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MEASUREMENT TECHNIQUES USED TO ASSESS THE INSTALLED POWER OF A HELICOPTER ENGINE

T.G. Morton

Rolls-Royce Limited,
Leavesden,
Watford,England.

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Garmisch - Partenkirchen
Federal Republic of Germany

Deutsche Gesellschaft fur Luft-und Raumfahrt e.V.
Goelhestr. 10, D-500 Koln 51, F.R.G.

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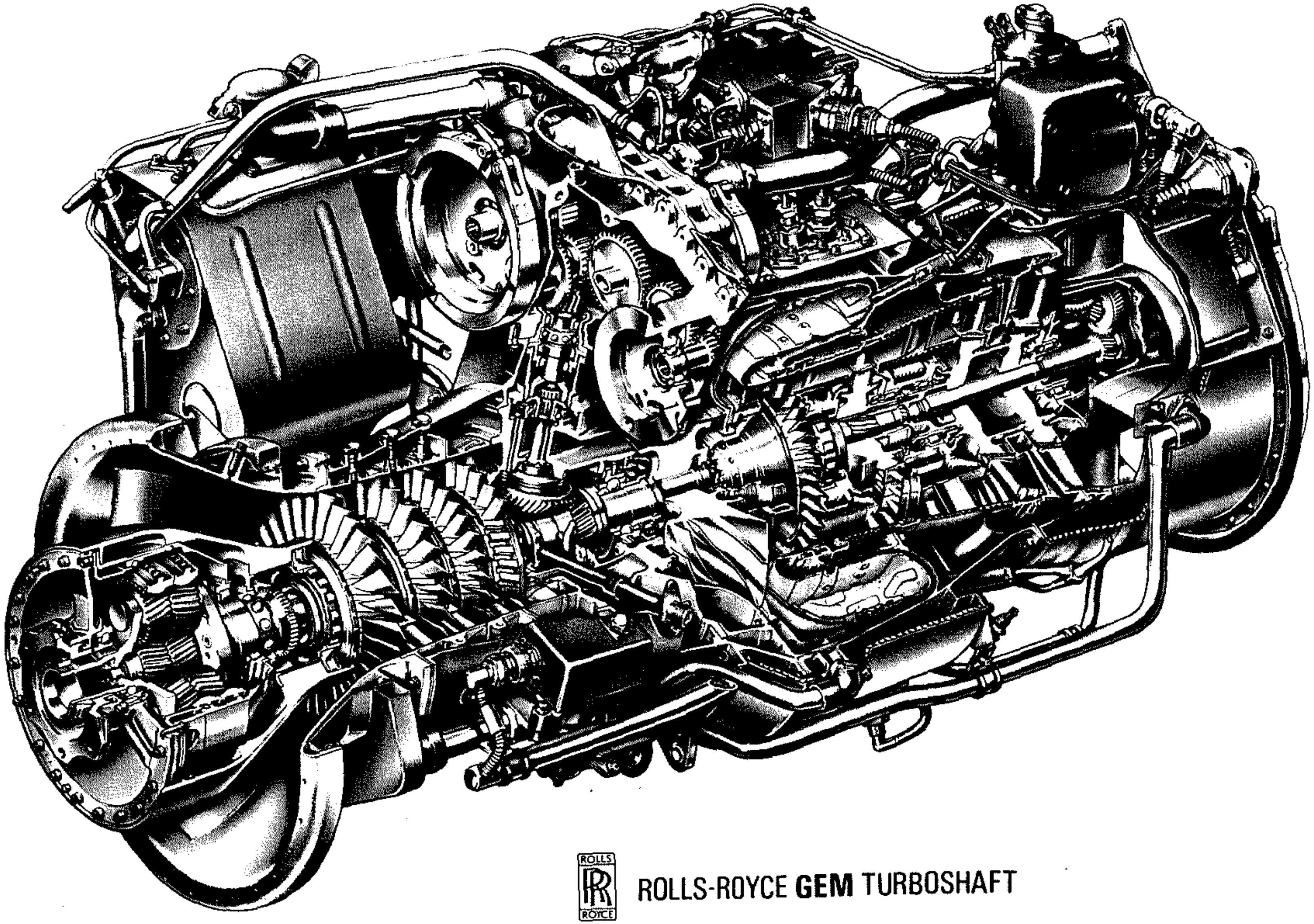
ABSTRACT

In order to improve helicopter performance predictions, it is important to quantify any change in engine performance between the test bed and 'as installed' in the aircraft, and to be able to attribute the reasons for any change as accurately as possible. This paper discusses the measurement techniques used to quantify this performance for a particular Rolls-Royce Gem Engine installation. Extra sensors were added to engines in a production Lynx helicopter which was fitted with recorder equipment in the cabin and flown to a defined schedule.

