32nd Wright Brothers Lecture

Supersonic Air Transport—True Problems and Misconceptions

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The transition from subsonic to supersonic transports will be the last opportunity of achieving major time savings on long range flights for some time to come, as hypersonic transport will probably not be flying before a few decades. The state of the art has progressed far enough to enable designers to match supersonic airplane stage fuel and reserves requirements with acceptable operating weight empty and economic payload. A supersonic transport design program faces several major technical problems. Design features and solutions incorporated in the CONCORDE are discussed, in particular, the aerodynamic design compromise between high-speed and low-speed requirements. Kinetic heat problems and choice of materials are also reviewed. As far as reliability and safety are concerned, in trying to move forward, a more rational approach has been used as compared to subsonic airplanes, especially when it comes to certification regulations. Finally, in the area of operations, problem matters are now well defined and the outlook is optimistic. Supersonic transports will cause new problems but they also have inherent advantages. In this area, certain problems have been somewhat exaggerated. On the whole, the supersonic transport looks promising.

Introduction

THIS 14th of July is a double celebration as I have been invited by the AIAA to deliver the Wright Brothers Memorial Lecture on the very day of our Bastille day. For me, this invitation is at once a great honor and a great pleasure.

What tremendous changes have been wrought since 1903, when Orville Wright made the first controlled flight! Aeronautics, then a realm surrounded with an aura of mystery in which moved only pioneers like the Wright Brothers, has since spawned two of the world's most flourishing industries: the aviation industry and air transport. And for something over ten years now, it has an equally prosperous junior: astronautics.

The intervening few decades have been marked with advances now taken for granted but which a little thought will show to be truly extraordinary. I do not propose to relate these at length, but rather to talk to you about what I have been concerned with daily these last few years, namely problems specific to the SST. First of all, however, it might be appropriate to consider these problems in relation to the general evolution of aeronautics or perhaps I should say of air transport.

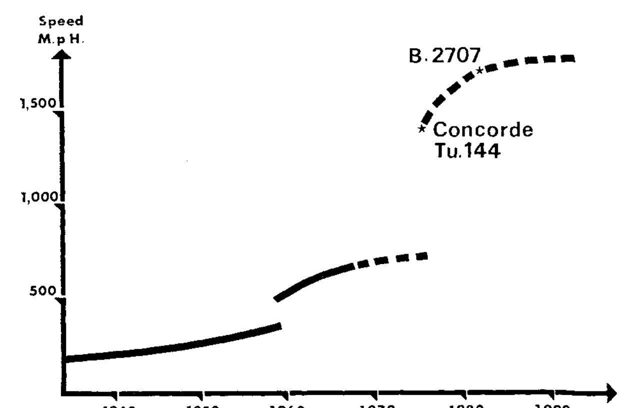

Fig. 1 Cruise speed increase.

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One of the most practical yardsticks for measuring this progress is the decrease in Direct Operating Costs (DOC). I will refrain from going into the finer points of DOC definitions, for we all know what is involved in broad terms. How, then, have the engineers managed to shrink DOC's over the years? They had two ways of doing this: to increase capacity—and with it the gross weight—and to increase flight speeds. In fact, we find that they have consistently applied both approaches concurrently.

Figure 1 shows the evolution in transport aircraft speeds. The gain in speed brings an attendant reduction in DOC's as technological advances gradually allow this gain to be achieved at not too great a cost.

This condition has indeed been fulfilled and we see from the curve that flight speeds have steadily increased while, at the same time, as shown in Fig. 2, DOC's have tapered off—though how much of this is due to greater speed and how much to greater capacity is not readily apparent. (In Fig. 2, for comparison, DOC are re-estimated taking into account U.S. consumer prices variation).

It would be a mistake to infer that the same trend in speed can be maintained for long. In fact, I am convinced that it cannot, and that the switch to supersonic transports

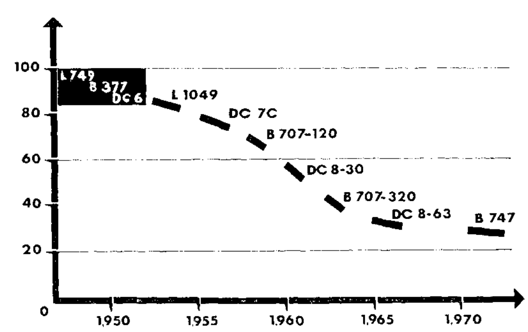

Fig. 2 Direct operating cost trend.

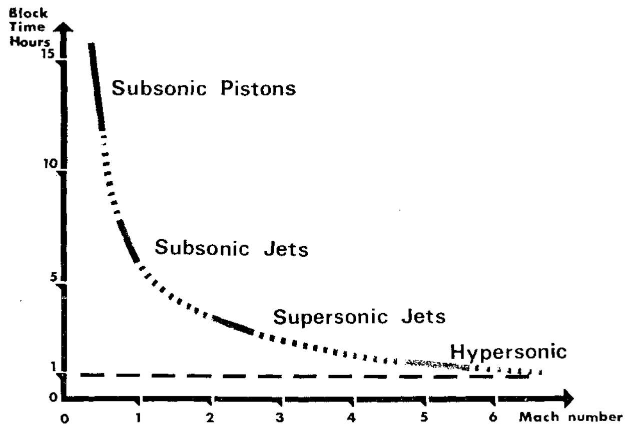

Fig. 3 Transatlantic stage; block time vs cruise speed.

will prove to be the last big step forward in this respect for many years to come.

While we are about it, let us dispose of one misconception. As shown in Fig. 3, aircraft in the Mach 2 and Mach 2.7 categories belong to the same family; the saving in time due to the increase in speed is $3\frac{1}{2}$–4 hr with the currently envisioned SST's, and these aircraft are no more different from each other than two subsonic aircraft flying at Mach 0.75 and Mach 0.90, respectively. Only, by achieving Mach 5 or 6, may we expect to pass yet another truly significant milestone. And to establish that this would be the ultimate stage, we need only remember that the average passenger must not be subjected to accelerations in excess of $\frac{1}{2}$g, which sets a lower limit of approximately 1 hr for the transatlantic crossing.

