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QUIETER AERO ENGINES - CAUSE AND EFFECT

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BACKGROUND

The growth of the air transportation industry has brought with it many benefits to nations and the individual. The business and holiday centres of the world are now but a few hours journey time from many suburban homes, and an increasing number of people are taking regular advantage of air travel. They are however, along with the many who never go further than posting an air mail letter, paying an increasing price for air services in the social inconvenience they must tolerate.

There is always a point where tolerance breaks down. In the case of aircraft noise that point was probably reached in the early 1960's, although it was not until comparatively recently that the buffer between the private citizen and government action was overcome and responsible authorities began to control the problem by legislation. Up to 1969, when the USA introduced the first Noise Certification scheme, the problem had been kept at bay only by a combination of modest restrictions and good public relations. In the UK aircraft noise was, in fact, recognised as a potential problem in 1920 when Winston Churchill denied the individual the common law right of action against the nuisance in the interests of an expanding civil aviation industry. Nevertheless, it did not become a serious problem until the introduction of the first commercial jet aircraft in 1958, when, faced with a possible operational ban at Idlewild (Kennedy) airport in New York and subsequently London's Heathrow, the industry was forced to act. With the imposition of noise limits at these two major airports the early pure jets were moderately quietened by the parasitic segmentation of the gas efflux system. The combined effect of such "jet silencers" and a noise abatement throttling technique after take-off temporarily bridged the gap between a go or no-go situation. However, this action did little more than to delay the full impact of the problem, for, as fig 1 illustrates, within a period of four years over twenty new types of jet were introduced into service, many of which were considerably noisier than the original Comet 4 and 707-100's.

During this period a Royal Commission was set up, headed by Sir Alan Wilson,[1] with the object of examining the growing problem of noise in all sectors of the community. Their judgement on the aircraft noise problem was that there would have to be a steady reduction in aircraft noise levels merely to offset the potential increase in traffic. A suggested figure was 7 PNdB reduction by 1970, or 1 PNdB per year, a rate of reduction which fig 1 indicates as generally achieved. Clearly however, it has been insufficient to contain the problem.

A relationship between number of operations and absolute noise level was developed at the time the Wilson Committee sat, known as the Noise and Number Index (NNI). A figure on this index often referred to as the boundary of acceptability is 35 NNI, and if we examine the growth of the area within this contour around Heathrow a more representative measure of the true growth of annoyance is obtained. This is shown in fig 2,[2] and is a very good indication of why the climate changed in the mid 1960's and governments began to take positive action on a broad front.

In fact the first real step came in the USA in 1965, when the President's Science Advisor conducted a seminar of Government and Industry noise experts, to develop an action programme to reduce noise exposure. As a result of this, early in 1966, the President directed that the Federal Aviation Agency should take positive action. An "aircraft noise alleviation programme" was developed resulting in the establishment of Government Committees to provide policy guidance, advise industry and recommend actions. On September 1st 1966, the Associate Administrator for Development of the FAA, Joseph D. Blatt, wrote a key letter to the aviation industry informing them that the FAA had submitted draft legislation to amend the Federal Aviation Act of 1958 to provide specific authority to regulate in the area of aircraft noise. The "Blatt letter" also addressed the question of establishing a basic descriptive unit that would be used in formal noise certification processes. At that time the most commonly used unit was the Perceived Noise deciBel (PNdB), but the Society of Automotive Engineers Noise Committee had begun to develop the Effective PNdB to take account of both duration and discrete noise content.

In November 1966, the UK convened an International Noise Conference, at which the delegates concurred with the concept of noise certification and also with the concept of a new descriptive unit. In consequence similar action to that undertaken by the FAA in the USA became the responsibility of the UK Board of Trade. The UK and the USA developed their own ideas along similar lines, and a Tripartite series of discussions, involving France, was instituted with the idea of bringing together certification requirements into an internationally agreed form. Ultimately this activity led to the ICAO setting up a special committee to deal with aircraft noise (CAN) and thence to several novel pieces of legislation. Late in 1969 the Federal Aviation Register was amended and Part 36[(3)] was born, followed rapidly by an ICAO Annexe 16[(4)] to the Chicago Convention, which was adopted in the UK as an Air Navigation Order. All these regulations define the maximum noise levels that any new type of aircraft is permitted to make if it is to enter commercial airline service. The regulations, in fact, define maximum levels at three significant community positions, one to the side of the aircraft flight track on take off and one beneath both the take off and approach flight tracks (fig.3).

Against the background of the moves towards noise certification, the airlines in Europe and the USA were examining several major new commercial airplane projects, and the associated engine manufacturers had for the first time to specify accurately to airframe manufacturers and potential customers noise levels which would ultimately satisfy certification requirements. Since such requirements had not been fully developed at that time the problems were diverse, for not only were the new engine proposals radically different from their predecessors, but there was a strong competitive situation with Douglas and Lockheed in the USA and the European Consortium requiring engines for their new aircraft, and Rolls-Royce, General Electric and Pratt & Whitney all offering solutions. Whilst there was a natural tendency to err on the side of caution when considering the possible noise legislation aspects, nobody wished to detract from the performance of his engine and be seen as uncompetitive.

The requirements for these aircraft, all around 400,000 lbs AUW, led to the development of the RB 211 from a family of engines being considered at the time. In the form finally selected for the Tristar this engine evolved as a 5:1 bypass ratio single stage turbofan rated at over 40,000 lb static thrust, with noise level requirements judged at around 10 PNdB below the noise of the then current large aircraft, the 707, DC8 and VC 10.

STATUS

We have learnt many lessons about engine noise as a result of the activity this vast new engine project generated, and the country has benefited by the construction of several significant new noise facilities, a number of which have been built with heavy Government investment. It is worth noting that up to the time the RB 211 was conceived, noise research in this country had been confined almost exclusively to work on existing engines on open air test beds, or even less reliable measurements induct on aerodynamic rigs. The subsequent years have been the introduction of specific major facilities directed at researching each noise producing component of the engine. The Ansty fan and compressor noise facility was the first of these in 1967 and the culmination has been the construction of a major flow duct for acoustic liner work, which has just entered service at NGTE[5], and a hot turbine and jet Anechoic facility due to be opened on the same site later this year.

It is worth looking fairly closely at the RB 211 programme to understand the problems created, the lessons learnt and the questions that it has promoted.

The layout of the RB 211 is illustrated in figure 4. It is compared, for reference, with the layouts of its fore-runners, the pure turbo-jet and the by-pass engine. The,most obvious difference is the amount of total airflow used in the gas producing process. In the pure jet all the air is compressed, mixed with fuel, burnt and expelled through a single propulsive nozzle. In the bypass engine up to 50% of the flow is ducted around the gas producing core. In the RB 211 over 80% of the air flow bypasses the core, where energy is generated to enable the turbines to drive the fan and the compressor systems. This cycle requires a far greater total airflow to achieve the same thrust than its earlier counterparts, and basic benefits are felt in the reduced jet noise from the much lower velocity jet exit conditions.