If the engine is considered as a thermodynamic unit, the input/output equation must balance. Test point data based on these inlet and exhaust conditions were obtained from both test bed and flight tests. Analysis of results when compared to a thermodynamic model of the engine, shows that the resultant data is very sensitive to the quality of measurements and will quickly show the deviation from predicted characteristics.



ROLLS-ROYCE **GEM** TURBOSHAFT

1.0 INTRODUCTION

During the design and development stages of a new gas turbine it is usual to find that future helicopter applications are often not specifically defined. As these application designs proceed, it is necessary to understand the influence of the installation on the predicted engine performance. In order to improve these predictions, it is important to quantify any change in engine performance measured in the test bed and 'as installed' in a helicopter.

Having quantified these changes it is necessary to obtain sufficient measurements to be able to attribute the reason for any changes to particular aspects of the installation design. Since relatively small differences are being measured it is necessary to design an instrument system capable of producing high accuracy results.

This paper discusses the measurement techniques used to quantify these aspects of engine performance of a Rolls-Royce Gem engine in a Lynx helicopter.

2.0 STRATEGY/PHILOSOPHY

An aero-engine can be considered as a thermodynamic 'black box', that is to say, if the inlet and outlet interfaces are clearly defined, the energy into the 'box' must equal that leaving the 'box'.

Measurements were therefore proposed at the interfaces and within the 'box' so that it could be shown that the operational performance was unchanged when the box was transferred from the test bed environment to that of an aircraft installation. Any significant change would indicate that external influences, such as intake profile, were affecting engine characteristics. This would be evident from data showing a change in relationship of such parameters as Power (SHP) and Turbine Entry Temperature (TET).

For the Gem installation, interface planes were chosen such that the total 'box' and instrumentation could be conveniently transferred from the test bed to the helicopter. At the engine inlet, the front face of the engine intake was chosen as the interface. In the exhaust plane it was not practical to install instrumentation into the engine. The interface plane was therefore moved to the front of the helicopter tail-pipe.

Special pressure and temperature probes were designed to quantify aerodynamic conditions at inlet and exhaust to enable a comparison between test bed and helicopter to be made. These sensors had been fitted to the engine to demonstrate that tail-pipe gases, say 100°C, were not re-circulating.

The other two very important parameters relating to the above energy equation are, of course, fuel flow in and power out of the 'box'. Since the engine has an accurate built-in torquemeter, it was possible to transfer this unit and the fuel flow vane direct from test bed to helicopter.

3.0 QUANTITIES MEASURED

Engine parameters that affect the aerodynamics and are available in a production Lynx helicopter consist of:-

Engine Rotor Speeds:-	
- L.P. spool	NL
- H.P. spool	NH
- Power turbine	NF
Power Turbine Inlet Temperature	PTIT
Engine Torque	Tq

To calculate power at a turbine entry temperature (TET), it is necessary to measure certain parameters and derive a combustion chamber temperature rise.

Probes were therefore fitted in the compressor exit plane to measure stream total pressure and temperature (P3, T3) which, together with fuel flow (WF), are use to calculate TET.

