PERFORMANCE RETENTION OF THE RB211 POWERPLANT IN SERVICE

B. L. Astridge
Rolls-Royce Limited

J. T. Pinder
Rolls-Royce Incorporated

INTRODUCTION

It is perhaps a statement of the obvious, but an understanding of the mechanisms of deterioration is essential in order that features to counteract performance degradation can be built into the basic design of an engine and nacelle. Furthermore, the interpretation must be continued in service for effective feedback to provide modifications which may be necessary in maintaining a satisfactory performance retention program.

The in-service assessment must, therefore, be accurate as to magnitude and causes and this requires consideration of:

1. The powerplant as a complete entity, i.e. the engine components and nacelle including the thrust reverser.

2. Measurement of performance in flight rather than by sole reliance on the scaling of test cell data to flight conditions (although some correlation should be possible).

3. The relationship of engine parts condition to overhaul performance and in-flight deterioration level of that engine.

Hence a performance retention program covers design, feedback to design, measurement and analysis of in-service experience and continuous review of the condition of engine components. These aspects are addressed by consideration of the RB211 engine in service in both the Lockheed L1011 Tristar and Boeing 747 aircraft.

PERFORMANCE RETENTION DESIGN FEATURES

Basic Design Features

Performance deficiency will arise when main gas path airflow, either past blade tip seals or through internal cooling air passages or leakage overboard, is excessive. Further major sources of performance loss will arise in the event that significant blade damage or erosion or aerofoil contamination arising because of dirt deposition on oil contaminated components takes place.

The RB211 was designed with features which address these problems, as indicated in Figure 1. Blade tip clearance control and internal cooling air passage seal clearance are considered in the structural design, thermal matching and the use of shrouded blades and stators. Overboard leakage is considered in both main engine casing design and powerplant sealing features such as the reverser seal. Limitation of core engine contamination and erosion is featured in the core engine intake configuration where the generous spacing of the core splitter relative to the fan, together with the wide chord fan, allows the majority of the ingested particles to be centrifuged through the bypass duct.

Details of the particular aspects relating to these features in the RB211 engine are shown in the following illustrations. Blade tip clearance control at all conditions is enhanced by the features illustrated in Figure 2. The three shaft configuration allows a short engine with stiff shafts and casings. Furthermore, the features which determine the gas path are separated from the structural casings and mounted with radial flexibility so that inertia and thrust forces in flight have minimum effect on tip clearances. The effectiveness of these unique features is reflected in the lack of initial performance lost in flight relative to the test bed passoff performance, the RB211 having demonstrated a deterioration including any losses associated with the first flight, of less than 0.3% SFC (specific fuel consumption) in 100 flights from new.

Thermal matching of static and rotating engine components is illustrated in Figures 3 and 4. Engines are, even in normal operation, subject to rapid changes in operating temperatures. Serious mismatch in expansion of the static and rotating components will result in large compressor and turbine blade tip and cooling air seal component excursions and, hence, wear such that, at stablilized conditions, large clearances will occur with a resulting serious performance deficiency. Engine axial matching is illustrated in Figure 3 and shows the HP (high pressure) turbine static and rotating seal members are located to a common datum, the HP location bearing and with load path structures exposed to substantially the same temperatures thus ensuring common expansion. The equally important radial matching feature in the turbines is shown in Figure 4. The HP turbine features a thermal control ring to restrict thermal growth of the static seal member to match the growth of the rotating member, the expansion of which is restricted to a low rate due to the mass of the turbine disc. The IP (intermediate pressure) and LP (low pressure) turbine static seal members are located in the turbine casings and their growth is matched to that of the discs and blades by a combination of casing insulation and external cooling with undercowl ventilation air. X-ray data obtained at various conditions has been extensively used to optimize the design of the features which fix the relative position of the seals and the blade tip fins and this has been achieved without requiring introduction of a scheduled turbine casing cooling air control system.

The air used to cool the turbine casing is also used to ventilate undercowl zones and is no more than the amount required for that purpose. An inherent performance loss does not, therefore, require debiting to the system. However, this powerplant air is taken from the fan stream and excessive leakage of this air, either through the ventilation system or directly overboard via reverser seals, etc., has a powerful effect on cruise SFC and a much smaller, and hence, more difficult to detect effect at static conditions. Consideration of the RB211 nacelle as a complete powerplant has included development of a powerplant leakage check for use in development programs and as a check of service experience. The efficiency of powerplant sealing with time has, therefore, been checked against new engine behavior as shown in Figure 5.

Feedback From Service

No resume of design features would be complete without consideration of the essential feedback of experience from service. There are many examples arising from RB211 experience and a few have been chosen as typical of the aspects discussed hitherto. The first is in the area of tip clearance control where experience with the RB211-22B dictated extensive changes to the HP turbine sealing arrangements for the RB211-524. The second relates to the control of compressor contamination resulting from oil leakage and the third to elimination of excessive variation in powerplant ventilation air, both of which have resulted in more minor but nevertheless, significant changes.

Figure 6 shows the changes in HP turbine shroud segment design for the RB211-524 version as a result of experience gained with the RB211-22B. In the earlier design the leakage paths shown arise in time from component distortion and wear, the NGV (nozzle guide vane) support ring distorting under axial load and the shroud segment leading edge fretting and allowing leakage and loss of axial location. In the RB211-524 design the offending joint in the NGV support ring is eliminated and the shroud segment location is changed from axial to radial under which conditions the sealing is reinforced by aerodynamic loading. It should be further noted that the RB211-524 shroud segment is of such a form that the segment base protects the leading edge of the honeycomb from erosion.

A modification which was designed to prevent oil contamination is sketched in Figure 7. Experience has demonstrated that excessive front bearing housing oil leakage was arising from an over generous hydraulic oil seal chamber volume.

On shutdown the excess oil occupying this chamber leaks into the IP compressor and acts as a base for contamination. A simple modification which has alleviated the situation was the introduction of a liner to reduce the oil chamber volume.

The third category of modification which has been introduced because of service experience is associated with the sealing of the powerplant undercowl ventilation air. Excess airflow was arising from variation in the birdmouth of the seal between turbine section undercowl ventilation zones. The addition of a more positive seal, as illustrated in Figure 8, has cured this problem.

Integrated Exhaust Pressure Ratio (EPR) System

In order to monitor a performance retention program it is necessary to be in a position to measure, accurately, the in-flight performance of the engine. Fundamental to this problem is the ability to measure the thrust setting of the engine. This is achieved in the RB211 by means of the integrated EPR system.