However, reduced exit velocities do not in themselves ensure reduced overall powerplant noise for, as figure 5 illustrates, the increased dimensions and work involved in the rotating machinery shows attendant increases in fan, compressor and turbine noise. In fact, if specific design action were not undertaken to reduce these sources, the turbo-fan would be no quieter than a low by-pass engine, a fact which is well illustrated by the JT3D engine in many 707's and DC 8's, and to a certain extent by the early JT9D powerplants in the Boeing 747's. Nevertheless, since the turbomachinery noise sources are generated within the engine, unlike the jet component, they are far more amenable to noise controlling techniques, and herein lies the reason why the RB 211, as a prominent example, is much quieter than older types of engine.

To understand the situation it is necessary to look at each noise source in turn.

FAN AND COMPRESSOR NOISE

Prior to the specification of the RB 211 type of engine we reviewed all fan and compressor research and development evidence in an attempt to develop a meaningful correlation [(6)]. In this work we recognised the existence of two fundamentally different characters of noise generated by a turbomachine, i.e. the discrete (blade passing tones) and the more broadly distributed background level, often referred to as vortex, random or sometimes erroneuously as white noise. The correlations developed highlighted the dependence of the intensity of the noise on the air flow velocity over the blades and the incidence of the flow relative to these blades. Other contributory parameters were the number of component stages and the spacing between the blades of each rotating and stationary stage. Moreover, theory suggested, and certain isolated aerofoil experiments confirmed, that there was a distinct dependence on the more detailed aerodynamic environment of each component stage in the turbomachine, and questions were also posed as to the intensity of generation of discrete noise at supersonic blade speeds, including the possible degeneration into multiple shaft order tones (buzz-saw noise).

At a fairly early stage in the programme it became clear that test evidence was required on a large scale high tip speed single stage fan, since the available information did not extend to supersonic conditions. Tests were therefore undertaken on an existing 5 ft diameter aft fan, designed to run behind an Avon engine, which was reworked to run well beyond its design speed. The aft fan tests were essential to the understanding of the basic noise from the type of fan being proposed for the RB 211. The results of these tests confirmed the dependence of broad band noise on the turbulence entering the fan, and hence defined as a prime requirement that the air flow approaching an RB 211 fan should be aerodynamically clean. Moreover it was considered essential that the fan should be a single stage device to avoid subsequent stages being the dominant noise source, by virtue of the disturbances created upstream in the primary stage.

A correlation had been developed at the same time for rotor/stator interaction noise, and the aft fan confirmed the laws developed for the higher tipspeeds. However, the aft fan was misleading in that there was no undue increase in discrete tone in supersonic tip speed, and there was only a mild development of buzz saw tones. We are still puzzled by this result, for the RB 211 did ultimately produce a buzz-saw signal which we must learn to control in future designs.

The design criteria for the RB 211 were therefore very much the same as for any other compressor. Having eliminated the concept of inlet guide vanes or bearing support struts ahead of the fan, and defined clean airflow conditions from the air inlet as essential, the maximum spacing between the fan blades and the OGV's was provided for, consistent with aerodynamic and structural considerations, and the blade and OGV numbers were chosen appropriate to theoretical generation and propagation criteria for fundamental tone elimination.

As regards the IP compressor, similar considerations lead to the conclusion that discrete tones at low engine speeds were likely to be the only problem, and design action was taken to keep these to a minimum.

Having defined the acoustic standard for the RB 211, we were anxious to see how the engine behaved in practice. However the first three shaft high bypass single engine to run was not in fact the RB 211, but the RB 203 Trent engine selected for the Fairchild Hiller F 228, an aircraft which in the event did not enter production. The measurements from this engine implanted considerable confidence in the levels predicted for the RB 211, with one exception. This resulted from the somewhat higher noise levels measured forwards of the engine than had been anticipated, but fortunately not sufficiently high to warrant consideration of any immediate special action on the RB 211, such as inlet supressors.

The first noise measurements on an RB 211 were made in November 1968. The standard of engine was different to the final production standard RB 211-22 engine for the Tristar, in that the preproduction engines had been released early for development purposes, with minor differences in powerplant design. The main difference was that it was a short duct engine, with the external gearbox on the core of the engine rather than outside the fan cowl, and this meant that there was a sharp "S" bend around the gearbox. The interservices pylon across the fan duct to the core of the engine also differed from the design for the Tristar, and it was necessary to mock up the cowl configuration to represent the production configuration for the early part of the development programme.

The early runs of the preproduction engine posed several important questions. Fig.6 summarises the peak PNL values measured forwards and rearwards from the unsuppressed engine, and also indicates our target levels set by consideration of the likely FAA certification requirements. (These targets were somewhat conservative in that no allowance was made for known static to flight changes in noise generation, or for overground propagation and reflection effects). The first point which caused concern was the high noise level forwards of the fan, which was only partially anticipated by the Trent results. At the approach condition in particular this level was very little below the rearwards noise, whereas the basic engine estimates had indicated that it would be at least 5 PNdB less. Moreover the levels of both forwards and rearwards components at this condition were somewhat higher than had been anticipated in specifying a standard of suppression to achieve the target levels. The difference between these early results and the target levels was the order of 10 PNdB rearwards, and 8 PNdB forwards. It was anticipated that the defined suppression kit would reduce the rearwards levels by a minimum of 5 PNdB and hence we were faced with the unforeseen situation where the engine was likely to be forwards noise dominated. Spectral analysis showed the increase to be due solely to the fan noise, and this mainly by virtue of a high rotor discrete tone level, although there was some increase in the broad band noise.

Although the rearwards noise was also higher than anticipated at higher thrusts, there seemed to be less reason for concern in that the level was only some 5 PNdB above the target and the acoustic kit had been designed to accommodate this margin. Moreover at full power, appropriate to the sideline condition, the target set had not accounted for overground or shielding effects, or for the jet noise reductions that would occur under forward speed conditions.

Clearly however, the situation, particularly at the lower thrust conditions, had to be fully understood and if necessary design changes specified early in the programme.

Two courses of action were therefore undertaken. Firstly it was considered prudent to specify an inlet liner for the powerplant, as an insurance against the final production standard engine revealing levels as high as those on the preproduction standard. This action was also considered an appropriate way to reduce the buzz component that had appeared at supersonic blade velocities. This phenomenon was not sufficiently important to contribute significantly to the Perceived Noise Level, but it was considered a likely irritant to passengers and communities, and a possible source of acoustic fatigue in the pod and centre engine inlets.

Secondly a research and development exercise was undertaken directed at a full understanding of the reasons why the fan noise was higher than anticipated, and to making any appropriate design recommendations. This work involved a study of the aerodynamics and acoustics of the fan over its whole operating range, and close investigation of the differences between the preproduction and final powerplant standard. Furthermore a 0.4 scale model of the fan was provided for research work in the Ansty fan noise facility.

After a detailed study of available noise and performance data several factors were pointed to as fairly positive reasons for increases in noise level. Some of them bear examination as an illustration of the intriguing nature of the noise business and the improvement afforded by close attention to detail.