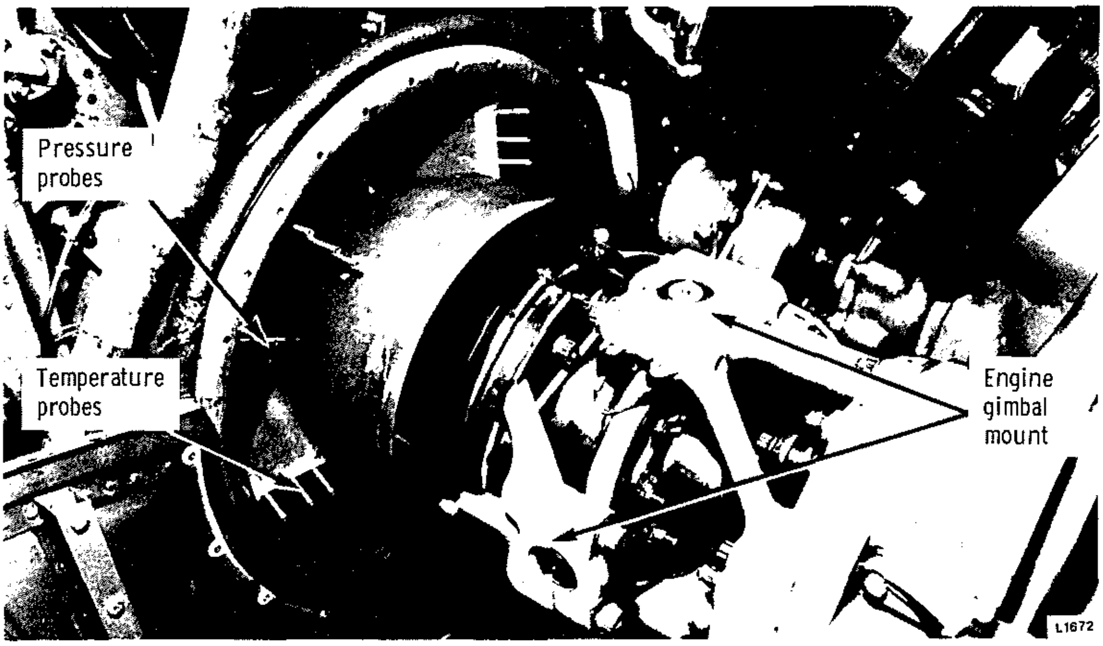


Fig.1. Plate showing relative position of the pressure and temperature probes in the engine air-intake

The cast intake of the Gem engine contains five radial spokes supporting the central reduction gearbox. Since it was considered necessary to obtain both pressure and temperature profiles, these spokes were used in the instrumentation design to support three pitot-type thermocouple probes per spoke, i.e. fifteen T01, per intake. To measure pressure profiles, three-point Kiel total pressure probes were designed to be mounted in between each of the above five spokes, i.e. fifteen P01, readings. Fig.1 shows these intake mounted probes in the aircraft installation. To quantify engine outlet conditions, eight two-point temperature probes (T8) were mounted in the front of the aircraft tail-pipe. Four wall static pressure tapping were mounted in the same place and measured on a peizometer ring (P8).

The reference pressure for the engine cycle was taken as the total pressure (PTOT) measured by the aircraft pitot probe. This pressure and the equivalent pitot static to total (IAS) were measured on two dedicated absolute pressure transducers. It was therefore possible to use differential transducers for the fifteen intake and one exhaust pressure and reference them to aircraft PTOT. Figure 2 shows diagrammatically the position of these sensors in the engine and their relationship with aircraft sensors.