Thrust is fundamentally related to nozzle pressure ratio and it, therefore follows that, provided it can be measured reliably, exhaust pressure ratio must be the most accurate means of power setting. However, this accuracy can only be achieved in a two nozzle engine by sampling the pressure in both streams and then deriving a mean of the two pressures which is weighted in proportion to the areas of the two streams. The RB211 integrated EPR system fits this requirement and its basic nature relating thrust and pressure ratio means that this relationship is virtually unaffected by deterioration. Hence, measurement of in flight performance is possible. The total system is shown diagrammatically in Figure 9 and shows the fan air to be sampled with three five point rakes and the hot nozzle by five four point rakes. Integration of the two nozzle pressures is aerodynamic by the simple block shown in Figure 10, the integrated pressure being sampled between two appropriately sized orifices. It should be noted that the fan nozzle pressure is always higher than the turbine exhaust pressure and the system flow is, therefore, always from fan to turbine exhaust. Carbon or other contamination risk is, therefore, minimal.

As a further refinement, the RB211 integrated EPR system is trimmed, by electrical means, in order to produce a relationship between integrated EPR and thrust which is common to all engines. This is required to take into account the change in the integrated EPR/thrust relationship brought about by variation between units within build tolerances, of the factors which influence this characteristic. Figure 11 illustrates the principle of trimming. The test integrated EPR/thrust relationship is checked to be within quality limits determined from experience, and the trimmer is selected to adjust the relationship, within trimmer steps, to a common characteristic for all engines. The pilot uses the control lever to select an integrated EPR and the trimming procedure previously described ensures that each engine produces the required thrust at the selected power lever setting. The assurance of minimum thrust with alternative setting procedures leads to some engines producing more thrust than required with consequent deleterious effect on component lives.

MEASUREMENT OF DETERIORATION

In Flight

The integrated EPR system described above, with the inherent insensitivity of its relationship to thrust with engine deterioration, allows consistent measurement of in flight performance. However, the reliability of in flight data and its method of interpretation can only be understood with some knowledge of the potential inaccuracies which can occur. At the risk of some over simplification Table 1 lists inherent inaccuracies arising from measuring instrument inaccuracies, both aircraft and engine, and, another prime source of variability, the normal aircraft Environmental Control System (ECS). The latter source of variability comes about because engine air is supplied to a common manifold such that engine to engine and duct loss variations can result in differing amounts of bleed being extracted from each engine in the installation. If the integrated EPR/thrust relationship were not substantially insensitive to deterioration a further variable for power setting at the basic parameter, EPR, would be necessary in attempting to interpret fuel flow changes as changes in fuel flow at a thrust, i.e., SFC.

Nevertheless it can be seen that up to ±2.2% variation in fuel flow at an integrated EPR could arise between engines due to the measurement inaccuracies. In a fleet of aircraft it would be expected that the incidence of inaccuracy would, in most cases, be random and that measurement of fleet performance, as an average, be possible, but that individual engine performance would be somewhat less reliable. Mean fleet data for the RB211-524 engine is shown on Figure 12. The flight monitor line is that established as representative of RB211-524 engines using both averages of larger quantities of flight crew recorded data and some specific aircraft audits. Variation in deterioration rates will arise from differences in operation procedures and rates as low as that shown in Figure 12 for specific audits have been recorded with confidence.

Having made these points, it should be noted that many of the instrument inaccuracies of Table 1 may remain consistent during a particular installed life and, hence, become systematic for the engine in question. This will become further reinforced if data can be recorded with the subject engines either operating without ECS bleed or at least isolated to a potentially reliable source, i.e., engine isolated to one ECS pack. If, indeed, the errors are systematic, it is possible to measure individual performance changes during an installed life, i.e., individual engine deterioration, and reasonable success has been achieved in that individually assessed engines have demonstrated characteristics similar to that established by fleet mean evaluation of flight data and comparison of pre and post-installation test bed data.

Test Cell Confirmation

It has been noted that the relationship between test cell and flight performance can be distorted in the event of large variations in powerplant leakage overboard, the effect at cruise being 2.5 times that at sea level static. In addition, the effect of component efficiency changes at cruise are smaller than at sea level and, therefore, test cell measurements of deterioration must be scaled down by the order of 25% for comparison with flight. This reduction has been derived analytically from engine models and proven in sea level/altitude test cell comparisons.

However, control of powerplant leakage has been a consistent feature of the RB211 design, development and operation and the relationship of measured flight deterioration to that indicated by pre and post service test cell checks could be expected to show consistency only with application of the latter scale.

This is confirmed by Figure 13 showing the current summary of RB211-524 experience. The curve is the current mean of considerable flight data and represents the difference between first flight performance and the performance at any point during the installation. The test points shown represent the difference in SFC, on the test bed, between the pre-installation pass-off test and post-installation performance checks scaled by 25% to represent component efficiency changes only.

Overhaul Deterioration

The total deterioration picture for a fleet is a composite of the rate of deterioration of installed engines and the amount of performance recovered by overhaul. This is usually illustrated by the familiar "saw tooth" plot. The relationship of overhaul performance to new engine performance is a function of the degree of rework applied. The modular design of the RB211 engine permits overhaul of individual modules to be carried out without stripping the whole engine and, therefore, it is important to understand the sources of deterioration such that the appropriate emphasis can be applied as the opportunity arises during shop visits. Examples of the type of overhaul practices pursued for the RB211 follow but as introduction Figure 14 can be shown as illustration of the increased scatter, relative to new, which is inevitable in modular overhaul. The mean level associated with this is, however, a not unreasonable 0.5 to 1.0% above that of new engines.

OVERHAUL PRACTICES

No discussion on performance retention would be complete without some reference to overhaul practices. The amount of overhaul work carried out at each maintenance shop visit for purely performance reasons needs to be judged against the economic return which can be expected from the work carried out. This is a continually changing picture. As the price of fuel continues to rise it now becomes feasible to carry out work which would not previously have been considered to be worthwhile.

This final section of the paper illustrates the effect which various levels of overhaul can have on the performance of the RB211.

RB211 Fan Leading Edge Restoration

The RB211 fan, in common with all other fans, suffers from leading edge erosion which, if allowed to carry on unchecked, eventually leads to the fan having a 'square' leading edge with resulting loss in performance. Tests carried out with ex-service fans which have this amount of leading edge erosion indicate that if the leading edge is restored correctly, by means of careful rounding of the leading edge, as shown in the upper illustration of Figure 15, and improvement in SFC of 0.4% can be obtained. If, however, the restoration is applied to a fan which has an eroded leading edge which is greater than 1.40 mm (.055 inches) thick it is essential that the blade is thinned and blended over the first inch of chord in order that the correct radius of leading edge can be applied. If this procedure is not carried out and the restoration is done as shown in the lower half of Figure 15, the benefits obtained will be minimal.