(i) Influence of Inflow Aerodynamics

The RB 211 fan had been designed to promote cut-off of the fundamental tone by selection of blade and outlet guide vane numbers. It was therefore surprising that the static test bed results did not reflect success in this area, there being a dominant tone at almost all power settings. Moreover the early tests revealed that this tone, and its harmonics, varied according to the type of air intake used. Three intakes were most frequently used, a conventional test bed flare, an airmeter section and a flight type pod. It was also noted that the tones generated were markedly unsteady with time, often varying by 10 dB or more, and even affected by local wind direction. These were effects that were not understood, and since they were having a significant influence on tone generation they warranted close investigation.

Two main lines of thought were pursued. Firstly there was the possibility that the presence of a strong ground vortex, often visible under favourable humidity conditions, was sufficient to distort the flow in the intake in a random manner so as to generate an unsteady tone. Therefore tests were undertaken on the engine, and on a research fan at Ansty, with a deliberately induced vortex, and vortex diffusers, but the results were inconclusive in that little effect could be deduced. The matter was taken no further in the light of other revealing work. This work revolved around a critical examination of the quality of the air flow at the fan face, with particular emphasis on the differences that occur between the static test bed case and the ultimate all important case of flight operation.

Consistent with common practice at that time, the three relevant intakes were designed with performance conditions in mind and not from an acoustic standpoint. Two were designed for static test bed running whilst the third was designed for the wing engines on the Tristar. However, a study of the boundary layer conditions behind the various intakes showed that the calculated thickness and unsteady circumferential distortions were quite different in each case, and moreover none of the static cases represented the conditions likely in flight. It was concluded that the flow conditions most likely to produce an unsteady distortion interaction tone with the fan, and high broad band levels, were present under all ground running conditions, but that this situation would not prevail in flight. It was therefore essential to obtain quantitative information that would throw light on the differences between the test bed and the airplane, and several important experiments were undertaken.

The first involved simulating flow ahead of the engine by using an existing propeller powered blower, normally used for cross wind performance testing. These tests indicated a reduction in fan noise from the engine with a fairly low flow velocity. However the more significant tests involved the RB 211 flying test bed, a VC 10 aircraft with the two port side Conway engines removed to house a single L 1011 pod installation (fig 7). We had not expected this vehicle to provide any useful RB 211 noise information, due to the presence of the noisier Conways, but in the event it has proved invaluable in our studies of tone generation.

The first experiment was a simple taxying test. Having taken measurements around the engine with the aircraft parked on its brakes, several passes along the runway under RB 211 power alone were recorded, and these all indicated reduced discrete tone levels. However, the magnitude of the reduction could not be specified accurately due to problems of the wing interfering with the noise pattern. The most detailed piece of information came from microphones installed in the inlet of the engine to monitor changes under varying engine and aircraft speed conditions during the flight programme.[11] The results were so informative that the installation was later extended to incorporate microphones on the trailing edge of the wing, giving good angular coverage ahead of the fan in comparative free field conditions. Sample results from the microphone in the engine intake are shown in figs 8 and 9.

The comparative traces in fig 8 show the fundamental blade passing tone time history under subsonic blade speed conditions. The two upper traces represent the static case and a flight speed of 150 knots. The different characteristics and levels from the two traces are remarkably informative, revealing that the unsteady distortion tone generated statically is reduced to comparative insignificance in flight as the flow becomes steadier and the boundary layer thickness reduces. This "cleaning up" phemonenon is perhaps best illustrated by the variation of the blade passing tone character at full speed during a take off. The lower trace exhibits an unsteady character at the start of the ground roll which gradually diminishes, so that at speeds above 60 knots there is almost no variation with time, other than the changes in level promoted by incidence variations at rotation and during the early climb.

The other significant feature that these tests revealed was that the design action taken to promote cut off of the fundamental interaction between the fan blades and the bypass outlet guide vanes was completely successful. The two spectra in fig 9 show a range of frequencies covering the fundamental and its early harmonics under static and flight conditions, with a notable reduction of the fundamental in flight. The harmonics are hardly affected. The fact that there is still any indication of a fundamental tone under flight conditions is due to the interaction with the core compressor, not the bypass guide vanes, and it has in fact been eliminated in the production engines by virtue of increased spacing.

The message from these tests is clear, in that static results are often governed by an interaction between the unsteady distortion in the inlet and the rotor blades, which is not present with a well designed intake in flight. It is essential therefore that future static tests are made compatible with flight aerodynamic conditions, or they will be most misleading. This is a problem that we are actively working on in our current research and advanced developed programmes.

(ii) Effect of Blade Incidence

The fan blades used in early development testing of the RB 211 were manufactured from a carbon fibre material. Due to the experimental nature of this material its properties were not fully understood at the start of the development programme, and the degree of untwist during running load conditions was found to be greater than anticipated. In fact the early tests showed a design point untwist about 3° greater than calculated, and a second series of tests were undertaken with a simple 3° change in blade orientation obtained by skewing the root fixing. The noise changes so induced were remarkable. As fig 10 shows there was an average reduction of over 5dB in the broad band level when the incidence was corrected. This was by no means the first indication of changes of this order, as our earlier correlations [6] had highlighted incidence as being an important parameter. We have nevertheless vigourously pursued the question in our research programmes, and of course verified that the production RB 211 has optimum incidence.

(iii) Effect of Duct Obstructions

There are two main obstructions to flow in the bypass duct of the RB 211. Both are present by necessity. The largest is the pylon extension across the top of the bypass duct. This carries the significant offtake services, whilst the second is the gearbox drive fairing at the bottom of the duct. On the preproduction engine, which provided our early noise information, the pylon was considerably thicker than that now in service. We were concerned that the pylon would produce a severe upstream pressure field which would interact with the fan to produce a discrete tone, and therefore conducted an exercise on a model research fan to examine the effect of pylon shape. Two of the tests reproduced the pylon shapes in the early and the production engines, and completely justified the effort expended in ensuring that the production standard presented minimum disturbance to the bypass flow. The noise impact is highlighted in fig 11, where the two pylon shapes are compared with the datum rig. The datum is a completely over-hung fan with no bypass duct discontinuity, a configuration impossible to reproduce in a practical engine. Clearly the whole spectrum level above 3,000 Hz (500 Hz on the full scale engine) is influenced by the pylon, with the production design being 10 dB quieter than the early design, and not very much noisier than the "perfect" datum case.

TURBINE NOISE

We had long recognised the significance of turbine noise in commercial pure jet and low bypass ratio transport engines, and therefore the turbine was an area highlighted in the design stage of the RB 211. Correlations [7] similar to those produced for fan and compressor noise were being developed from work on engines and a newly commissioned special turbine noise facility, but since the industry doubted the relevance of turbine noise, a specific demonstration was undertaken, using a Conway of the type in service in the VC 10 aircraft. These tests involved the alternate screening of rearwards propagated compressor noise and suppression of turbine and hot jet noise. This was achieved by the provision of a two stream nozzle system, as opposed to the normal mixed single stream of a production engine. Fig 12 illustrates some of the findings based on noise measurements taken at the peak noise position to the rear of the engine. The upper trace represents a spectral analysis of the total noise from the engine, and discrete tones from both the compressor and the turbines are clearly evident, but from this trace alone it is not clear exactly where the turbine and compressor broad band noise components lie. Fitted with an extended hot stream pipe, which ducted the exhaust gas to the jet muffler, measurements were again taken at the same point in the noise field, and the results obtained are shown by the lower trace in the figure. At the low frequency end of the spectrum the jet noise component from the hot stream mixing with the outside air has been eliminated and there is a subsequent reduction in jet noise. However, the significant change to the original spectrum is a reduction of the turbine discrete tones and broad band component which comprise most of the noise above 5,000 cycles per second.