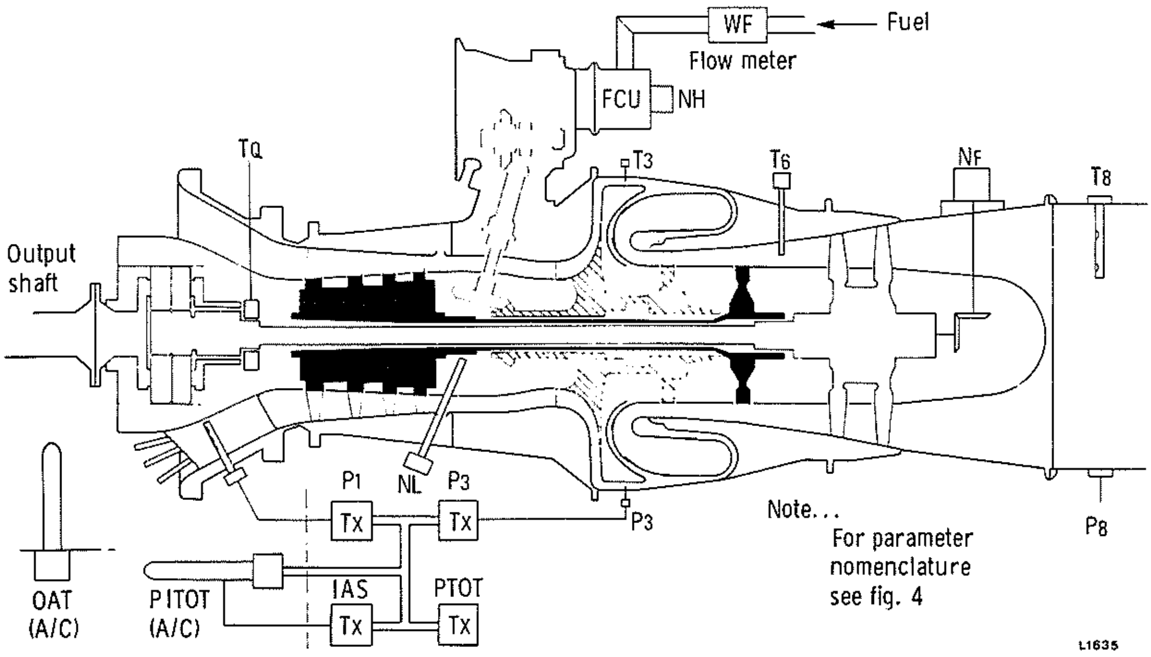


Fig.2. Sensors used for flight trials

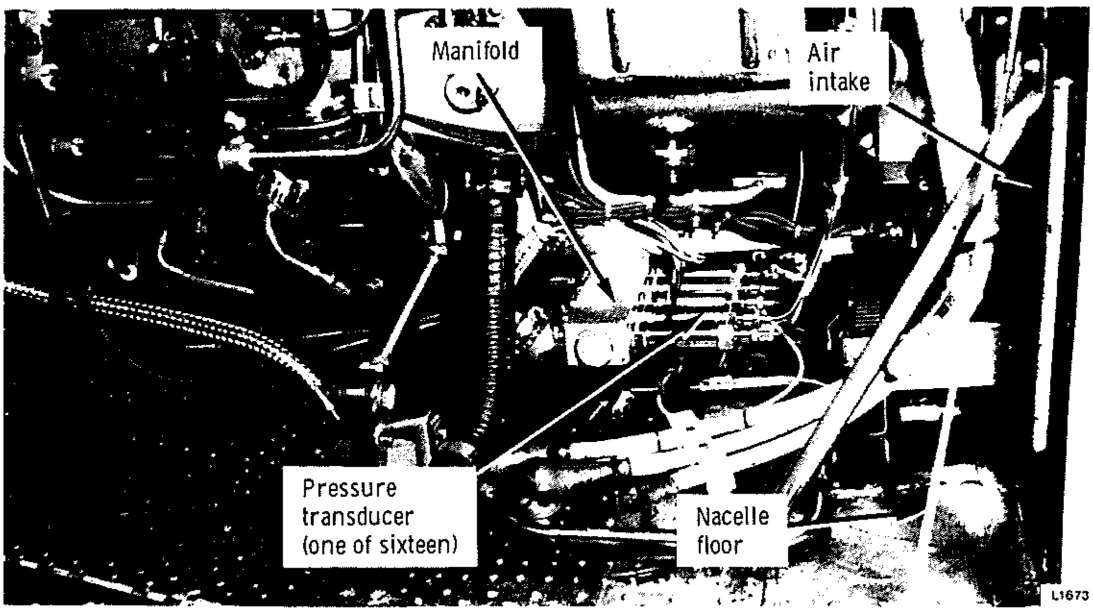


Fig.3 Plate showing installation of manifold and intake pressure transducers

Each engine therefore had sixteen transducers mounted on a manifold and connected to the PTOT line. The installation design solution is shown in Fig.3 which clearly illustrates the confined space available for special instrumentation.

Free Air Temperature is usually a difficult measurement to make on a helicopter. For this test two OAT probes were mounted on the underside of the fuselage, a position previously found to be most representative. This air temperature was used as a datum to monitor any temperature rise in the intake at the T01 plane.

A list of all the parameters measured and associated accuracies are listed in Fig.4. A Root Mean Square (R.M.S.) accuracy is derived from the individual component accuracies in the system. The repeatability is estimated from system design but substantiated by repeated calibrations throughout the flight trials.

Ident	Parameter	Transmitter	System Design Accuracy				Repeat-ability
			Sensor	S.C.U.	DAU	RMS	
P01	Intake Total Pressure	3-Point Pressure Rakes Transducers Type PDCR 10/L/A	±0.5 inch water	-	±0.25% FSD	±0.63 inch water	±0.5 inch water
T01	Intake Total Temperature	3 Chromel/Alumel Thermocouples per Engine Spoke	±1.0°C	±1.0°C	±0.25% FSD	±1.5°C	±0.25°C
NL	L.P. Rotor Speed	PCU Ground Test Socket	-	-	±0.25% FSD	±0.25% FSD	±0.1%
NH	H.P. Rotor Speed	Tacho-Generator	-	-	±0.25% FSD	±0.25% FSD	±0.25%
NF	P.T. Rotor Speed	Tacho-Generator	-	-	±0.25%	±0.25%	±0.25%
P3	H.P. Compressor Delivery Pressure	Single Point Pressure probe with SE180 transducer	±0.25% FSD	-	±0.25% FSD	±0.35% FSD	±0.25%
T3	H.P. Compressor Delivery Temperature	4 Chromel/Alumel Thermocouples meaned	±1.0°C	±2.5°C	±0.25% FSD	±2.96°C	±0.5°C
WT	Fuel Temperature	Resistance Temperature Bulb	±0.5°C	±0.5% FSD	±0.25% FSD	±1.02°C	±0.5°C
T6	Power Turbine Inlet Temperture	6 Chromel/Alumel Thermocouples meaned	±1.0°C	±5.0°C	±0.25% FSD	±5.68°C	±1.0°C
T8	Power Turbine Outlet Temperature (i.e. Tail-pipe)	8 Probes each with 2 Chromel/Alumel Thermocouples, all meaned	±1.0°C	±5.0°C	±0.25% FSD	±5.68°C	±1.0°C
PTOT	Aircraft Pitot Total Pressure	Transducer Type PDCR 60/A	±0.25%	-	±0.25% FSD	±0.35%	±0.1%
IAS	Indicated Airspeed	Transducer Type PDCR 10/L/A	±0.5 inch water	-	±0.25% FSD	±0.63 inch water	±0.5 inch water
P8	Tail-pipe Static pressure. Mean of 4 points	Transducer Type PDCR 10/L/A	±0.5 inch water	-	±0.25% FSD	±0.63 inch water	±0.50 inch water
WF	Total Engine Fuel Flow	Faurie Herman Flow Vane Type TR1024 16 NM	±0.25%	-	±0.25 FSD	±0.35%	±0.25%
TQ	Engine Torque	Phase Displacement Torquemeter	±1.5%	±0.5%	±0.25% FSD	±1.60%	±0.5%
O.A.T.	Outside Air Temperature	Resistance Temperature Bulb	±0.5°C	-	±1.5% FSD	±2.75°C	±0.25°C