RB211 IP Turbine Shroud Segments

The maintenance of the minimum tip clearances at vital performance conditions, such as climb and cruise ratings, is essential if the best economy of operation is to be attained. A particular area where tip clearance control has a very powerful effect on performance is the turbine. As previously explained, the RB211 utilizes a particular structure and turbine casing cooling air system which ensures that the axial and radial growth of the rotors and cases are closely matched during the important parts, from the performance viewpoint, of the flight.

All RB211 turbines utilize a honeycomb static tip seal segment and many of these honeycomb seals are pre-profiled. The shape of this pre-profile is designed to be closely similar to, but slightly smaller than, the shape obtained from service wear patterns and a careful running in procedure is then carried out prior to the engine carrying out its performance acceptance test in order that the turbine can machine out the excess honeycomb in a controlled way, thus ensuring a precise matching of the turbine to the honeycomb seals. The benefits of this careful pre-profiling and running in procedure are that the turbine knife edge wear is minimized, thus allowing the turbine to be used again without the necessity for regular knife edge rework and that the performance obtained after this is that which will be attainable by the customer.

In overhauling these seal segments, however, it is vitally important that the honeycomb is correctly positioned on the carrier plate since, if this is not done, the correct relationship between the turbine rotor and its tip seals cannot be maintained. While this may appear to be a statement of the obvious on several occasions the quality of some of these reworked seals has not always been perfect. Figure 16 shows on outline of an IP turbine shroud segment and many examples have been observed where the honeycomb has been too short or out of position by significant amounts and tests carried out using new IP turbine shroud segments made with honeycomb mis-positioned by 1 cell (0.068 inches) width have indicated that a loss of SFC of approximately 1.5% can be expected. This loss in performance is directly attributable to the turbine becoming disengaged from its seal segment.

RB211 HP System Tolerances

In the days when fuel was relatively inexpensive many tolerances were written into overhaul manuals which, although satisfactory from the mechanical standpoint, were not always optimized for fuel economy. Examples which are shown here concern the amount and type of damage to compressor blades, rotating air seal and rotor tip clearances. The following examples indicate the amount of improvement which can be achieved when the acceptable limits are modified to take into account the need for economy rather than considering mechanical integrity alone.

RB211 Rear HP Turbine Stepped Seal. On introduction of the HP feed standard of HP turbine, it was necessary to raise the chamber pressure to the rear of the HP turbine to maintain the correct bearing load. This was achieved by introduction of a balance piston seal and removal of HP3 flow restriction upstream. The flow of the cooling airflow is then controlled by the balance piston seal and the stepped seal and is critically dependent upon the quality of these seals. The cooling air to the rear of the HP turbine is illustrated in Figure 17.

In investigating the poor standard of overhaul of one operator it was discovered that the operator was consistently working to the maximum allowable radial clearance allowed by the manual for the stepped seal. The maximum limit had been set at a time when fuel was much cheaper and it presented no mechanical hazards. The limit was reduced to an amount which is more appropriate to fuel economy and, as shown on the CUSUM trend plot, Figure 18, the average level of TGT (Turbine Gas Temperature) has been reduced by an average of 3.6°C, equivalent to a reduction in SFC of approximately 0.35%.

Blade Dressing. In investigating the effect of overhaul manual limits on performance, with the intention of making economical modifications to the overhaul manual limits, the HP system illustrated on Figure 19 was removed from an ex-service engine which had just undergone a performance evaluation. It was decided to arbitrarily reduce the amount of blade dressing associated with the HP compressor to one-half that allowed in the overhaul manual and to tighten the HP compressor tip clearance to within book minimum + 0.005 inches. In addition to this all HP turbine seals were checked for compliance with the book. The inspection revealed that, with the exception of excessive dressing on one stage, always a subjective judgment, the machine was within book limits but not the stated goal. In order to achieve these goals two stages were rebladed to reduce tip clearance and dressing to the new limits and a few blades were changed for similar reasons on 3 of the other 4 stages. In addition to this, although within limits, it was decided to fit new static air seals to the HP turbine. In the event the assessment was that the amount of dressing was reduced to a little over one-third of that deemed acceptable by the overhaul manual. The net effect of these changes was to reduce the level of TGT by 12°C and the SFC by 1.1%, an amount which is consistent with an improvement in HP system efficiency of 1.7% together with a reduction in cooling airflow of 0.8%.

The economics of these changes are now being assessed.

The design of successive members of the RB211 family of engines has been continually modified to take into account experience gained from service engines, but each has retained the original unique features of separation of structural and gas path casings and modularity together with the ability, by use of integrated EPR, to have its performance monitored accurately in flight. With the current price of fuel, a 1% sustained reduction in SFC is worth approximately $30,000/year/engine and it is easy to see that fairly major changes in overhaul practice, which were once uneconomical, are now becoming eminently desirable and will become more so as the price of fuel continues to advance. The structural features of the RB211 ensure that the rate of deterioration in performance is low and that the cost of overhauling the engine is minimized.

TABLE I

RB211 ENGINES

ACCURACY OF IN FLIGHT MEASUREMENT OF FUEL FLOW AT AN EPR

SOURCE OF VARIABILITY	POTENTIAL INACCURACY OF MEASUREMENT	EFFECT OF FUEL FLOW AT AN EPR
FLIGHT CONDITION		
MACH NUMBER	±0.01	±1.06%
TAT	±2.0°C	±0.46%
ALTITUDE	±30 METRES	±0.46%
ENGINE INSTRUMENTATION		
EPR TRANSMITTER AND GAUGE	±0.45%	±1.7%
FUEL FLOW	±0.5%	±0.5%
ENVIRONMENTAL CONTROL SYSTEM FLOW VARIATION BETWEEN ENGINES	±0.25%	±0.5%
RMS ACCURACY		±2.2%