Let us bear in mind that it is no doubt perfectly reasonable to make a Mach 2–2.2 aircraft if it is built now, using light alloy, or a Mach 2.5–2.7 aircraft if it is built a little later, using titanium. Yet the missions devolving upon these aircraft do not differ fundamentally. The stage times are about the same, and above all the thermal balance is controlled in the same way: by using fuel—conventional fuel—as the heat sink, with no further precautions. This no longer applies in the case of a hypersonic aircraft, which would have to use a different fuel or resort to some other cooling device, quite apart from the acceleration problem I just mentioned. In short, from Mach 3 upwards, the difficulties add up very fast while the returns diminish. In fact, it appears that hypersonic aircraft will not be worthwhile until the day they can be justified by a sufficient traffic growth over stage lengths of 5000–10,000 miles. This would produce the breakdown shown in Fig. 4 (on which the logarithmic scale enables the respective traffic magnitudes to be more clearly portrayed). However, we are not there yet,

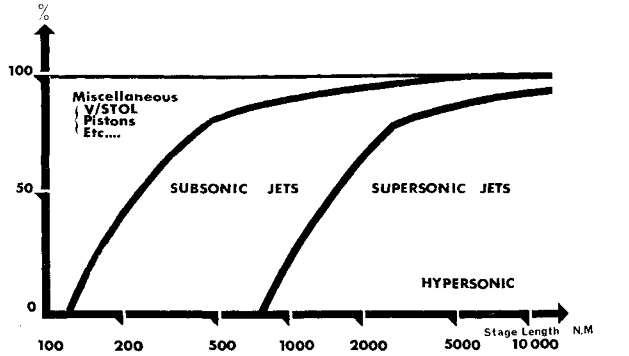

Fig. 4 Air traffic share breakdown including hypersonic aircraft.

Table 1 Subsonic vs supersonic weight breakdown comparison

	Subsonic	Supersonic
Fuel, including reserves, %	38–40	47–49
Operating weight empty, %	47–48	44–45
Payload, %	12–15	6–9

and the figure claims to be no more than a mere forecast for the 21st century.

It is still fairly easy to forecast flight speeds, but gross weight prediction is not so simple. Figure 5 shows their history. In point of fact, any extrapolation must allow for traffic trends and, as you know, much can depend on whether the growth rate is taken as 8% or 15% (which are for all practical purposes the limit figures quoted in the forecasts).

Summing up, then, the way seems fairly clear: increase the flight speed in step with technological progress and increase the gross weight as and when such increase is warranted or demanded by traffic growth. These improvements will be automatically reflected in the DOC figure. Two things remain paramount, however, in any such evolution, namely: 1) to improve safety and reliability and 2) to take operational requirements into account, which is not to say that they can remain static and I say so most emphatically.

Given this fairly clear pattern, how do SST's shape up on the eve of their entry into service? What are their true problems? And what are the misconceptions being entertained about them?

Performance

We might as well admit right away that, like all their forerunners, SSTs will not give their best performance as soon as they go into service. Like all other aircraft, they will begin in a modest way and improve with time. As you were able to see from Fig. 2 just now, the 707 had a DOC close to that of the DC 7. It has since diminished by 30%. The pattern of evolution in SSTs can be expected to be comparable, as we shall see presently.

How will the first SSTs compare, performancewise, with the current long-haul subsonic jets? Table 1 gives you some idea of the payload vs takeoff weight capability.

The figures given are no more than orders of magnitude but they speak for themselves: fuel consumed plus reserves are up by some 9% and this must be made good by a reduction in empty weight and/or payload. But the payload cannot be allowed to drop below the indicated figures, for notwithstanding faster turnrounds and a greater potential (CONCORDE, for example, is designed for some 14,000 transatlantic flights as against 7000 for a subsonic aircraft), profitability would otherwise be impossible.

We had therefore to gain 3% on the empty weight. You who are familiar with the problems involved in reducing aircraft empty weights, can appreciate the magnitude of this achievement.

It must be realized that designing a supersonic airplane isn't quite like building a powered buggy. You all remember what the first automobiles looked like—a motor mounted

Table 2 DOC breakdown

Fuel		Approx. 30%
Man-hours	Crew Maintenance	Approx. 20%
Items affected by aircraft and spare prices	Depreciation Insurance Financing Spares Tooling	Approx. 50%

Table 3 Safety reserves according to TSS-OPS 5.7

1	Standard mission plus: Missed approach Climb, diversion and 30 min alternate hold at 15,000 ft Enroute reserves (to be determined for each route; might be 3% of block fuel on North Atlantic)
2	One-engine failure: Destination or alternate must be reached with fuel available for 30 min hold at 15,000 ft
3	Two-engine failure or pressurization failure: Any airport appropriate for landing must be reached No holding

on a buggy chassis. Our job is altogether different. Building a supersonic airplane means not only a change in engines and geometry but also a shift in the state of the art. Indeed, the compromise must be a little more advanced in all respects than on subsonic aircraft: refinements in design to save weight, and more automation to alleviate the crew's workload since the same functions must be performed in a shorter time. Yet these advances must be made without compromising safety. On the contrary, parallel efforts are made to increase it. Many of the solutions adopted stem from these three joint requirements.

But it so happens that we nourish great hopes from the very hurdles which we find we must clear from the performance standpoint. For the fact that the weight of fuel is 5–8 times the payload also means that 1% saved on fuel consumption means a 5–8% gain in payload.

In other words, the improvement in propulsion efficiency will be far more effective than on subsonic aircraft. On the whole, we think that there is every reason to believe that SSTs will offer a greater development potential than subsonic aircraft.

This can be established cursorily by reference to the figures. Our current estimates are that, given substantially the same weight, the SST will have a DOC of 1.3, if we take that of the subsonic transport as 1.

To see whether it can be dropped to 1 or even below, let us take a look at Table 2, which gives a DOC breakdown per types of cost. The purchase price of the SST may come down: the techniques involved, which seem very sophisticated at present, will become more conventional, hence less costly. A 10% saving on the buying price would mean a 5% saving on the DOC.

But it is the weight breakdown which will provide the most significant gain. Let us now turn to Fig. 6 which reproduces the weight breakdown in Table 1.

Assuming constant prices, highly likely gains of 1% on the OWE and 5% on fuel consumption would raise the payload

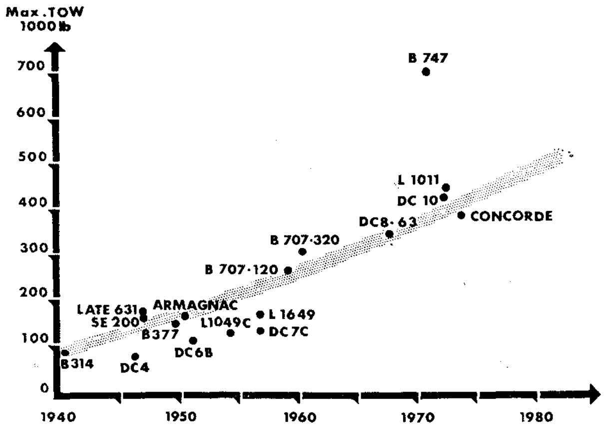

Fig. 5 Maximum takeoff weight trend.

from 7.5–10.35% of the takeoff weight. A simple calculation shows that the DOC then drops from 1.3 to 0.94.