Because the fan and turbine system in the RB 211 are larger than in the Conway, it can be easily understood why it was considered important to adequately suppress the turbine component. It was calculated that the turbine noise would appear at around one half of the frequency at which it appeared on the Conway engine, thus pushing the frequencies into the critical part of the audible range. Close attention was therefore paid to the spacing between the rotating and stationary members of the turbine, and to the velocity distribution over the latter stages of the turbine.

At an early stage in the development programme it was necessary to confirm that the level of turbine noise, predicted in the project stage to be significant enough to demand the provision of turbine liners, manifests itself at the critical operational conditions. However, the somewhat high level of fan noise on the preliminary engine prevented definitive tests before a production engine became available. Nevertheless in preparation for the availability of an appropriate engine, a special muffler was constructed consisting of a short jet pipe with an axial splitter arrangement, designed to virtually eliminate turbine noise. This was eventually run using an engine with full fan duct suppression and progressively increasing amounts of turbine lining. The results, illustrated in figure 13, show that the turbine component has a significant impact on the overall rear quadrant noise, even under static conditions, particularly at the lower engine powers applicable to approach conditions. This result was a clear justification for the liners specified for the airplane powerplant, for with fan noise reducing in flight the turbine component would assume even greater significance.

ACOUSTIC LININGS AND POWERPLANT CONFIGURATION

Because the basic design of the RB 211 lowered the jet noise well below the turbomachinery sources, it was possible for the first time for us to consider internal acoustic absorption as an integral part of the solution to the noise problem on a commercial jet engine. It was estimated at the conceptual stages of the engine programme that acoustic linings would be required to reduce the rearwards radiated engine noise by about 5 PNdB in order to meet the most stringent certification case, that related to approach to land. To achieve this amount of suppression it was necessary to prescribe linings for both the fan and turbine ducts, but, for reasons already discussed, it was not considered necessary to incorporate acoustic linings into the fan inlet. However, it was essential that the inlet configuration did not adversely influence the basic noise produced by the fan, and therefore such concepts as blow-in doors were rejected on the basis that this would introduce flow disturbances in the same manner as inlet guide vanes, which had already been rejected in the main engine design.

With a suppression target of 5 PNdB in mind a study was undertaken to establish the most effective way in which the powerplant design should be directed in order to achieve this figure consistent with minimum drag, minimum SFC change, and minimum cost and weight penalties. Three configurations were considered, varying from a short fan duct with radial and circumferential acoustic splitters, through an intermediate length cowl to the extreme, a full length cowl with coplanar exit nozzles [8]. After an exhaustive trade-off study it was decided that the medium length cowl configuration best suited the requirements of the Tristar airplane, and that both fan and turbine ducts would require acoustic treatment to their inner and outer walls.

Once the RB 211 engine had been selected by Lockheed for the Tristar a co-ordinated programmebbetween the two companies was initiated to develop the most effective absorber configuration, based on the intermediate length duct and to develop the materials and structures to be built into this cowl. Up to that point both companies had been involved in independent research programmes, both of which showed a preference for a fibrous based laminar absorber giving good broad band insertion loss characteristics, the optimum means of producing the required attenuation. The initial specification therefore provided for fibrous absorbers throughout the bypass and turbine duct, and weight saving was achieved by the use of plastics in the area of the engine where temperatures were low. Whilst a mechanical development programme was carried through to the point where an accurate specification of the materials was possible, the concurrent acoustic programme showed that the fibrous face-sheets could be replaced by perforated plate, with considerable mechanical advantages and reduced problems of contamination. Therefore, at an appropriate point in the programme the specification was altered to provide for an all perforate standard of acoustic kit for the Tristar engines (fig. 14). As discussed, by that time it was also considered necessary to provide an element of forward noise suppression by lining part of the intake walls.

Despite the drawbacks of the preliminary standard engine it was decided to use it as a vehicle for the acoustic absorber development programme, in conjunction with the test work being done on the flow duct facilities at Rolls-Royce and Lockheed. A slightly shorter than full scale mock-up of the production standard duct was designed to attach to the short fan duct, and this was tested firstly in a definitive hard wall state, and then containing a series of development suppression liners. These included both metallic and plastic fibrous designs, and simple circular-hole perforates, all of which had already been screened in a specially constructed flow duct facility. Provision was made for measurement of the environmental sound pressure level, so that the flow duct facility conditions could be tailored to suit the conditions appropriate to the different areas of the engine.

Liner technology was an area undergoing rapid change, due to the rate at which an understanding of their properties was gained, and the early results from the engine was an important stage in the process. Such results are illustrated in figure 15. They show that the degree of attenuation first achieved varied from between 4 and 8 PNdB at low engine powers to between 6 and 9 PNdB at high powers. Even under static conditions the potential for suppression was clearly great enough for us to be confident of achieving, and in some cases even improving on, the target certification requirements. When forward speed fan noise reductions were fully accounted for it became clear that all requirements would be more than satisfied.

Looking closely at figure 15 it is clear that the fibrous ducts performed more uniformly than the perforate over the engine speed range. This was expected, since changing engine power produces a variation in environmental sound pressure level and flow duct velocities which perforates are extremely sensitive to. Although perforates are capable of producing attenuations of the same order of magnitude as fibrous materials, which are less sensitive to the environment, there is a problem of judgement in tailoring the liner performance to the conditions in the engine duct. Therefore careful study of the varying environmental conditions had to be undertaken, before the final production standard design was frozen. The success of this work is reflected by the results labelled "optimised duct" on figure 15, the attenuation over the whole thrust range revealing little variation, and the overall noise reduction being around 8 or 9 PNdB. The true effect of the liners is perhaps best shown by spectral analysis, as typified by figure 16, a constant 100 Hz bandwidth analysis over the whole frequency range of significance. The upper trace is the unsuppressed engine. It should be noted that the majority of the peaks and troughs are not due to the source but are ground reflection augmentations and cancellations. The true tones appear at around 1.4, 2.8 and 4.2KHz in the case of the fan and around 5.2, 6.1 and 8.0 KHz for the turbine.

The middle trace shows the effect of the bypass duct treatment alone, with the significant reductions in the 1 to 5 KHz range, whereas the lower trace adds effect of the turbine duct liners. This trace is perhaps the best demonstration of the importance of the turbine component in the total RB 211 noise signature, for the liners reduce the level over a wide range from about 1 to 11 KHz. The lower trace also reveals the full effect of the fan duct liners to be over 10 dB between 1 and 5 KHz, with the tones reappearing and notionally showing potential for further reductions. However, since further tone reduction occurs naturally with a good standard of air intake under flight conditions, the turbine noise assumes greater significance in the total picture.