RB211 Performance retention features

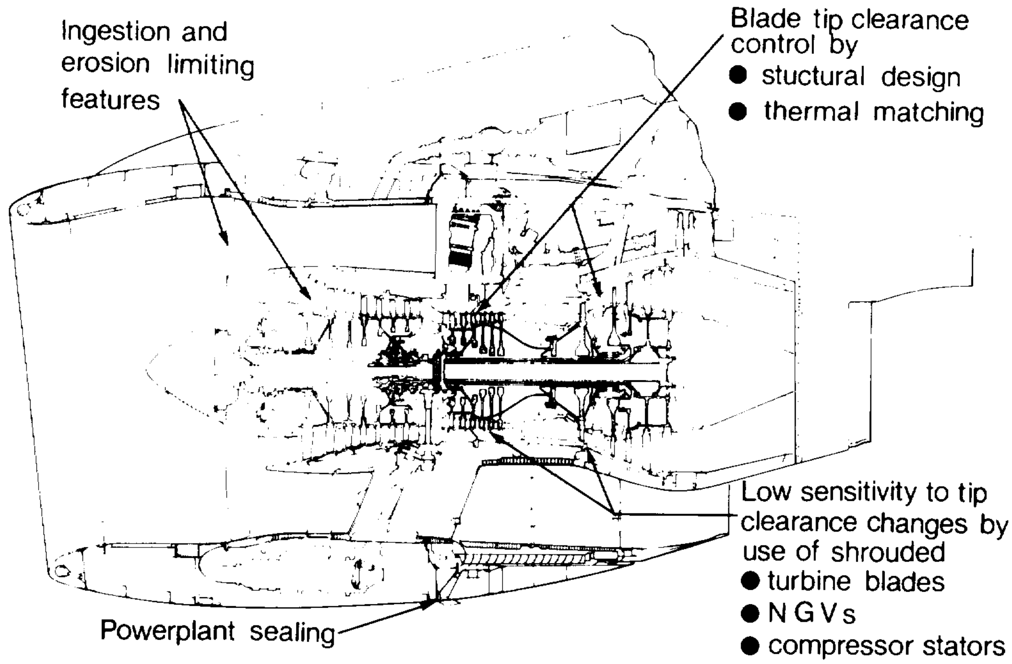

FIGURE 1

RB211 Load carrying structure

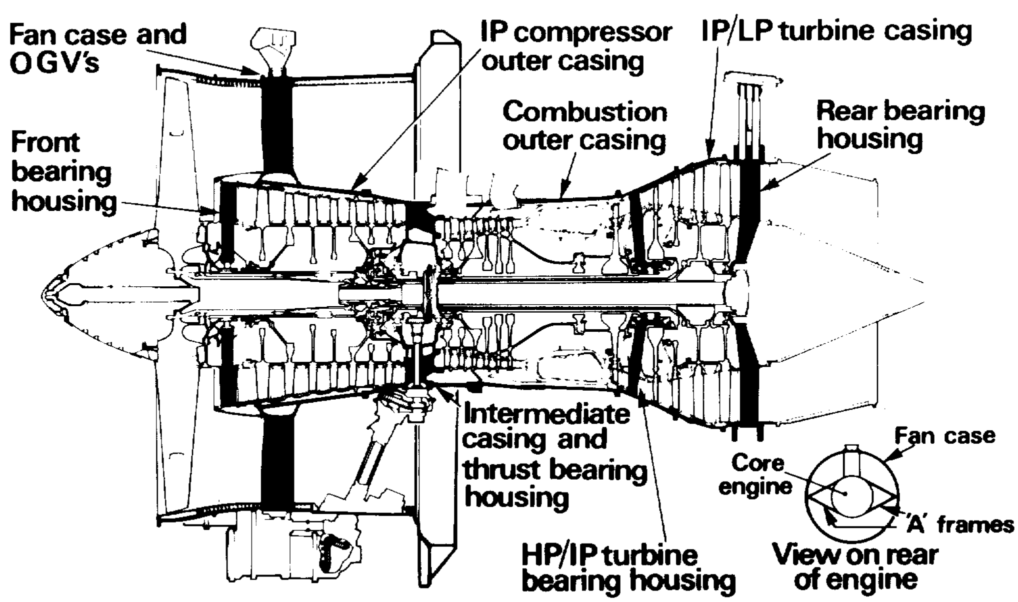

FIGURE 2

RB 211 HP turbine tip seal matching

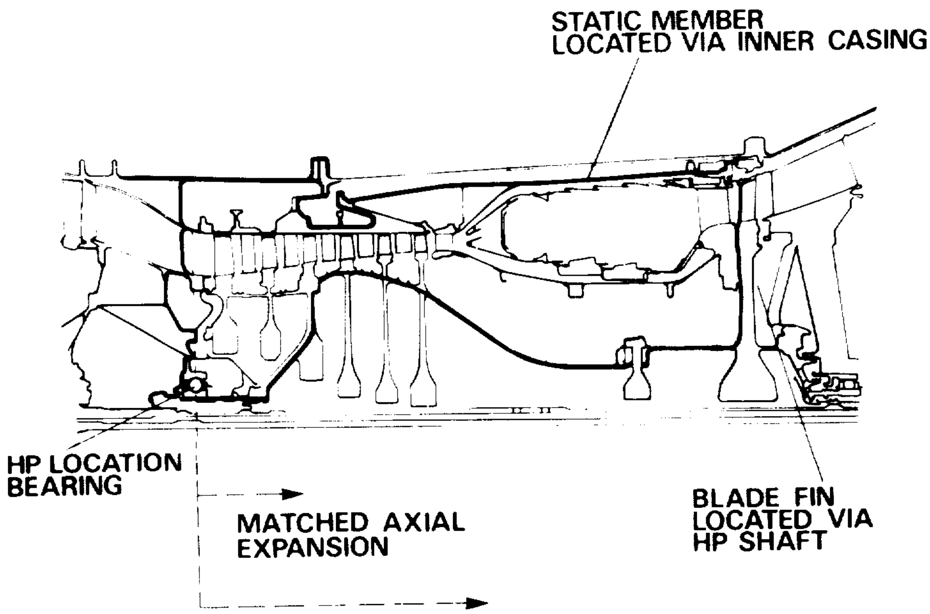

FIGURE 3

RB211 524 Turbine tip seals

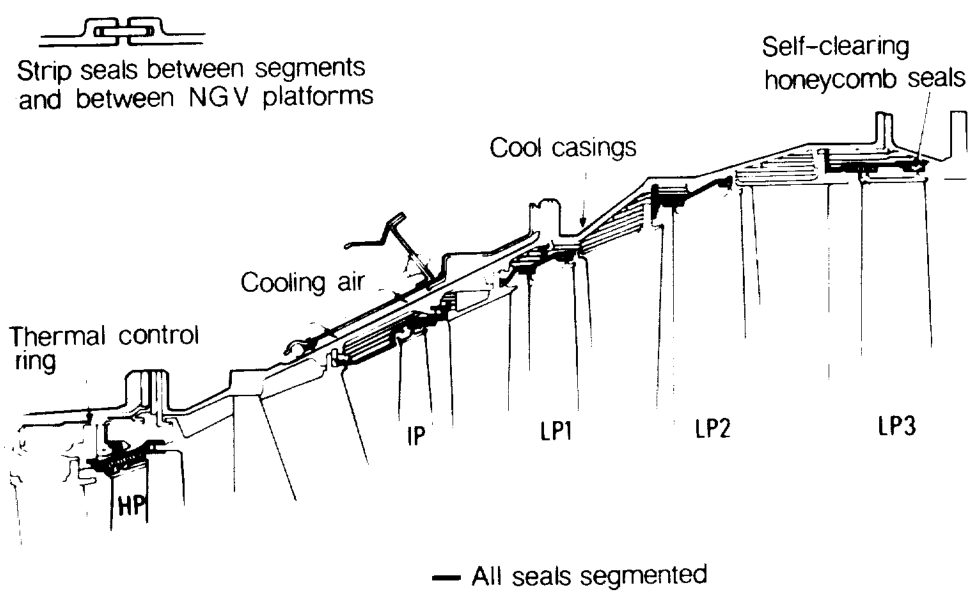

FIGURE 4

RB 211 powerplant leakage