Fig.4. Instrumentation accuracy for installed power investigation

4.0 RECORDING SYSTEM

Summarising the quantities to be measured it can be seen that there are twelve main engine parameters and thirty intake parameters per engine to be recorded during the flight and test bed programme.

Flight test experience at the time of this system design pointed to one obvious solution. For some years UK Ministry of Defence had contracted Plessey Electronic System Ltd., to produce digital flight recording equipment to meet the needs of an Engine Usage Monitoring programme being undertaken by the British Services. This system became known as EUMS equipment.

Rolls-Royce had experience of over 2000 hours of flying this equipment in the Lynx Flying Test Bed (FTB) for development purposes. It was therefore proposed that an adapted version of EUMS be designed into a system capable of meeting the requirements of the new programme. The design concept of this measurement system is shown in Fig.5 illustrating the interaction of all the sub-systems used.

The standard EUMS was designed to meet ARINC 573, a specification defining the salient points of flight data acquisition systems. One accepted output format is 32 data words per second in serial form. This data stream is assembled into a major frame consisting of four x 64 word sub-frames which is fundamental to the system design.

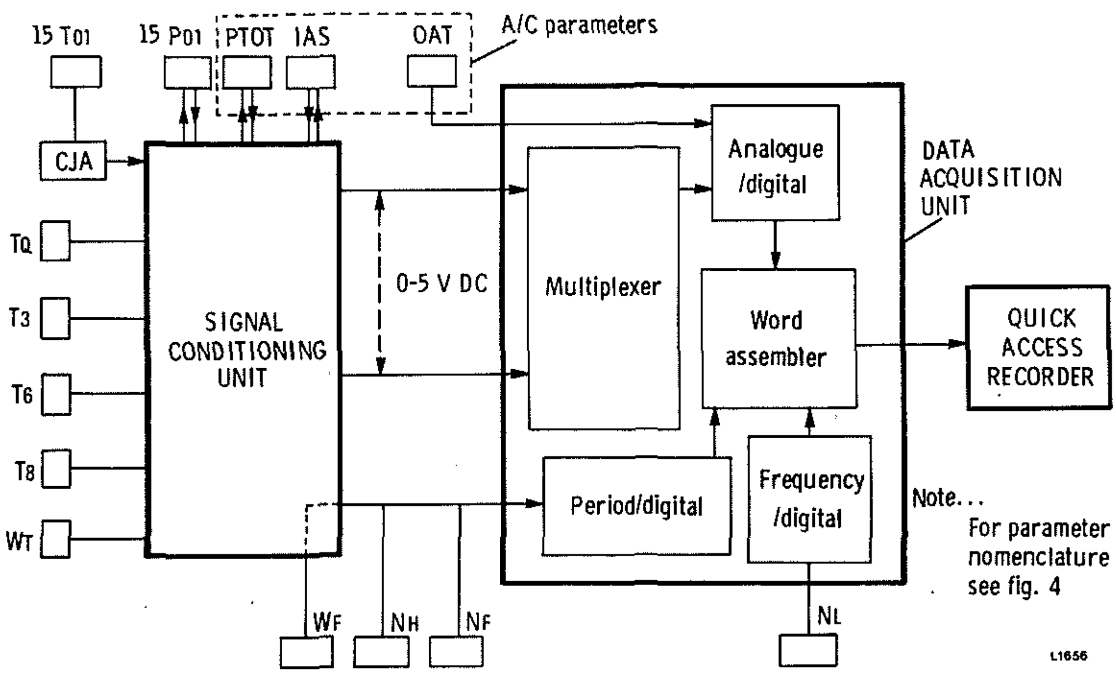


Fig.5. Measurement system used to assess installed engine power

Since the Gem engine has a very fast response it was decided that the main engine parameters (12 off) should be sampled at a rate of twice per sec. Eight words could then be allocated for the thirty intake parameters per engine. These parameters therefore required pre-multiplexing which enabled fifteen intake temperatures to be scanned in the first sub-frame and fifteen pressure in the second sub-frame. A scan of all parameters would therefore be repeated every four sėconds.