Assuming the same gains, the subsonic transport's DOC drops from 1 down to only 0.83. Now subsonic aircraft are not going to make any weight savings without a corresponding increase in the buying price, and, as for fuel consumption, there has been far more time to experiment, so that there is certainly less latitude. Ultimately, as SST technology becomes more commonplace, so the supersonic transport's DOC will tend toward that of its subsonic counterpart. DOC will tend toward that of its subsonic counterpart. And as I was just saying, it is those present narrow margins of ours, precisely, which give us broad scope for the future.

I would like to revert for a moment to the question of reserves. The over-all design does not depend on them a great deal, but the way the plane is to be operated does to a great extent. The quantities of fuel quoted previously include reserves amounting to about 9% of the takeoff weight. This is a maximum and should be compared with the FAA's projected figure of about 8.5% and with 7% or so of the Anglo-French regulations (TSS-OPS 5.7).

Table 3 provides a very concise summary of the TSS-OPS, from which you can see that the requirement provides ample safety, which, of course, is as it should be.

In fact even the figure of 7% is arguable, for it hardly seems right to apply worldwide a rule that was formulated primarily with New York and a few other major airports in mind. In fact, TSS-OPS 5.7 does provide for a number of special cases.

Let us nevertheless assume a figure of 7%. This means that, under the TSS-OPS 5.7 regulation, airlines are left with 2% of the takeoff weight with which to optimize the flight regularity-payload compromise as they see fit. We be-

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Pierre Satre, born May 4, 1909 at Grenoble, France, was educated in Marseille. He is a graduate of Ecole Polytechnique (Class of 1929) and Ecole Nationale Supérieure de l'Aéronautique (Class of 1934). He started his career as an Aeronautics Engineer in various ministerial offices.

In March 1941, he was appointed Chief Engineer at SNCASE-Toulouse (later to be known as Sud Aviation). In this capacity, he was in charge of a number of military and commercial aircraft, among them the Armagnac, Grognard, and Durandal, a Mach-2 fighter plane, and finally the well known Caravelle with rear engines.

Appointed Technical Director of Sud Aviation in 1959, he is, specifically, Technical Director of the Concorde project.

Mr. Satre is an officer of the Légion d'Honneur and Commander of the National Order of Merit and a member of AIAA; he has been awarded the British Silver Medal, as well as numerous other French and foreign medals.

He is married and has five children.

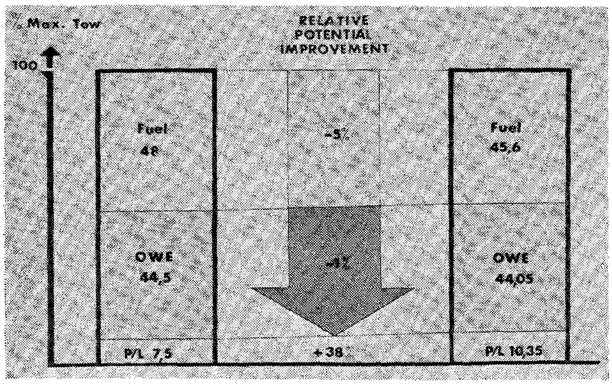

Fig. 6 Anticipated improvements.

lieve this would be by far preferable to imposing statutory reserves not strictly necessary for safety, for, like the empty weight, the fuel weight must be determined even more precisely than on subsonic aircraft because of its economic implications.

In short, the performance problem with SSTs is a genuine one but let us not add to it through excessive conservation on reserves based on a misconception. Presently, when I go on to examine operating problems, I shall show why it is no exaggeration to speak of excessive conservation, especially when reserves equal to or greater than those on subsonic aircraft are being contemplated even through the contingencies likely to be met on the journey are far fewer. And while we are on the subject of performance, let me turn right away to another misconception.

The takeoff and landing speeds associated with delta wing aircraft are higher than with other aircraft. Some have inferred from this that landings in particular would present difficulties. At no time was this view shared by the chief pilots of our customer Airlines, who from the outset has posed the problem in stark and simple fashion: speed is important, but less important than flying qualities. The CONCORDE's flight tests have shown how right they were: thanks to excellent flying qualities, landings at 160 kt can be controlled without any trouble, and you will find confirmation of this in Table 4.

This leads me straight on to the origin of these relatively high takeoff and landing speeds, namely the aerodynamic compromise between high and low speeds.

High-Speed/Low-Speed Aerodynamic Compromise

There are at least three requirements to be met in designing an SST: 1) The airplane must be configured for supersonic cruise flight. 2) It must adapt readily to subsonic flight, notably for takeoff, for landing, and also, for holdings prior to landing until such time these holdings can be reduced. 3) It must possess excellent flying qualities throughout the flight envelope.

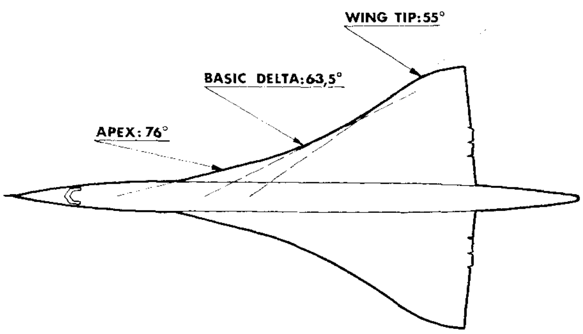

Fig. 7 Wing plan form.

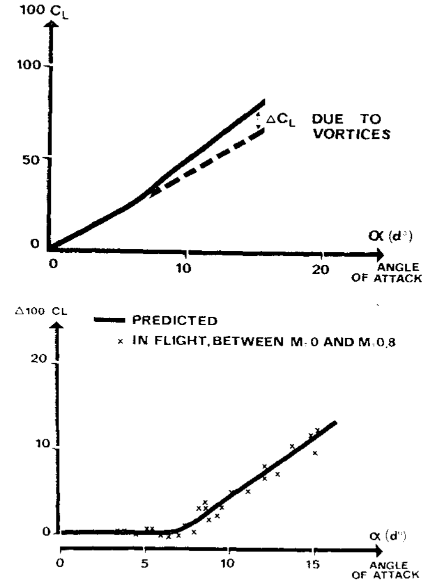

Fig. 8 Concorde lift curve and lift increase due to vortices.

Now although the third requirement can be met by making the necessary refinements, the first two are in direct conflict. The subsonic regime is of considerable importance in the over-all economics of the SST, as portrayed diagramatically in Table 5.

You will observe that the requirements imposed for holdings and diversions have a determining effect. This being so, the attractions of variable geometry as a means of resolving this contradiction are manifest, and I am not surprised that Boeing attempted a breakthrough along these lines. Their design study, the only one to have been taken far enough, was necessary to establish that the variable geometry solution is not yet ripe. This is not to say that we shall not see back with us some day. But so far the 3 SST design projects feature near-fixed geometry, I say "near" because the droop nose and the air intakes do feature variable geometry, which makes my task simpler. I shall simplify it still further by confining myself to what I know well: the solutions adopted for the CONCORDE.

Starting with a pure delta wing with 63.5° of sweepback, we set about looking for improvements, with special emphasis on low-speed qualities.