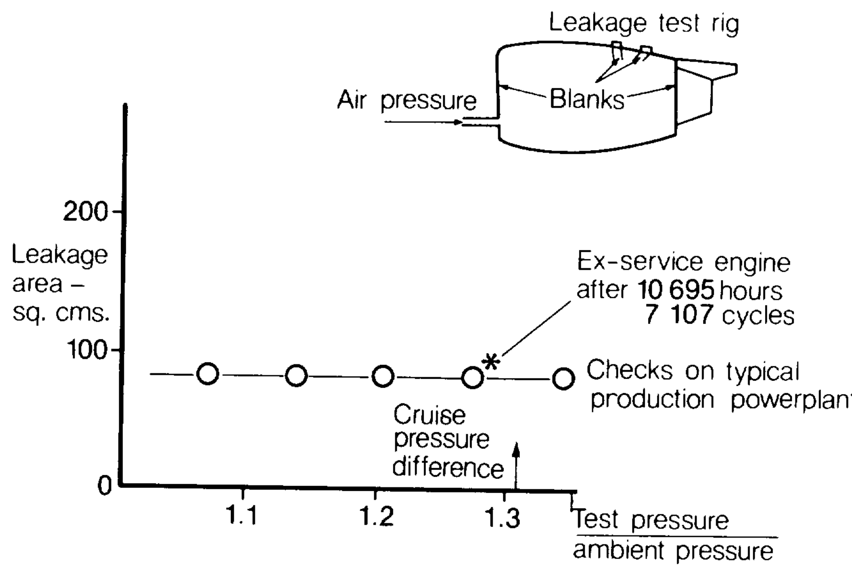

FIGURE 5

RB211 Revision to HP Turbine shroud segment design

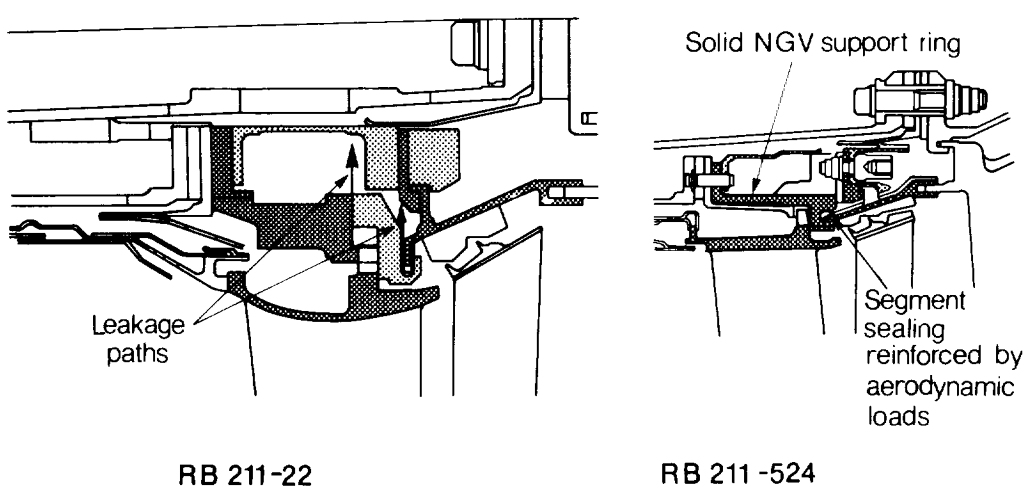

FIGURE 6

RB211 IP compressor rotor front stub shaft hydraulic oil seal

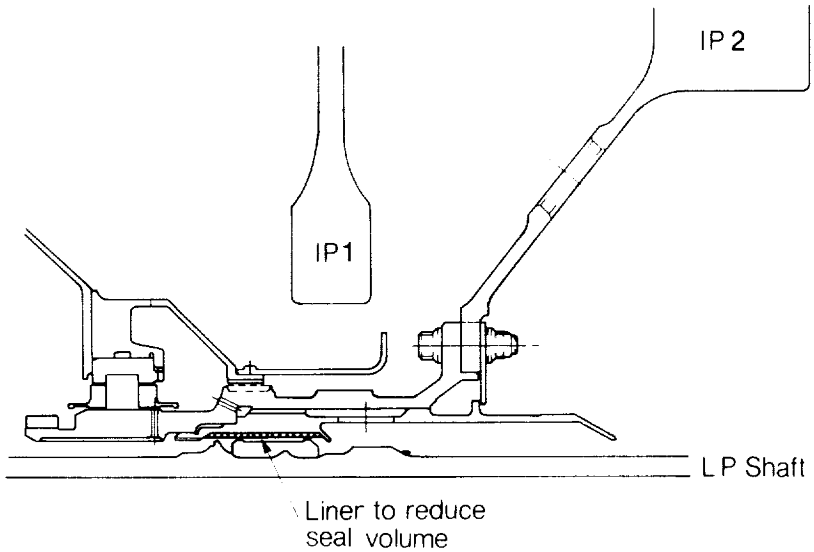

FIGURE 7

RB 211 Control of pod ventilation Zone 4A/4B bulkhead

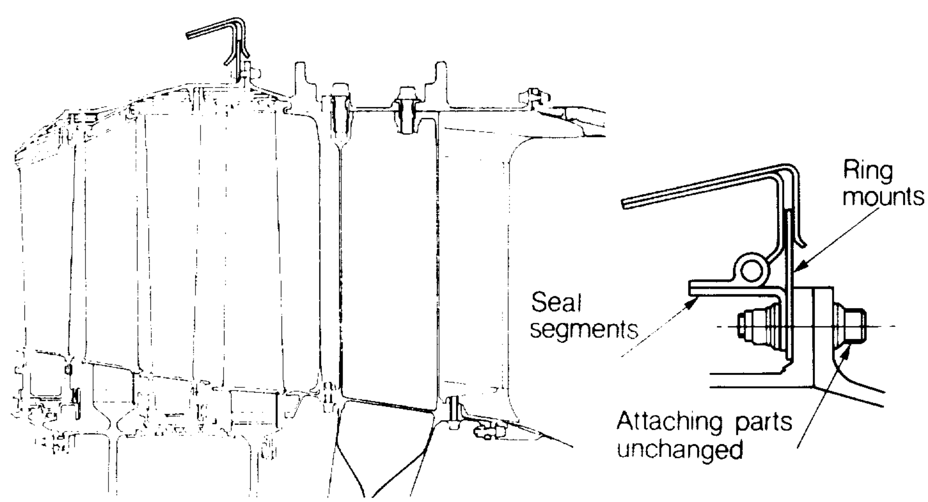