JET AND TAILPIPE NOISE

Jet noise has long since been the subject of intensive work by almost every engine, airframe and associated manufacturer involved with the noise problems of the aircraft industry. However, most of this work had been directed at the high speed sector of the velocity range (i.e. that part if it concerned either with low bypass ratio or straight turbo-jet engines), and very little information existed in the low speed area relevant to the new high bypass ratio engines. Consequently, although jet noise was not expected to be a significant problem on the RB 211, it was important to establish that the laws for the higher speed regime did apply down to the particularly low velocities experienced during the operation of a high bypass ratio engine at approach power. This work was carried out on a specially commissioned low speed coaxial jet noise facility and from this emerged indications that the normal jet noise laws did not apply [9]. In the RB 211 development programme sufficient data was accumulated to support the earlier conclusions that jet noise was not of major significance, but it demonstrated beyond reasonable doubt that at low powers the exhaust noise was dominated by tailpipe sources. Figure 17 illustrates this by comparing the jet noise level, predicted from recent model tests done under ideal conditions, and the predicted tailpipe level against the aircraft measurement under approach conditions. The predictions, which reflect a 15 to 20 dB dominance of tailpipe noise, fit the measured data extremely well.

In consequence tailpipe noise is a subject which has received close attention since its importance was recognised. Progress has been made in understanding its origins.,although it must be admitted most areas of the engine core are implicated in its generation and a full understanding will not be available overnight. Figure 18 indicates the variety of possible sources, and highlights one major problem, the postulated existence of both internal acoustic signals and pressure disturbances that affect the external jet mixing region. In short, although labelled tailpipe noise, the problem is undoubtedly aggravated by the external interaction between turbulence and the jet structure.

ENGINE AND AIRCRAFT DEFINITIVE LEVELS

In the period between the RB 211 programme launch and the first Tristar flight the US certification rules became firm. Prior to the first flight of the Tristar in November 1970 the research and development test results were reviewed in an attempt to assess how well the aircraft rated against FAR Part 36 requirements. Side-line and take-off were not seen as a problem, but we had always been concerned about the approach case. Remembering that the first runs of the preproduction engine had shown unsilenced forward and rearward arc levels some 8 and 10 PNdB above the target, there was a large deficit to be made up before passenger service was possible.

All the effects discussed in earlier sections were considered and a simple book-keeping exercise undertaken, as illustrated in figure 19, fo- the forward and rearward sectors. The effects of blade incidence, pylon interaction and forward speed all had a bigger impact on the forward noise than the rearward signal, where core engine sources are present, but the effect of the duct liners offset this sufficiently to conclude that the Tristar would be up to 3 PNdB better than the requirement.

3 EPNdB is not a large number, and therefore there was naturally a high level of interest in the early flight tests and subsequent certification programme. Teams from Rolls-Royce and Lockheed monitored the early flights, and these results dispelled any early anxiety. The aircraft proved to be well inside the limits at all operating conditions. At approach the predicted 3 EPNdB region turned out to be 4 EPNdB, and the take-off noise was so low that a throttling procedure on take-off did not prove to be advantageous, the margin at this point and the lateral point being an average of 10 PENdB below the requirements.

Since absolute levels at certification points are often meaningless on their own, a better way of indicating the improvement this standard represents is to examine the contour of constant annoyance, or "footprint" generated by the aircraft. A useful measure is the area enclosed by the 90 PNdB footprint, which for the Tristar is something less than 8 square miles. Compared to current long range jets, where the equivalent areas are anything over 50 square miles, the improvement is most marked. Effectively an airport neighbour would need to move 3 to 4 times closer to the airstrip to sense the same noise as he does today from long range aircraft. Even compared with the smaller tri and twinjets, where the areas are often around 30 square miles, the improvement is still significant (Fig.20).

THE CHALLENGE OF THE FUTURE

The RB 211 has set a technology standard from which we must advance. The gradual introduction of aircraft with engines of this type will reduce the noise problem around existing airports from this point on. Moreover, taking Heathrow as an example (Fig.21), by 1990 the nuisance area will be down to that of around the mid 1950's [(2)]. Any acceleration of this rate of progress is unlikely to come from quieter engines in major new airframes, unless there is some reduction in noise from the many established types that will still be in the service at that time. Government and Industry alike are working on that problem.

Nevertheless there is another extremely important reason for developing significantly quieter engines. There are indications that a new system of transportation will be required in the 1980's to meet the demands of inter-city communication. Such a system would require the development of either existing small peripheral airstrips close to large urban communities, or the building of new airports. These ideas, know widely as reduced or short take-off and landing systems (R/STOL) can only come to fruition if the noise problem is solved to a point where the aircraft concerned do not dominate the existing noise climate which, in such areas, is at a relatively low level. The kind of improvement necessary to solve the CTOL problem is small compared to likely R/STOL requirements.

Consider the situation. Land commands a high value in the developed nations, and suitable available sites close to urban communities are likely to be relatively small, so that an inter-city airport will have a runway length of no more than 5,000 ft at the outside. "Downtown" airports will be even smaller. As fig.22 indicates the community will become sited closer and closer to the airstrip, and in the case of a V/STOL system could be as close as 500-1,000 ft. from the departure point. Noise levels in the 80-85 PNdB range have been freely discussed as the maximum that an urban community would tolerate by day, and even lower levels are required during the evening and night. Such levels at short distances, represent an improvement of anything between 15 and 25 PNdB over todays best standard, depending on the size of aircraft considered. Already it has taken 15 years in service to achieve this order of reduction in the CTOL field, and every extra dB reduction is more difficult and more expensive to achieve.

This then is the challenge. Where, though, is such a vast reduction in noise to come from ? It cannot come from the engine alone, for already there are tangible signs that the airframe itself is a noise item to be reckoned with, with the noise of the landing gear and flaps possibly being only 10 dB or so below the current approach noise levels from the new engines [10]. There will have to be a concerted effort by the engine and airframe industry to achieve the target levels, and all possible noise reduction features will have to be included. The engines will probably have to be mounted in a novel way to take full advantage of airframe shielding effects, and the new jet noise floor from high bypass systems reduced even further.

From the engine standpoint we will need to improve the understanding of all the component sources, whether or not they appear significant at the moment. Today however they appear to have the following rank order of importance:

1. Fan Noise
2. Tailpipe Noise
3. Turbine Noise
4. Jet Noise

Work has been proceeding on each aspect of the problem over recent years, but interest in the first two items has assumed greater importance of late. The problem of tailpipe noise is recognised as being the most significant barrier to noise reduction programmes, since its origin is still undefined. We know that this component is a combination of internal acoustic signals and pressure fluctuations that produce noise at the nozzle exit plane and in the jet mixing region. We know that the combined effect of these internal and external sources can produce levels 10 - 20 dB greater than the pure jet mixing noise, and hence the concern. The solution will probably come from a major improvement to the aerodynamic standard of the engine core, including the combustion system and turbine, but there is much work to be done before that point is reached.