Since the standard EUMS equipment is designed to interface with a limited number of signal types, it was necessary to undertake signal conditioning of some sensor outputs from the engine. Plessey therefore designed and manufactured a special signal conditioning and multiplexing unit (SCU) to interface between the sensors and the standard Data Acquisition Unit (DAU) of the EUMS equipment.

Similarly, Servicon Dynamics Ltd., engineered a special 30-Channel Cold Junction Thermocouple Amplifier Unit for the intake sensors. This unit provided outputs range 0 to 5 volt to match the DAU interface levels. Each of the 32 pressure transducers contained individual amplifiers producing this 0 to 5 volt output range.

The DAU scans the input parameters, converts to digital signals and assembles these in the predetermined order of the format. Output from this DAU is passed to a Quick Access Recorder (QAR) which uses standard digital tape cassettes. These cassettes have a 2-3 hour capability but are usually changed for each flight. A base board was used to mount all this equipment on the rear of the cabin floor as shown in Fig.6. This provided good accessibility for calibration and cassette changes.

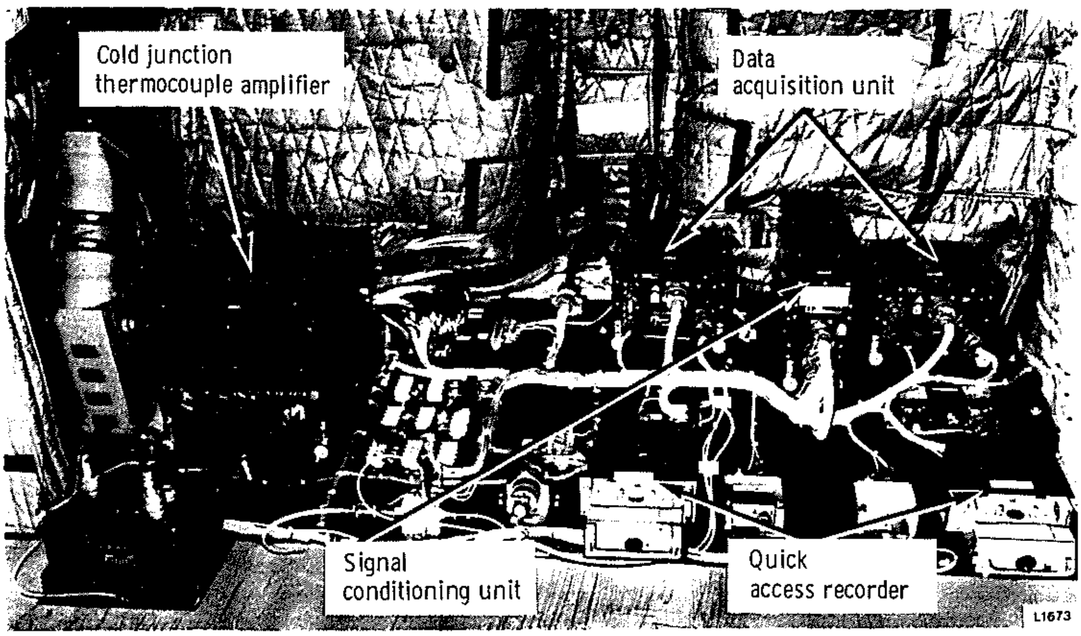


Fig.6. Rear view of cabin showing equipment and recorders on baseboard

5.0 GROUND DATA PROCESSING SYSTEM (GDPS)

Rolls-Royce (Bristol) operate a G.D.P.S., under contract to MoD(PE) to replay the cassettes from the EUMS programme produced at squadron level. It was therefore very convenient that cassettes from this special flight programme could utilise the same system.

After replay the flight data was scaled to engineering units and stored on disc file of a main frame computer, available for all appropriate analysis programmes.

6.0 TEST PROGRAMME

To demonstrate repeatability of engine performance and integrity of data, the programme was planned to include test bed, flight test and repeat test bed engine testing. It was felt necessary to undertake this classical A/B/A sequence to demonstrate that the engine characteristics had not changed during the flight programme.

The system design was such that both engines with appropriate sensors and all recording equipment could be transferred from test bed to aircraft and back again. This approach has the very significant advantage that if the measurement system is designed for good repeatability, very small changes in engine behaviour can be detected.

System through calibrations were undertaken both on the test bed and in the aircraft after engine and equipment installation and commissioning. Such calibration provides a very accurate relationship between known engineering units at input and the output of the measurement system. For parameters with a non-linear relationship sufficient data points were obtained to produce polynominal type curve fits which were subsequently used to scale the test data.