A sharply swept apex (about 76°), as shown in Fig. 7, produced a triple advantage: 1) a reduction in the thickness ratio at the wing root, plus an arrow planform, both favorable factors for supersonic flight, 2) a forward shift in aerodynamic center location, which in turn shifted

Table 4 Concorde 001—first landings

No. of flight	Approach speed, kt	Touch down		
		Air speed, kt	Vertical speed, m/sec	Bank angle $d°$
1	167	160	1.1	0.9
2	171	168	0.5	0.6
3	175	165	0.6	0.7
4	171	166	...[a]	0.4
5	179	171	...[a]	0.2
6	175	169	0.5	0
7	176	172	0.8	0
8	174	168	0.8	0.4
9	165	150	...[a]	0.2
Mean values	172	165	0.7	0.4

[a] Cinetheodolite failure.

Table 5 Importance of subsonic regime

	Route Paris–J.F.K.–3200 nm			
	Block time		Fuel consumption	
	Supersonic	Subsonic	Supersonic	Subsonic
Standard mission—no holding (ideal case)	79%	21%	84%	16%
15-min holding (average case)	74%	26%	81%	19%
200-min diversion + 30-min holding (critical case under which requirements are set)	62%	38%	75%	25%

the heaviest loads into the most rigid structural area and facilitated accommodation of the landing gear, 3) a more intense attached leading edge vortex resulting in greater lift at low speeds.

Much work was also done on the shape of the wingtip, and the process of improving it aerodynamically has gone on until just recently. It turned out that reducing the sweep to 55°, by truncating the delta slightly, improved the lift drag ratio in subsonic flight against a very small tradeoff in the supersonic regime.

This ultimately led us to the ogee delta planform shown in the figure. It is more difficult to depict the wingtip camber and twist, though optimizing them is important. Finally, the dihedral must be chosen with due allowance for wing deformation in flight (which is significant despite the small span: 16 in. at the wingtip in cruise relative to static on the ground) and for the ground clearance.

Optimally configured in this way, the wing has already demonstrated its qualities in subsonic flight (Fig. 8). This confirmation fills us with confidence that our expectations for supersonic flight will be borne out and that the changes decided upon as between the prototype and the production aircraft will have the desired effect.

Studying the propulsion system on the ground is more difficult. First, the interactions between the intake, the engine and the nozzle are highly complex; second, none of our test facilities provided complete simulation of flight conditions. The margin of uncertainty is therefore greater.

Thus, making the final choice between major options is doubtless less simple. Although all 3 SST projects ultimately settled for a fixed delta wing by the end of their design studies, the powerplants are of the direct flow type in two cases and of the bypass type in the third. The advantages, from the drag and weight standpoint, offered by the direct-flow type made us decide in its favor, and we use a development of the British Olympus turbojet, the Olympus 593.

The problem of configuring the propulsion system for supersonic/subsonic operation is not so much an engine problem as an air intake and nozzle problem. In the case of

Table 6 Caravelle structural fatigue test results (without landing gear)

Number of cycles applied to specimen:		100,000
Number of damages during testing:		99
Number of modifications decided:		7
Number of flight cycles completed:		up to 30,000
Same damages as during testing	0.5 cracks 0.3 fastener failures 0.1 fretting corrosion	9
New types of damage	0.2 cracks including one due to stress corrosion	2

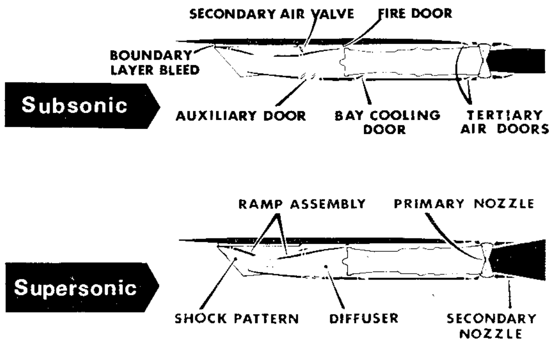

Fig. 9 Concorde power plant.

the CONCORDE, the fact that the nacelles were grouped in pairs imposed a two-dimensional air intake. This is schematized in Fig. 9. I will spare you the description of these intakes and merely repeat that it is all very difficult to match up and optimize. I believe one of the hardest problems in designing a supersonic transport to be the configuring of its propulsion system. This is indeed a thorny technical problem, for just now we saw the enormous economic importance of fuel consumption.

On CONCORDE, so far, the system has functioned satisfactorily in subsonic flight, and while it is difficult to dissociate drag from thrust, we can say that the theoretical figures have been borne out to within the measurement error. As you know, I am not yet in a position to tell you how the system will behave in supersonic flight.

Thermal Problem and Choice of Materials

I am obviously still less in a position to talk to you about fatigue in supersonic flight. In fact only the operational aircraft themselves will provide us with in flight fatigue data since our objective is a service life of 45–50,000 hr, over half of which will be under high-temperature conditions.

The structural behavior will be investigated by fatigue tests on a full-scale structure which will be subjected to mechanical and thermal loads, with suitable amplification coefficients to insure safety.

Figure 10 represents the equivalent of a flight cycle: the mechanical loads are applied twice, the thermal loads once, amplified by 15–20%. This procedure gives the specimen time to cool down.

Our confidence in these tests is founded, in the main, firstly on the component tests and secondly on experiments with the CARAVELLE, the results of which are summarized in Table 6.

During these CARAVELLE fatigue tests, 99 damages were noted. Seven modifications were decided upon and introduced, since which only 9 damages have been recorded in service, even though many of the aircraft have now logged more than 20,000 hr (and some as many as 27,000–28,000 hr)

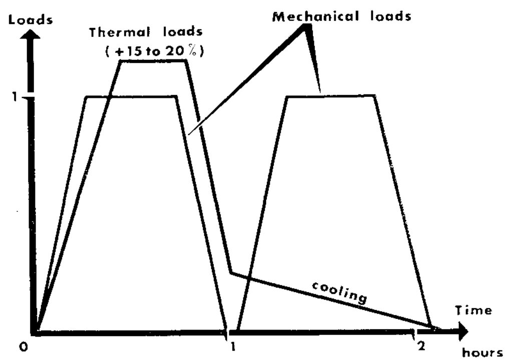

Fig. 10 Fatigue testing.

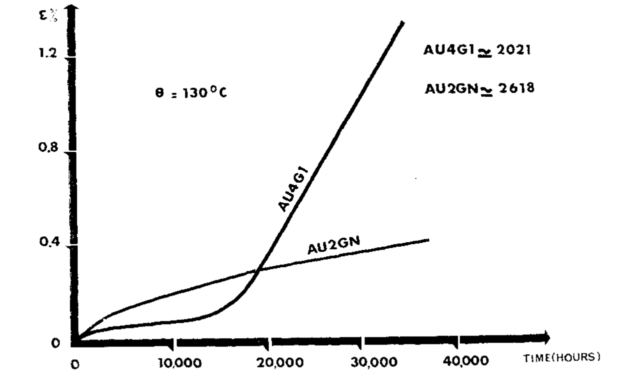

Fig. 11 Creep strain of AU4G1 and AU2GN sheet metal specimen (ONERA results).

out of the 30,000 hr of life, the test was designed to guarantee initially. Based on the accumulated in-flight experience, the actual fatigue life will be much greater.