The understanding of fan noise has developed, with the identification and isolation of the major discrete tone mechanisms as a noteworthy step. More than ever was expected, the aerodynamic standard of the inlet, with the avoidance of distortion as a major priority, is one key to a low level of fan noise. This means that the powerplant and engine design must be fully integrated, and moreover carefully selected with the position of the engine on the airframe in mind. Beyond that, and the maintenance of a basically low blade speed and sensible blade/vane numbers and spacings, large reductions in fan noise will probably only oome from the optimum use of acoustic linings, or perhaps the engineering of an acceptable choked intake - a feature which is an excellent prospect acoustically but a mechanical nightmare.

We have made significant inroads into the turbine noise problem by virtue of the amount of specialised experience on this component on our turbine facility. We believe that the combined efforts of our current knowledge and the new facilities coming along will enable us to reduce this source in line with the other engine sources, since apart from basic reductions possible, the turbine is most readily affected by the use of linings. The dimensions of the core engine exhaust duct, combined with the high frequency characteristics of the turbine, all enable the liners to be most effective.

In the past two years some good quality model jet noise work has successfully isolated this component from the tailpipe sources that have obscured it in the past. It is clear that the mixing noise on high bypass ratio engines is of even less significance than we thought at the outset of the RB 211 programme, but even so at some point it will once again tend to become the noise floor. We see the need for research into the noise from low velocity coaxial jets, an understanding of the jet structure and a definition of engineering solutions that will reduce levels even further. History has shown that each new major aircraft has grown, and with it the engine has grown. A simple way of uprating engines is to increase temperatures and exit velocities, and we must be ready to counteract these increases with noise reduction techniques.

The design and use of acoustic absorbers is a field that will benefit from increased research activity. Now that we have a new national flowduct facility in this country at NGTE, we will be able to develop some of the novel ideas that have been generated in recent years. If we can optimise the effect of liners we will be able to show tangible gains in engine and powerplant weight, a factor always uppermost in the aircraft designers mind.

ACTION

Work on all these aspects is proceeding apace. The major programmes in hand cover two fields. The first is the long term component research effort, which is almost completely funded by the Government and guided by NGTE, who also have their own complimentary programmes. The second is a field of work we are calling Advanced Development, which is normally funded jointly by Industry and the Government. Because this field of work utilises full scale machinery, it is by nature expensive, and the total commitment can easily be twice the basic noise research spend.

Two significant pieces of work fall into the latter category. These are the Quiet Engine Demonstrator Programme based on the RB 211 (QED) and the Quiet Variable Pitch Fan Demonstrator Programme based on the M45. The programmes are under the guidance of the Derby and Bristol Divisions of the Company respectively, with Dowty Rotol as a third partner in the VP fan programme.

The long term objective of the RB 211 QED Programme is an engine around 10 PNdB quieter than today's standard. As an intermediate goal we have set a halfway objective, i.e. 5 PNdB less, with minimum modifications to the power-plant. In fact this phase leaves the rotating machinery unaltered, modifying only the inlet and exhaust systems to improve the aerodynamic standard and introduce more acoustic lining where appropriate (figure 23). This first phase of the programme has been running since mid 1972, and it will last for a total of two years, there being a full demonstration of the silencing kit during 1973. The second phase, which is currently being planned, should follow immediately, although this will involve changes to both the fan and turbine systems and will therefore be a more major engineering exercise.

The M45 based VP fan programme, which is running in parallel with the RB 211 work, is directed more at the short field type of operation and utilises the engine which has been selected for the VFW Fokker 614. It embodies a much lower tip speed fan than the RB 211, and combines this with the novel concept of variable pitch, for both noise and thrust control reasons. It will also examine the question of tail-pipe noise at very low primary exhaust velocities, a field of work which is vital to the development of engines quiet enough for true STOL operation.

The research and advanced demonstrator programmes will provide us with a wealth of test experience in the next two years or so. To make full use of this information an equal effort is required on the theoretical aspects of noise generation and suppression and some good fundamental experimental work. There is never a lack of ideas from the theoretical experts on any noise source, but all too frequently these theories are restricted in that they are not quantitative. To be useful to the engineer they must offer guidance on the relative strength of the multitude of sources, so that time and effort is not wasted examining those of no practicable significance. Within the spectrum of membership of the British Acoustical Society there must be members with much to offer the aero engine designer. We would welcome your contribution to this extremely vexing problem through, for example, the Society's Aerodynamic Noise Group, for any practical solution to the noise problem can do nothing but good for the UK Industry and for communities at large.

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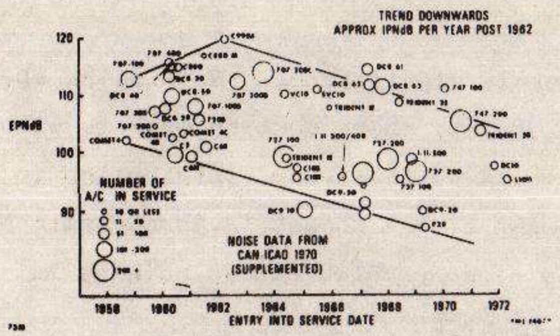