To produce engine datum characteristics, the initial test bed running was undertaken in the production test configuration, i.e. with 'ideal' intake and exhaust pipe. Data was obtained over most of the operating envelope of the engine.

A Lynx aircraft intake and exhaust pipe were then fitted to the engine in the test bed and the sequence of testing repeated. Both engines were passed through this test programme.

Initial flying of the aircraft was aimed at a 'shakedown' of the equipment, instruments and engines transferred from the test bed. These first few flights highlighted a number of minor equipment faults which were identified and rectified. Typical problems were intermittent faults on fuel flow signal conditioning and pressure transducers exhibiting drift, which were therefore replaced.

Normal test techniques consisted of continous cassette tape recording during engine running but incorporating an event marking device. This was used on both the test bed and aircraft recordings enabling the test engineer to press a button which event marked the recording at each test point in the schedule.

It was therefore possible during analysis to select 32 seconds of data at each test point. These test points may have been a series of power settings over the range, various forward speeds or whatever was appropriate to that part of the trials investigation.

At about the fifth flight in the programme it appeared that a good valid data stream was being added to the main frame computer store.

7.0 ANALYSIS AND VALIDATION TECHNIQUES

7.1 System Proving and Validation

Initial analysis of this data showed that the temperature of the intake T01 was about 3°C above Outside Air Temperature (OAT). With such a small temperature rise, it had to be proved that conduction errors were not present in the intake temperature sensors due to inadequate design.

Before the engines went to test a spare intake was fitted with sensors as shown in Fig.1 and bolted to the inlet pipe of a large compressor facility capable of passing the full air mass flow of the engine. To simulate environmental conditions the intake was connected to a source of hot oil which passed through the central main reduction gearbox space and out of the normal scavenge port at the bottom. The test programme varied the oil temperature and the air mass-flow to represent engine conditions. Results showed that under worst conditions the error did not exceed 0.8°C.

Since analysis of flight data showed a delta 'T' (T01 - OAT) of about 3°C, a special proving flight was undertaken to verify sensor accuracy. The aircraft was flown at 2500 ft at 100 kts and at stable conditions the port engine was shut-down. These conditions were flown for one hour to allow the complete engine and all thermocouples to cool down to 'through' air temperatures.

Subsequent analysis of this data showed that T6 and T8 thermocouples took most of the shut-down hour to cool but a 32 second data set at the end gave the following results, which include two standard deviations of each data set.

	T3	T6	T8	Average	T01	OAT
°C	11.50	12.43	11.33	11.74	11.94	9.31
2 Sigma	$\pm$0.83	$\pm$1.06	$\pm$0.85	$\pm$0.92	$\pm$0.23	$\pm$0.20

The average of the three parameters over the time period shows good correlation with the T01 average. Standard deviations show that parameters T3, T6 and T8 were less stable, perhaps because of residual heat under 'windmilling' conditions. T01 had minimal scatter with a difference of only 0.2°C from the average of the other three parameters. All of these planes showed a consistant datum shift of about 2.5°C from the OAT measurement. Since different measurement system design was used for T01 as compared to planes T3, T6 and T8, it was concluded that valid data was being recorded.

Fig.7a shows the relative position of the intake thermocouples and pressure probes. The intake temperature data from the above test was entered into a polar plotting routine used on the mainframe computer. This programme produces a best curve fit both radially and circumferentially through the data provided. Fig.7b shows a typical temperature profile in the intake plane after the one hour shut down. Fig.7d shows the equivalent profile at high altitude and high single engine power conditions.