Moreover, these damages occurred only on a limited number of aircraft (usually fewer than 10 and never more than 20) out of more than 200 CARAVELLE in service, and generally did so in the course of the first 10,000 flight hours.

We consequently place great reliance on this over-all test which enables appropriate preventive measures to be taken in the great majority of cases. Yet it is no more than a check and an ultimate precaution, intended merely to bear out the structural options we made. How did we go about making these choices?

The fundamental criterion in the choice of a light alloy was the resistance to creep. Figure 11 shows the good strength characteristics of the selected alloy (AU2GN, similar to your 2618) and why a very well-known alloy like AU4G1 (similar to 2021) had to be discarded in spite of all its qualities: good mechanical properties and imperviousness to stress corrosion, and the fact that it is an alloy which is now fully mastered in the industrial sense.

Our studies have since led us to set a limit of 0.1% on creep strain (Fig. 12). It should be noted also that cold-working reduces the creep strength of AU2GN, as shown in Table 7. All conventional sheet-metal forming had therefore to be ruled out on CONCORDE, which implied some revamping of our workshops. In fact the CONCORDE was instrumental in bringing about another change as well: it was partly responsible for the advances made in numerically-controlled machine-tools in Europe.

Figure 13 shows a 20-ft panel being machined by such methods, and Fig. 14 a frame web machined from the solid, where 335 lb are machined down to 25 lb.

Because it is designed for creep strength, the aircraft is over designed for creep/fatigue interaction at frequencies of under 20 cycles/hr approximately. This is schematized in Fig. 15.

Table 7 Effect of cold working on the creep strength of AU2GN

Condition	Drop in creep strength, %
Quenched and tempered	0
Quenched and stretched 1.5%, tempered	15
Quenched and stretched 6%, tempered	23
Quenched and stretched, tempered, stretched 1.5%	40

I should like to add that, from the fatigue standpoint, testing of large structural elements bore out the structural solutions we adopted, in addition to the choice of the alloy itself.

In short, we have developed satisfactory solutions with AU2GN for most of the airframe, though it also includes steel—mainly for the landing gear—and titanium. I should like to repeat here that to put the question "titanium or no titanium" is yet another misconception. Just what use is made of titanium depends primarily on the mission envisaged for the aircraft. I have already said that titanium was no doubt necessary at Mach 2.5, but not at Mach 2. I would add that even it is not necessary, its use can be justified all the same, though of course it would be introduced gradually. Subsonic aircraft use titanium. So far the CONCORDE has made scant use of it: about 1.5% of the structural weight on the production aircraft, whose definition is in the process of being frozen.

Yet in the prototype defined three years earlier, the figure was only 0.5%, and there can be no doubt that it will rise further still. For instance, we are studying the possibility of introducing titanium rivets instead of the present monel rivets. If it is adopted, this modification alone will raise the proportion of titanium by 0.5%. If a somewhat higher speed were envisaged for a second-generation CONCORDE, the leading edges could in turn be made of titanium. However, I shall not dwell on this any longer as there are a few more misconceptions I must dispel.

Improving Reliability and Safety

Although we now think this problem has been fully mastered, we must include it among what I have called the true problems. For, I must say, to have applied existing rules purely and simply would not have made any sense.

As I have already said, we are not building a powered buggy. Yet some of the things one reads or hears suggest that that is precisely the way the SST is thought of in some

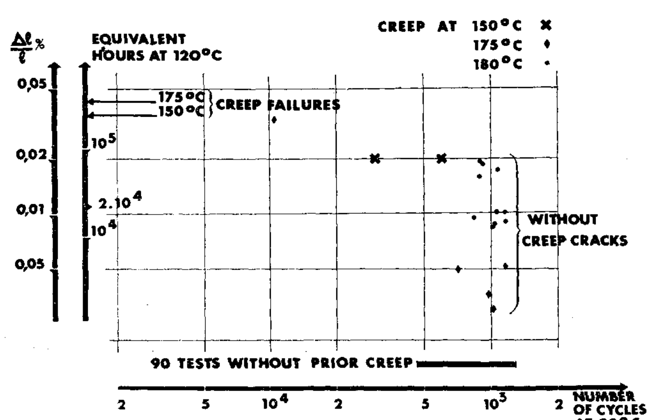

Fig. 12 Post-creep fatigue strength.

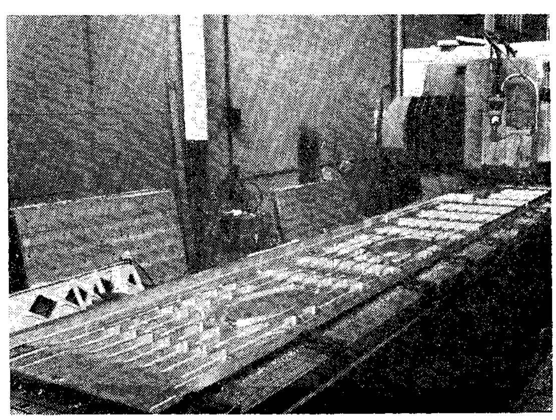

Fig. 13 Numerically controlled machining of an upper wing skin panel.

Table 8 Systems safety assessment of number of channels

		System 1 (EG powered flight controls)	System 2 (EG INS)
Data	MTBF	5000 hr	2000 hr
	Single failure probability in 1 hr	2.10^{-4}	5.10^{-4}
	Accident probability in the case of a total system failure	Approx. 1	10^{-5}
Accident probabilities	Simplex system	2.10^{-4}	5.10^{-9}
	Duplex system	4.10^{-8}	25.10^{-13}
	Triplex system	8.10^{-12}	125.10^{-17}
Preferred system		Triplex system 8.10^{-12}	Duplex system $2.5.10^{-12}$

quarters. In other words, these people talk as if the solutions used on current aircraft were adequate to resolve the problems of the supersonic transport. I must caution you against that notion.

The CONCORDE project and the rules which were drawn up for certification of the aircraft were reviewed concurrently in order to achieve enhanced safety and reliability. From the outset we set ourselves a goal, which emerges clearly from Fig. 16.

This graph, which is drawn from an ITA publication, gives a very clear idea of jet aircraft loss probabilities and the way they evolve. In the case of subsonic jets, it has dropped from an initial 1 in 100,000 hr to 1 in 400,000 hr operation—a figure that has been maintained for several years. With the CONCORDE, the objective we set ourselves was one loss in 10 million hr. We shall not succeed from the very start, but we do hope to achieve a curve of the kind shown, equalling from the start at least the current rate for subsonic aircraft, and ultimately tending toward the target rate.