Fig. 1 Flyover Noise Levels at ICAO Measuring Point

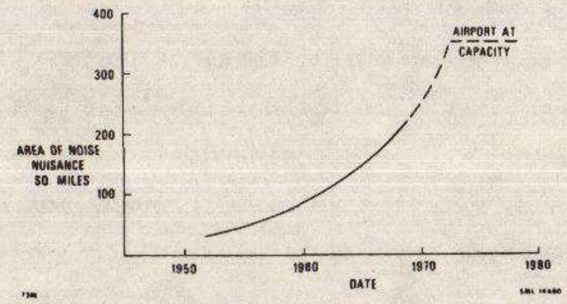

Fig. 2 Growth of Noise Nuisance around Heathrow No Wide Body Aircraft

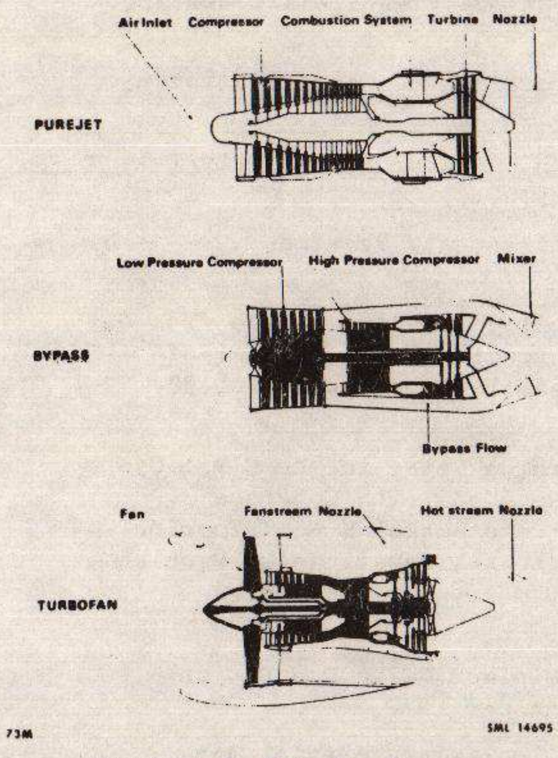

Fig. 4 Typical Engine Layouts

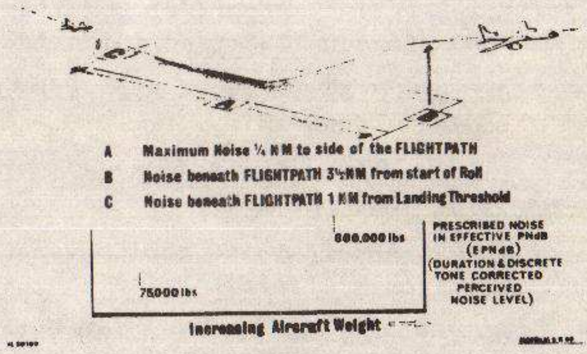

Fig. 3 Certification Objectives

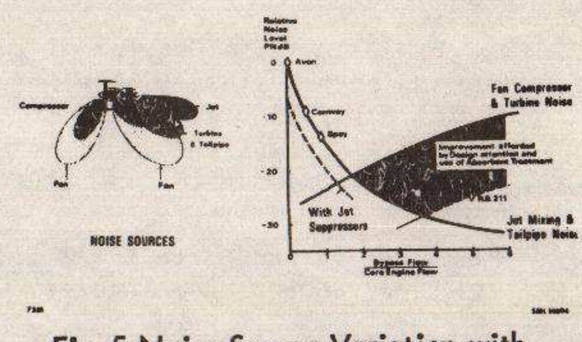

Fig. 5 Noise Source Variation with Bypass Ratio

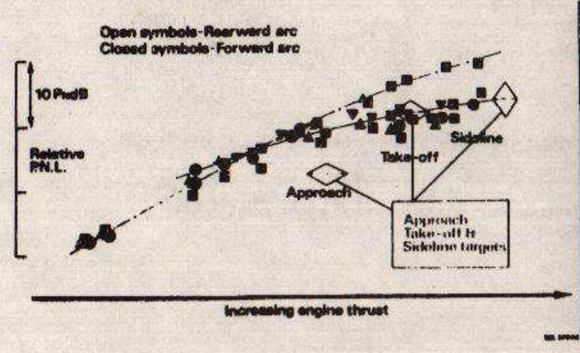

Fig. 6 Pre-Production Unsuppressed RB211 200 ft Sideline Noise

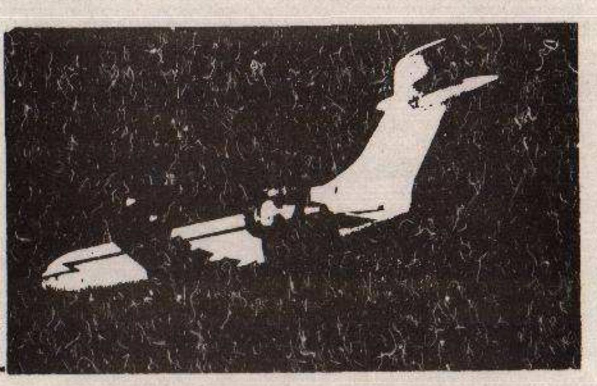

Fig. 7 Rolls-Royce VC10 Flying Test Bed

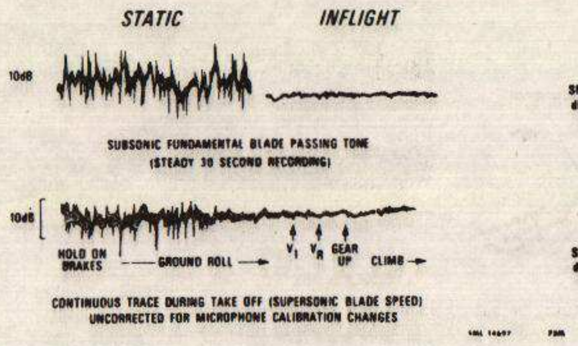

Fig. 8 RB211 Inlet Duct Microphones Static and Inflight

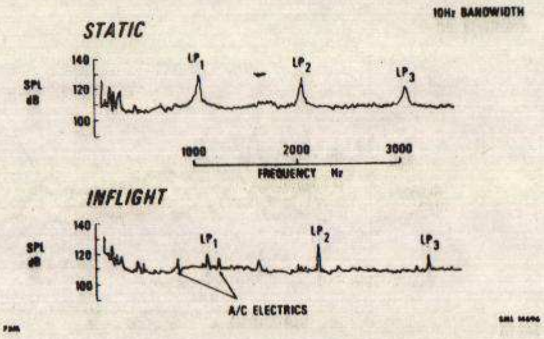

Fig. 9 Lowspeed Static and Inflight Spectra

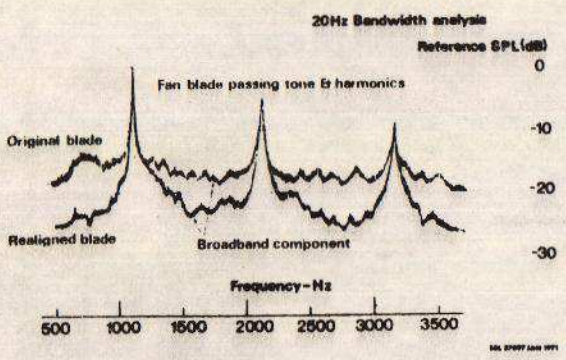

Fig. 10 Effect of Blade Alignment

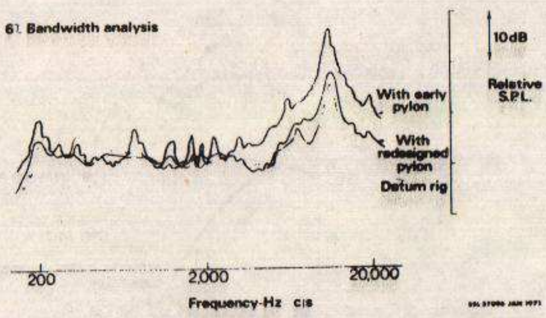

Fig. 11 Effect of Services Pylon Shape on Noise Generation

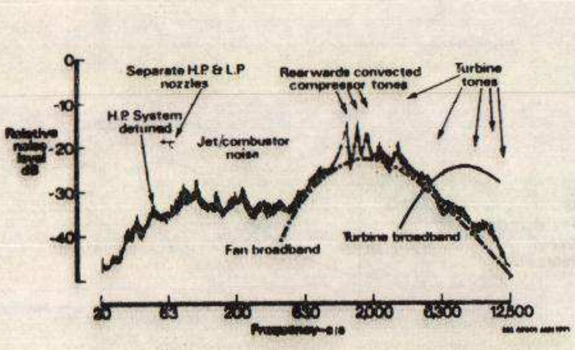

Fig. 12 Compressor and Turbine Component Sources

