The cost/benefit relationship reached a lower level than ever before.

By contrast, for the first time in history a further big increase in speed - by introducing SSTs - is neither greatly needed nor would it bring about reduced operation costs or fares. The seat-mile costs of current SST models, as well as of improved SST projects conceivable in the future, are, in fact, so high that the operation would be grossly uneconomic, even if subsonic first-class (or higher) fares are applied, and even if no overland restrictions are imposed due to the sonic boom. And at such fares SSTs can take over at most half of the long-haul first-class markets and an even smaller proportion of the medium-haul first-class markets, the portion of the economy-class markets that can be encroached upon by SSTs at first-class fares being negligible.

Moreover, the SST market penetration will be further reduced because there seem to be no prospects that the SST sonic boom can be decreased to such a very low level that it would be acceptable to people on land, considering the self-evident, decisively significant condition that those people who are in the greatest need of undisturbed sleep - the sick and old and those who suffer from sleeping

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[x] Dr Lindell is Vice Chairman of ICRP and Chairman of its Committee on External Radiation.

difficulties - must not often be awakened by the boom at night or if asleep in daytime.

Thus, and again for the first time in history, a new type of aircraft, the SST, would not be permitted to fly over inhabited land at the speed it is designed for. This exceptional drawback would from the outset make the SST a cripple among civil aircraft.

The operation costs being very high, the extent to which air passengers will fly the SST being quite small and the benefit to those who can afford to use it being at best moderate, the cost/benefit relationship for SST enterprises would be exceedingly high. In a world of limited resources and great poverty this fact alone, thus disregarding social "diseconomics", appears to be a sufficient reason for abandoning plans on civil supersonic flight, until and unless SSTs can be built which have roughly the same operating costs as subsonic jets so that they could operate economically at economy-class fares.

The issue at stake would seem simple enough if the commitments to introduce two SST models, the TU-144 and Concorde, had not come to the present advanced stage. In particular with respect to Concorde the facts that roughly two billion dollars have already been invested, that series production of 22 aircraft (in addition to two pre-production aircraft) is in full swing and that, when this is written, BOAC and Air France have ordered five Concordes each, might appear as an unsurmountable obstacle for abandoning the projects.

These commitments cannot, however, be taken as a justification for exposing, on an international level, the public to serious pollutions and hazards. Still less should the commitments be accepted as an incontrovertible evidence that mankind has already irrevocably entered the "supersonic age".

It should follow from the observations made in this paper that minimum international requirements for introduction of SST ought to be

(1) that they are forbidden to fly supersonically over inhabited land,

(2) that they comply with airport noise standards for contemporary subsonic aircraft, and

(3) that it has been proved that no adverse effects result from sonic booms over sea, cosmic radiation or exhaust emission in the stratosphere.

In conclusion, the course that will be followed with respect to introduction of the Concorde and TU-144 into international service, and as regards further developments of and plans on introducing new-generation SSTs, will be of great significance not only for civil aviation but also as an example of the ability of Man to steer technology when there is a conflict between alleged economic advantages and detrimental social effects.

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Corrigendum: In the paragraph preceeding eq. (12), page 9, the reference should be No. 58 instead of No. 24.