FIGURE 8

RB 211-22 IEPR system general arrangement

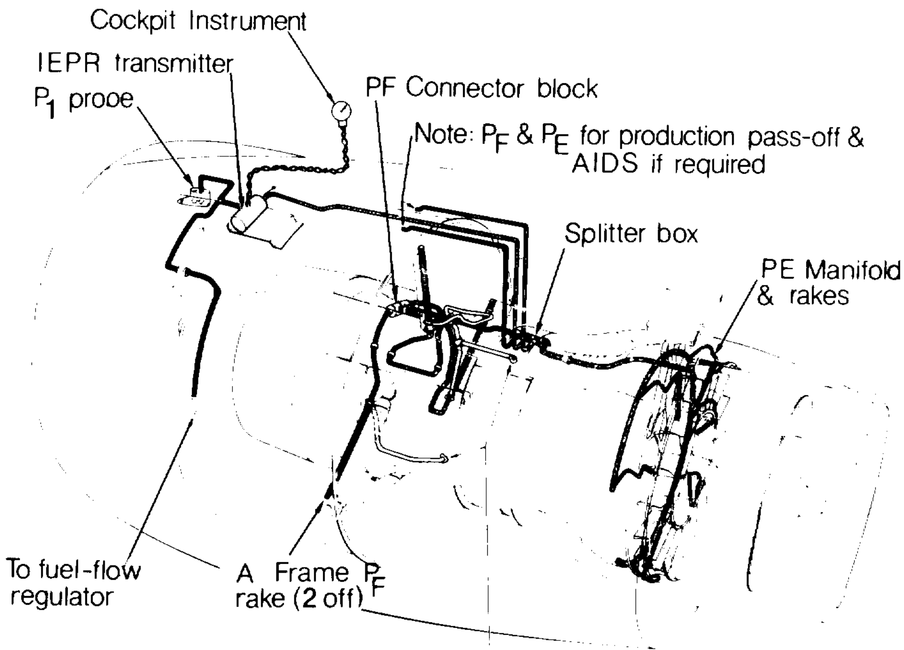

FIGURE 9

RB211 EPR System integrator block

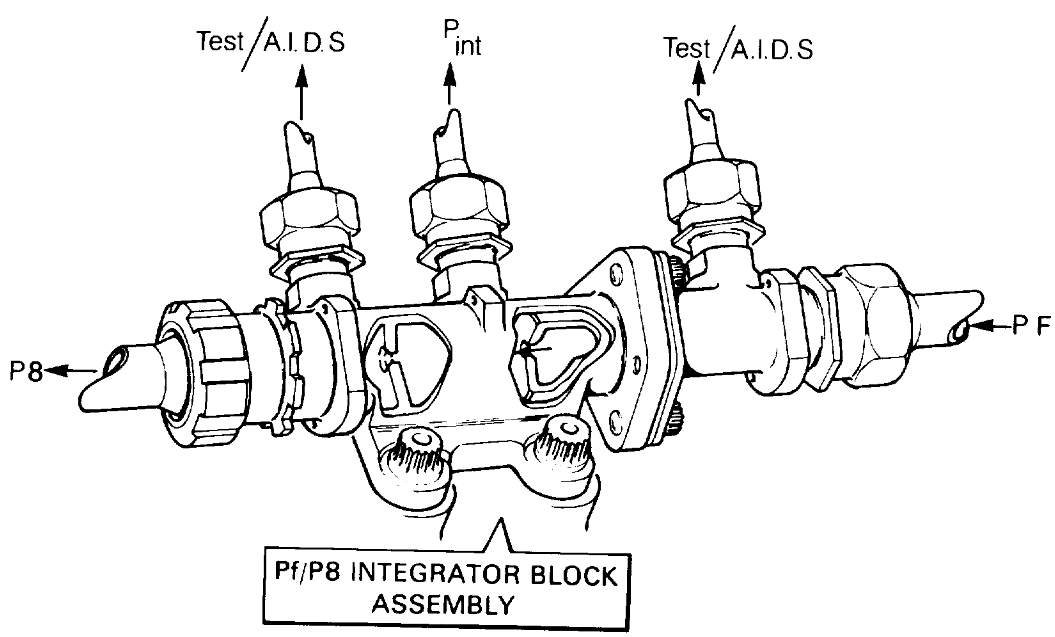

FIGURE 10

Selection of EPR trimmer on pass off

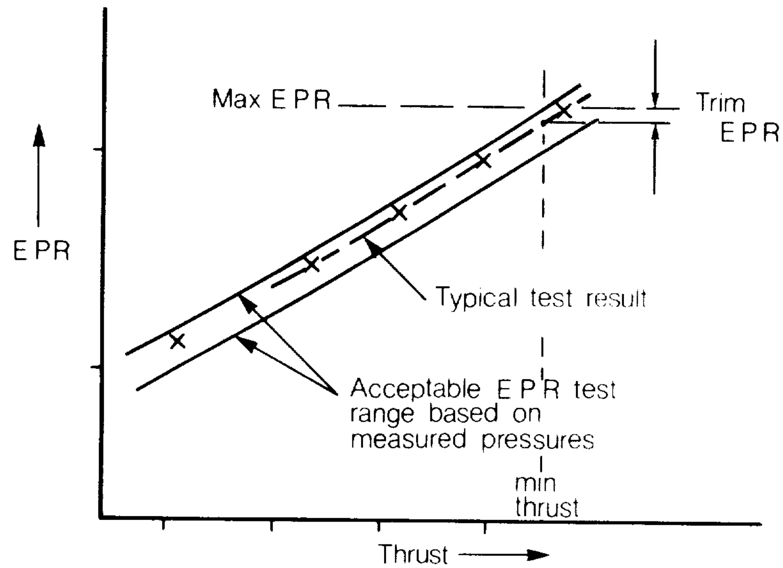

FIGURE 11

RB211-524 In flight deterioration