At this point, I would like to stress a fact which stands out in the figure, namely that absolute safety is a pipe dream. What is more, to reduce the hazards as much as possible on specific items is not the proper course either, for the means at our disposal are limited, so that efforts must be directed with discernment, where they are going to be most effective. For instance, many people consider that, for the price and weight allowed for rafts on transoceanic flights, the aircraft could be equipped with more effective altimeter or anti-collision warning systems, for example. In other words, there can be no question of concentrating on, for example, the most reliable power flying control units or the most reliable powerplant without bothering about the rest. The aim is to have the safest and most reliable complete airplane with the means at one's disposal. The development effort should therefore be directed to the less reliable systems, with special emphasis on those affecting flight safety.

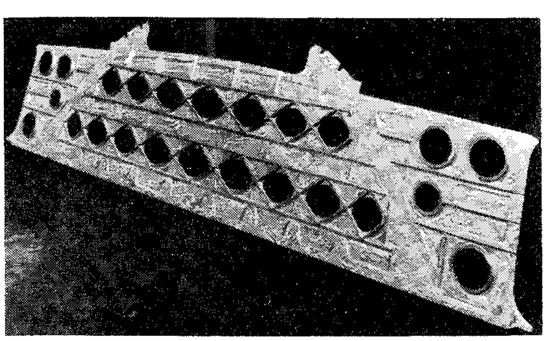

Fig. 14 Center web of frame 66.

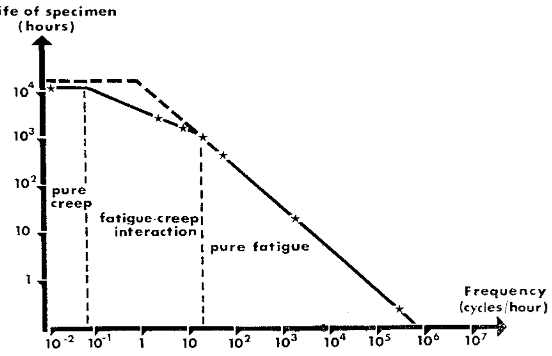

Fig. 15 Fatigue-creep interaction at 150°C.

How can this be done in practice? Well, given a set of circumstances, one must determine what snags could arise and what their probability and consequences are going to be. Relatively harmless consequences can be accepted with a fairly high frequency. Serious consequences must have a very low probability rating so as to remain consistent with a loss probability of less than 1 in 10 million hr. In practice it is difficult, and usually outright impossible, to evaluate probabilities of 10^{-8} with any accuracy. In point of fact, the double failure concept means that probabilities can be brought down to more manageable magnitudes: 10^{-3} or 10^{-4} per flight hour. Table 8 shows how.

Many systems have MTBFs of 1000–10,000 hr, and it is precisely these MTBFs which must be checked. Having done this and having approximately estimated the probability of a disastrous accident linked to a failure in the system being checked (e.g., 1 or 10^{-2} or 10^{-4}), calculation will show whether the system must be duplicated or triplicated. Naturally the calculations in Table 8 are highly simplified. But the figure does nevertheless illustrate my point well, namely that, despite its relatively low MTBF, system 2 does not substantially improve safety unless something is done about system 1. Assuming only those two systems existed on the aircraft, the step to be taken would be to improve the MTBF of system 1.

In actual fact, since we cannot achieve better than 10^{-9} or 10^{-10} on many systems, it is quite illusory to seek values beyond 10^{-11} or 10^{-12} on other systems, and any efforts along such lines will necessarily prove of no avail. It would be tantamount to digging valleys instead of cropping the peaks in order to avoid colliding with mountains. Yet there are people who still dig valleys. In my view, the increasing number and complexity of on-board systems, especially on SSTs, precludes this luxury.

In the case of the CONCORDE, the tests as a whole were conducted along these lines: to obtain a degree of safety consistent with our goal. In the case of certification too, the

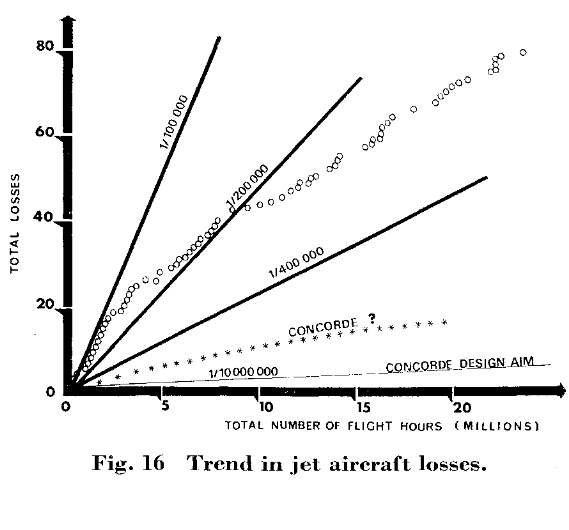

Fig. 16 Trend in jet aircraft losses.

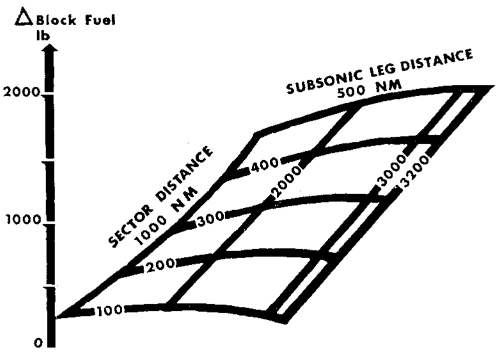

Fig. 17 Effect of subsonic leg during climb.

authorities laid down similar requirements. In fact, these requirements pose particularly tricky problems where flying qualities are concerned because these qualities are not easily quantified. The underlying principle, however, which is to concentrate equally on all items and not to be content with simply applying ready-made rules, remains the same.

There are two good illustrations of this: the choice of a safe initial climb speed V_3 and the problem of speed stability in transonic flight. On conventional aircraft V_3 is taken as 1.3 times the stalling speed. But delta wing aircraft like the CONCORDE have no stalling speed, which meant revising the concept of safety associated with the choice of V_3. Manifestly, the administration's routine process of reapplying the former rule was out of question in this case. After examination of the problem, the Anglo-French authorities decided to adopt a new datum speed, namely V_{ZRC} (zero rate of climb), and to impose, inter alia, the following requirements: 1) $V_3 > 1.25\ V_{ZRC}$, 2) V_3 permitting a normal acceleration of 1.6 g, and 3) V_3 enabling the aircraft to be controlled according to the criteria of TSS Standard 5, which I shall not go into here.

What is important is that these requirements collectively insure attainment of the required degree of safety, which was implicit in the former 30% margin over the stalling speed.