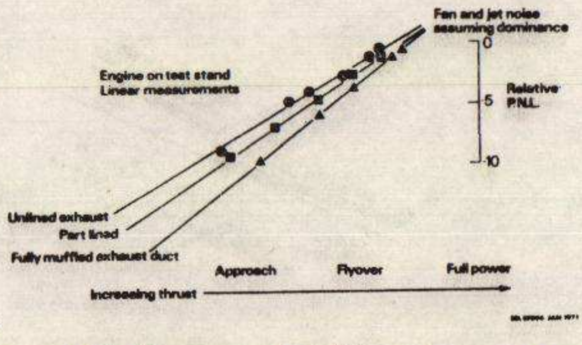

Fig. 13 Relevance of Turbine Component

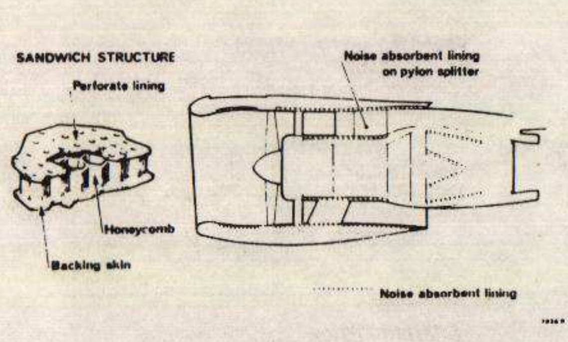

Fig. 14 RB211 Noise Absorbent Linings

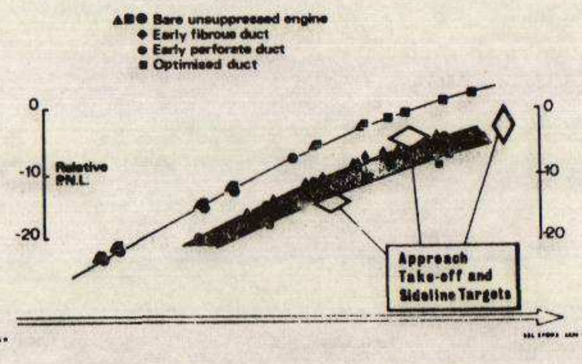

Fig. 15 Development Fan Duct Liner Results

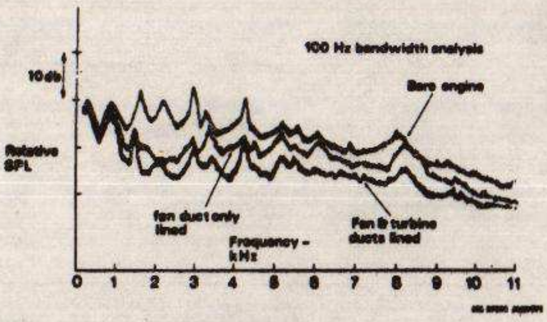

Fig. 16 Effect of Duct Liners - Preliminary Standard Engine

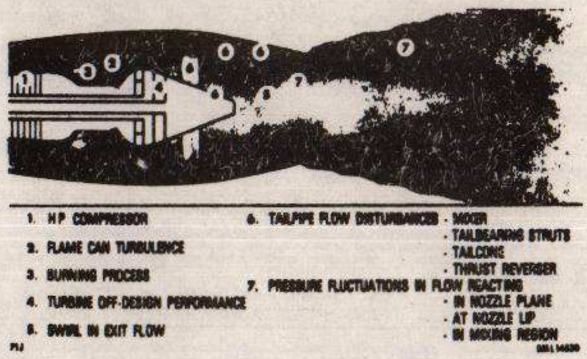

Fig. 17 Possible Tailpipe Noise Sources

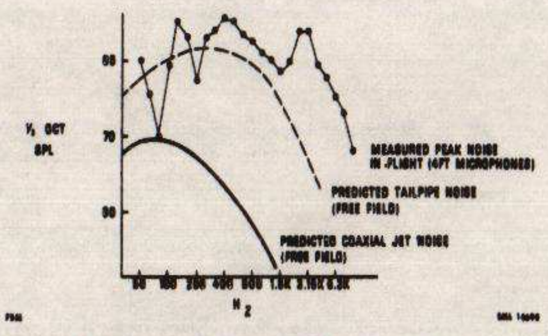

Fig. 18 Comparison of Jet and Tailpipe Noise - RB211

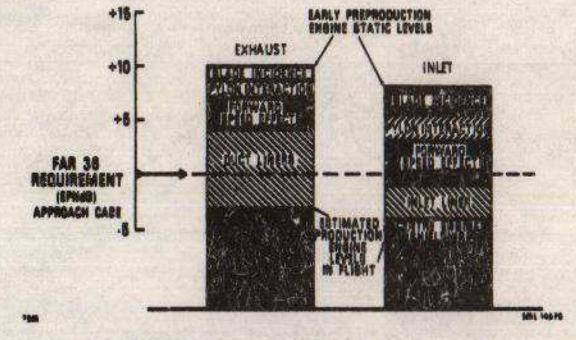

Fig. 19 Estimation of Aircraft Noise Levels from Development Information

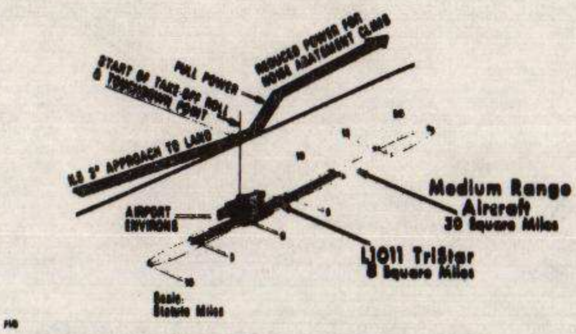

Fig. 20 90 PNdB Noise Contour Tristar and Current Aircraft

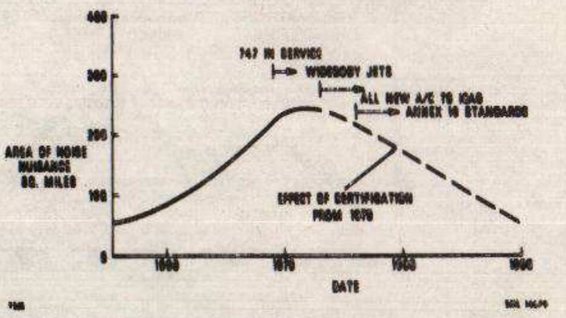

Fig. 21 Effect of Noise Certification on Heathrow

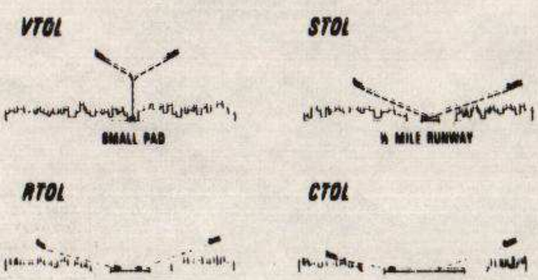

Fig. 22 Runway Length and Community Proximity

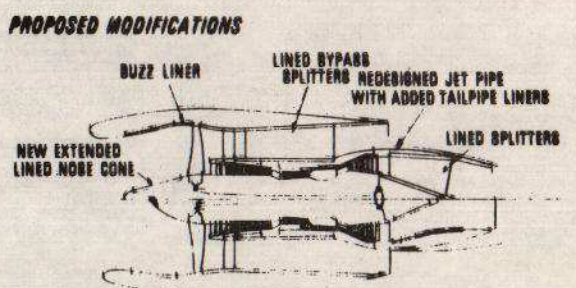

Fig. 23 RB211 5 PNdB Quiet Engine Demonstrator