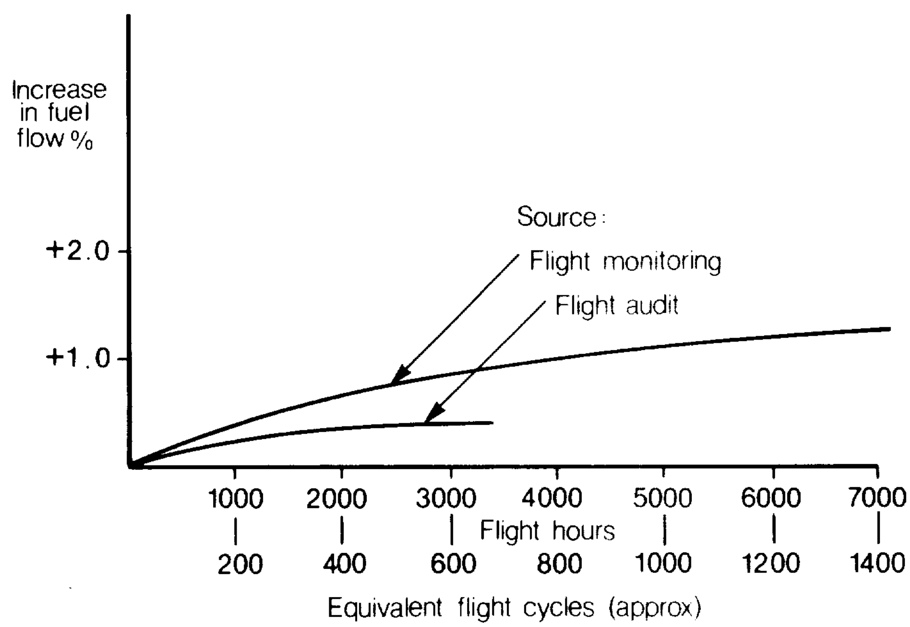

FIGURE 12

RB 211-524 Comparison flight monitor and test cell derived deterioration

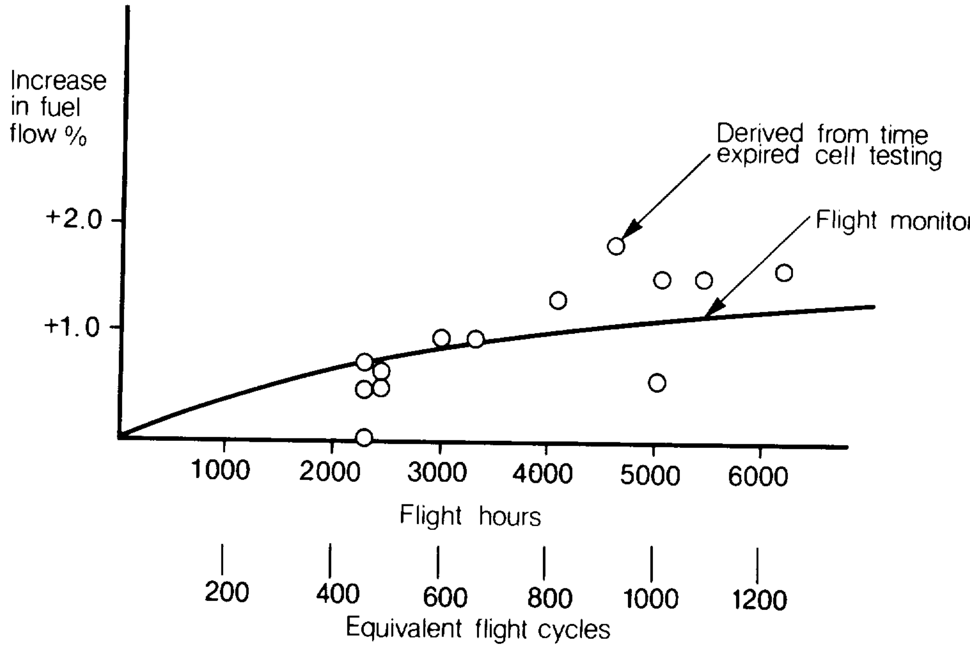

FIGURE 13

RB 211-524 Overhaul engine pass off performance relative to new

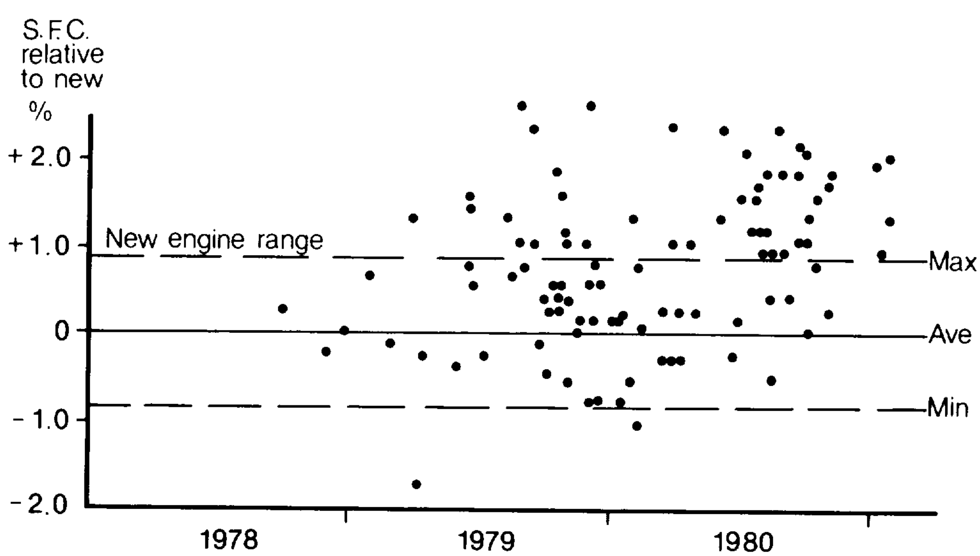

FIGURE 14

RB 211 Fan leading edge restoration

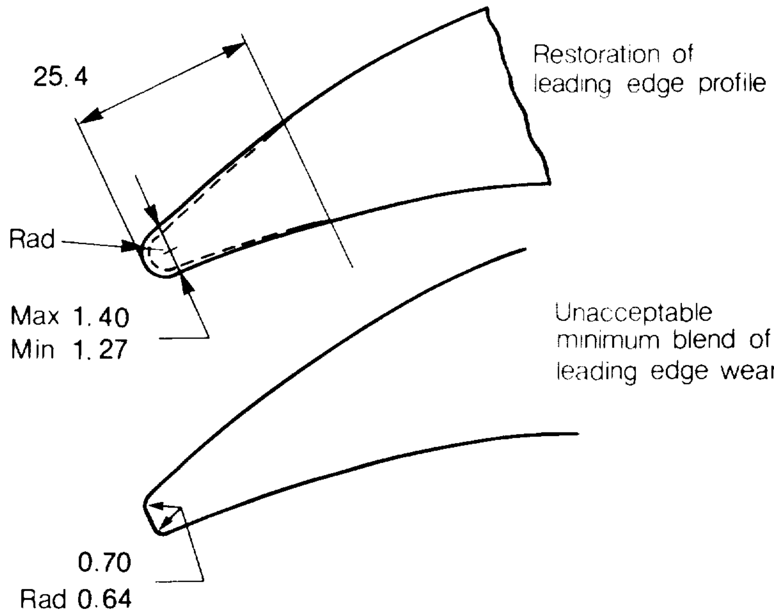