As to speed stability, of what use is it in the transonic phases since the aircraft is accelerating continuously? Of no use at all. The true aim here is to assure safety by reducing the crew's workload as far as possible during this phase. Yet static stability does not necessarily mean good handling qualities: the Spitfire is an excellent example of an unstable aircraft which was easy to fly. Moreover, to add more black boxes is to add more possible sources of failure, and if they serve no useful purpose then the level of safety is reduced. Only the flight tests can show what must be done. These examples show that the rules must be revised as soon as a change of any significance occurs. And this is what was done to make the CONCORDE a safe airplane.

Operational Problems

The first question is, must the SST bring an upheaval in air operations? In everything we did, at any rate, the primary concern was to insure that it should not. Admittedly, it is not possible to comply strictly with ICAO resolution A 14-7. A necessary exception, for instance, is flight through the subsonic levels at supersonic speeds. Thus, the CONCORDE initiates transonic acceleration at 25,000 ft and reaches 42,000 ft at Mach 1.6 after covering 120 naut miles in 10 min. Clearly, this flight phase is not exactly compatible with subsonic aircraft in that traffic lane, particularly if the supersonic jets are to be fed into the lane at 10-min intervals.

The SSTs have their compensations, however. A delta wing aircraft will accept a level flight leg at around Mach 0.9 against a slight increase in block consumption [about 300 lb for 100 naut miles in the case of the CONCORDE (Fig. 17)]. We are convinced that this characteristic will allow traffic compatibility problems to be resolved at best.

As for the rest, we have abided by the ICAO's recommendations concerning safety, ground facilities used in common with the subsonic aircraft (especially aerodromes), a minimum of special services, a noise level not exceeding that of subsonic aircraft, and compatibility with the all-round economics of the subsonic services. Yet rumors of all kinds, often ill-founded, concerning the operational problems of SSTs keep cropping up periodically not to say continuously. Let us take stock of the situation.

In the first place, in contrast to what generally happens in the case of technical problems, the solutions, here, are beyond the constructor's control. He is confined within a frame-work imposed by rules and recommendations, by common usage, and by what constitutes the ultimate operational criterion, namely optimal operation. Moreover, this framework varies with time.

A case in point is the noise problem. In view of the performance penalty, the natural tendency would be to accept a high noise level for the SST. But because we did not wish ours to be the noisiest, the limit we stipulated for the CONCORDE is based on the figures already recorded with other aircraft (Fig. 18).

In the meantime, more restrictive regulations on noise control have been formulated. Of course, the noise problem is undoubtedly a true problem, but it is an altogether different matter for the manufacturer if the requirements are laid down after the design has been defined instead of before. Ten years are needed to create a really new airplane, and to modify its fundamental characteristics during the latter years requires acrobatic feats that are better avoided.

As regards the noise problem in the case of the CONCORDE, Fig. 18 shows you that we are keeping to our objectives, namely to remain substantially within the envelope of existing aircraft, with a slight increase in side-line noise that is offset by an improvement in overflying and approach noise levels. But we would consider it abnormal to apply requirements set forth 3 or 4 yr after the airworthiness certificate had been applied for, provided of course that safety was not involved. And the same applies to all manufacturers. By the same token, the time needed to adapt the ground facilities must be counted in years, and we know that whatever needs new aircraft may have must be stated fairly early. In this connection, one cannot over emphasize the importance of the working group on SSTs set up by the ICAO. The scheme could be generalized, and the coordinated planning concept recently propounded by the ICAO, which seems excellent to us, could be implemented through those channels. All we ask is that the motto should be "evolution," not "revolution." Additional time limits or sufficient advance notification would save much unnecessary effort and insure that problems are dealt with correctly.

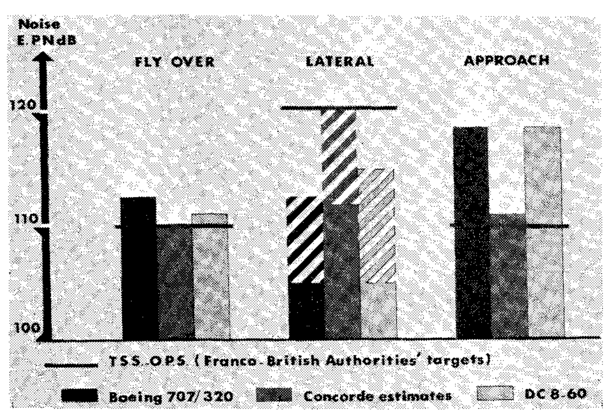

Fig. 18 Community noise comparison (ISA sea level).

Or, at any rate, most of them, for there is one exception to the rule. I refer to the sonic boom, about which reliable information will not become available until very late.

At the moment we know that the general public is usually up in arms if it is exposed to sonic booms producing overpressures of 10–20 psf, but that it does not seem to be put out even if it is exposed daily to a few bangs of about 2 psf level. SSTs will produce overpressures in the order of 2 psf. And knowing that overpressure is not the only factor which governs the effects of sonic boom, what must the conclusion be? Frankly, we are surprised to find some people being quite emphatic already.

Anyway, with a little patience we shall all be in a position to judge from factual evidence. Suffice it to say at this stage that studies like the joint NASA-FAA study, which seek to place the focusing zones in predetermined areas where they will be the least nuisance, seem to us of great interest. For as Fig. 19 shows, the limit could well lie within this zone, at any rate from the overpressure standpoint. But we are seeking to minimize focusing effect by selection of an appropriate climb and acceleration profile.

Fortunately, the other problems are easier to grasp if not to actually solve. Let us begin by disposing of 2 misconceptions concerning ozone and radiation. Ozone is almost completely dissociated at the temperatures encountered in the air-conditioning circuit, and it is quite simple to install additional means if necessary. As for radiation, it could be dangerous anywhere between twice and twenty times in an 11-yr solar cycle, depending on estimates. During these very rare emergencies, the SST would descend to a safe level, which would of course have to be higher than the level used by subsonic aircraft, since flight times are shorter. Or could it be that subsonic planes have a problem which has been completely neglected so far. . . ?

Let us eliminate another problem which, though a very real one, is not peculiar to the SST: that of transporting the passengers from the aircraft to the center of the city. Figure 20 shows why the supersonic passenger will be more sensitive to loss of time. In any case, any gains made here will be beneficial to all. A reasonable target would be for the times involved here not to exceed half the block time.

We are then left with the problems connected with accomplishment of the mission: waiting for the departure, the strict observance of timetables, air traffic control in the departure zone, choice of the route and separation in cruise flight, air traffic control in the arrival zone, holdings, diversions and the determination of reserves.