FIGURE 15

RB211 I.P. Turbine shroud segment

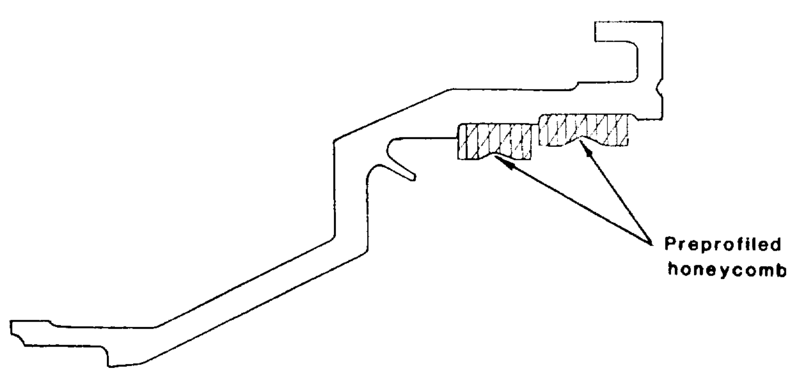

FIGURE 16

RB211 Turbine internal cooling airflow

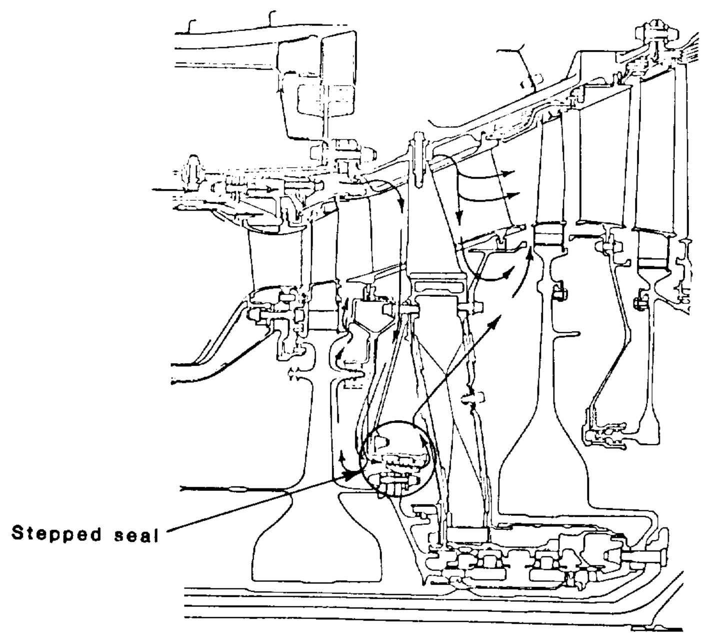

FIGURE 17

RB211-22B Test bed takeoff T.G.T. cusum plot

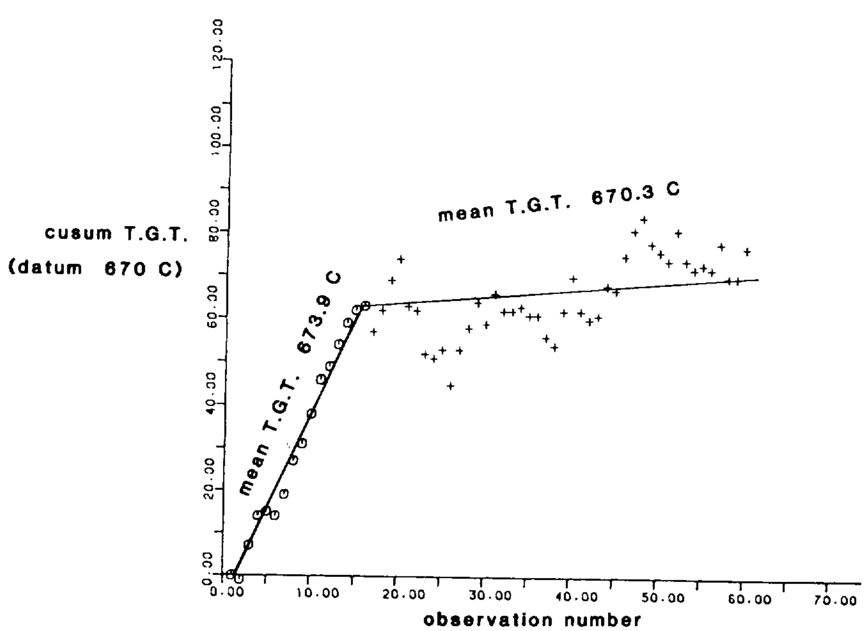

FIGURE 18

RB211 H.P. System

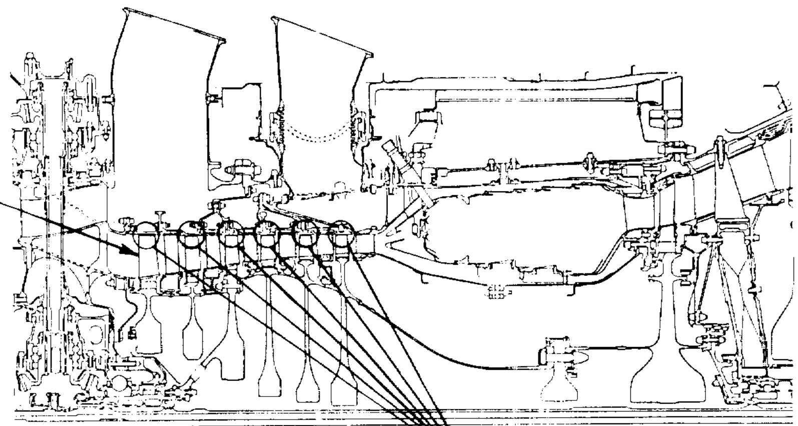

FIGURE 19