I cannot dwell here at length on all these problems, which have yet to be cleared up. I should merely like to make a few points which relate to them in varying degrees, for a few serious and interesting indications are beginning to emerge from studies which have been undertaken. 1) The SST is far less sensitive to weather conditions than subsonic aircraft. This means that it can be allocated a set geographical route without being penalized, namely the great circle path between the point of exit from the departure zone and the point of entry into the arrival zone. This also means that there is far less uncertainty about en route consumption than with subsonic aircraft. The same safety level can be maintained with a lower percentage of reserves to cover the route. Some airlines have estimated 3% of block-fuel to be the really useful figure, i.e., for covering 98–99% of contingencies without encroaching on the other reserves. If you compare this figure with those put forward in the draft regulations—which contemplate plate as much as 7%—you will understand why I was talking about excessive conservatism just now. 2) Cruise climb is an interesting proposition economically and could have proved a source of difficulty for intersections. But a geographically fixed network of routes considerably simplifies the problem of intersections, and solutions compatible with cruise climb are being studied. 3) As for the question of separation, it is now an established fact based on millions of flight hours that separations in cruise flight are extremely safe. There was still some hesitation about reducing them; however, new techniques, and inertial navigation in particular, should bring about this reduction. But a fundamental parameter in inertial navigation is the duration of the flight. Hence, because of the shorter flight times, SSTs will enjoy even more accurate navigation than subsonic aircraft. In point of fact, the NATSPG's experts and we manufacturers have reached the same conclusion, namely that lateral separation for SSTs can certainly be 60 NM, possibly less. 4) In suggesting that uniformity in the matter of safety is a must, I shall be restating a concept already put forward here. Now, the terminal areas of large airports are far less safe than the international routes. Consequently, that is where efforts must be concentrated. In addition, congestion of these zones is a cause of considerable financial losses for the operators. And the problem will become even more acute for supersonic transports because the flight-hour costs more in their case. It is well known and the calculations presented at the IATA conference in Lucerne, for example, have borne this out that the margin between complete saturation and roughly normal traffic flow (with, say, an average holding time of a few minutes) is no more than 20%. It must be agreed to spread traffic so as to limit it to 20% below saturation and thus, preserve normal operating conditions. This does not prevent progress by any means: if new methods can set back the saturation point, traffic can become denser, but in our view air transport is not sufficiently organized. The irrational situation existing in today's Air Transport is unique, and cannot be found in any other organized transport system. There is much left to be done in this area for the benefit of all concerned. 5) In the case of the SST, gains will be more substantial, as shown in Table 9. It has been suggested in some quarters that priority be granted to the supersonic jets. In our view, an all embracing solution would be by far preferable, and at the same time it would alleviate the problem of reserves, which we manufacturers cannot resolve. In spite of our efforts to improve their performance in subsonic flight, SSTs will have reserves representing over 20% of their block fuel.

As for the unfortunate passenger, the less said the better. I have personally already done Montreal–New York in

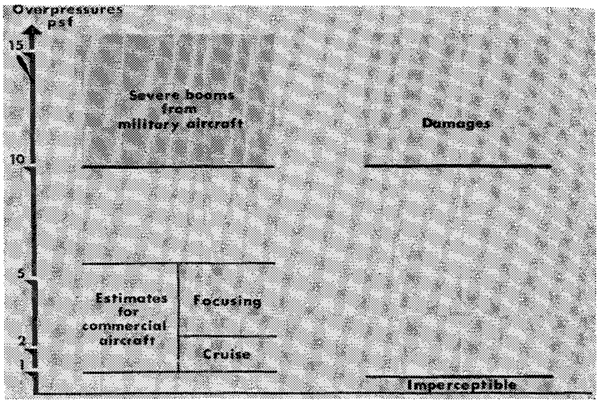

Fig. 19 Sonic boom.

Table 9 Protracted hold fuel penalty

		Boeing 707	Concorde
30-min hold at 10,000 ft 200 kt	lb fuel	6000	15,500
	% block fuel	5%	10%
30-min hold at 10,000 ft 300 kt	lb fuel		10,200
	% block fuel		6.5%

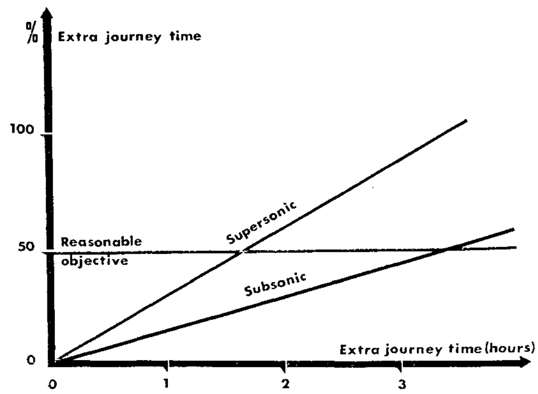

Fig. 20 Effect of extra journey time (transatlantic journey).

3 hr and 45 min, i.e., at a block speed of 80 mph, on an aircraft which was supposed to fly at 500 mph.

Conclusion

What must we conclude from this review of the SST's problems? In the first place, much still remains to be done by the aircraft constructors. Our task is all the more fascinating because we are very far from having solved all our problems. And in any event, the era of supersonic aviation is close at hand. As I have said, our current difficulties are precisely those in which we also place greatest hope: if a loss of 1% fuel consumption means a 5% loss in payload, then a 1% gain on fuel consumption must mean a 5% gain in payload.

About the progress of aircraft, I gladly note, which my presence here today shows once more, the atmosphere of cooperation existing in the western world. And I wish to convey my thanks to the U.S. industry for its contribution to the CONCORDE effort. The collaboration between the United States and Europe is already widespread in the field of engines and equipment; I hope it will soon extend to the aircraft as well.

But it is not enough to keep building more advanced aircraft. Ground facilities, and airports in particular, must also keep pace. There can be no question of accepting as permanent the holding constraints currently being imposed on aircraft at certain airports.

This is no easy problem, as we are well aware, but it must absolutely be solved at all costs. We find it difficult not to compare the stringency of the noise level reduction projects with the looseness of many of the projects for dealing with ground facilities and air traffic control. The former are too severe, the latter not sufficiently so.

My personal conviction is that neither of these problems can be resolved by a stroke of magic—no more the noise problem than the congestion problem. Both are going to require patient effort and a start has been made by all concerned. What are needed simply are directives and reasonable time limits. The trait specific to SSTs in both cases is their marked sensitivity, which heightens the disadvantages of whatever constraints are imposed.

However, I feel confident that the efforts of aircraft manufacturers and the authorities will converge toward reasonable compromises that will result in a gradual improvement of the present situation, yet remain compatible with potential technical advances.

And while we hesitate to become involved in problems which either simply do not exist or have been incorrectly stated, we are ready to cooperate to the best of our ability to solve the two problems I just mentioned, or any real problem for that matter.

In the last few years, the misconceptions entertained about the SST have often been highlighted at the expense of its true problems. I thank you for the opportunity you offered me to review all these problems, and to express my confidence in the brilliant future of supersonic transport.