Temperature and pressure measurements taken in the intake plane

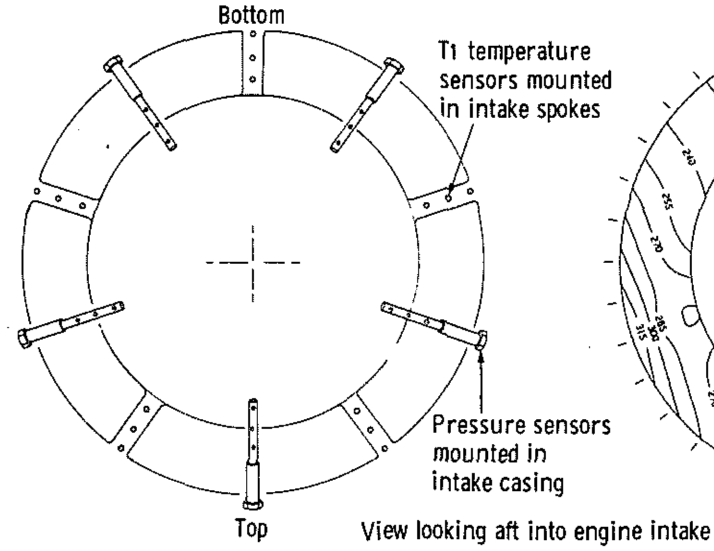


Fig.7a Position of temperature and pressure sensors in Gem engine intake

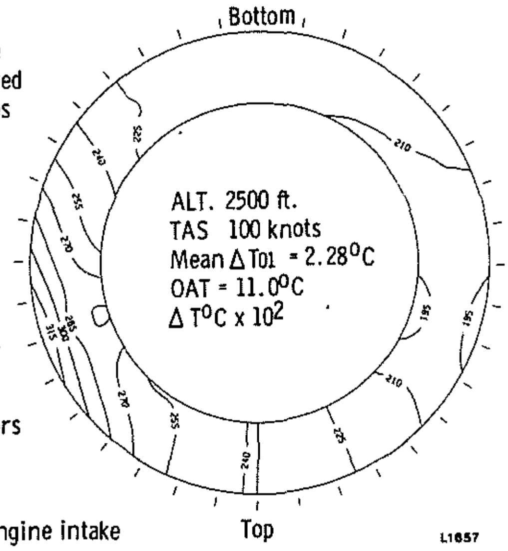


Fig.7b Intake temperature profile after one hour shut down

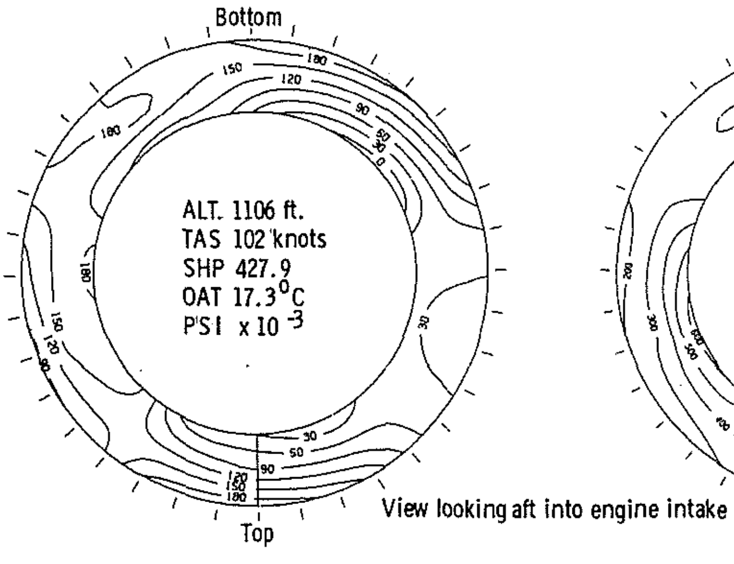


Fig.7c Typical intake pressure profile

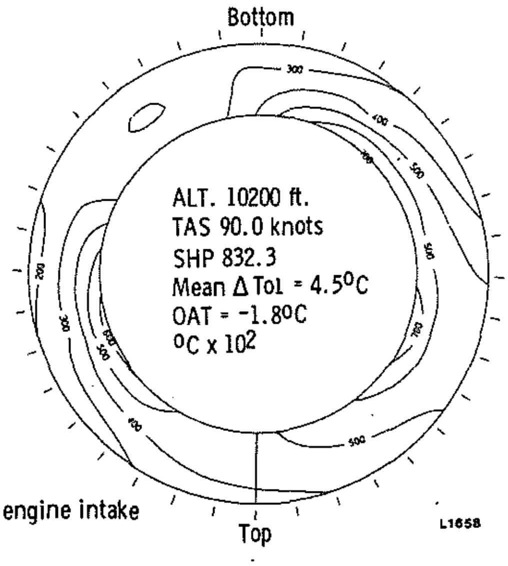


Fig.7d Typical intake temperature profile at high engine power

7.2 Data Analysis

During the 36 hours of flight testing a very large amount of raw data was accumulated in computer store. To enable detail investigations of engine behaviour, a suite of programmes was written to assist specialist engineers in the analysis of this data.

This system and procedure proved a very powerful tool to 'sift-out' the relevant aspects from a large data bank. With multiple terminal access at visual display units (VDU) a number of engineers could carry out simultaneous analysis. Hence an aerodynamicist could be evaluating intake characteristics whilst an engine performance engineer carried out thermodynamic analysis between plane 1 and 8.

Having substantiated the T01 sensors, a broad analysis of the intake temperature rise was undertaken. This showed that the best correlation could be demonstrated between delta 'T' and engine shp. Fig.8 shows a mass data plot of event marked points from 14 flights. A best curve fit was applied to this data and a definition of the two standard deviation lines added.

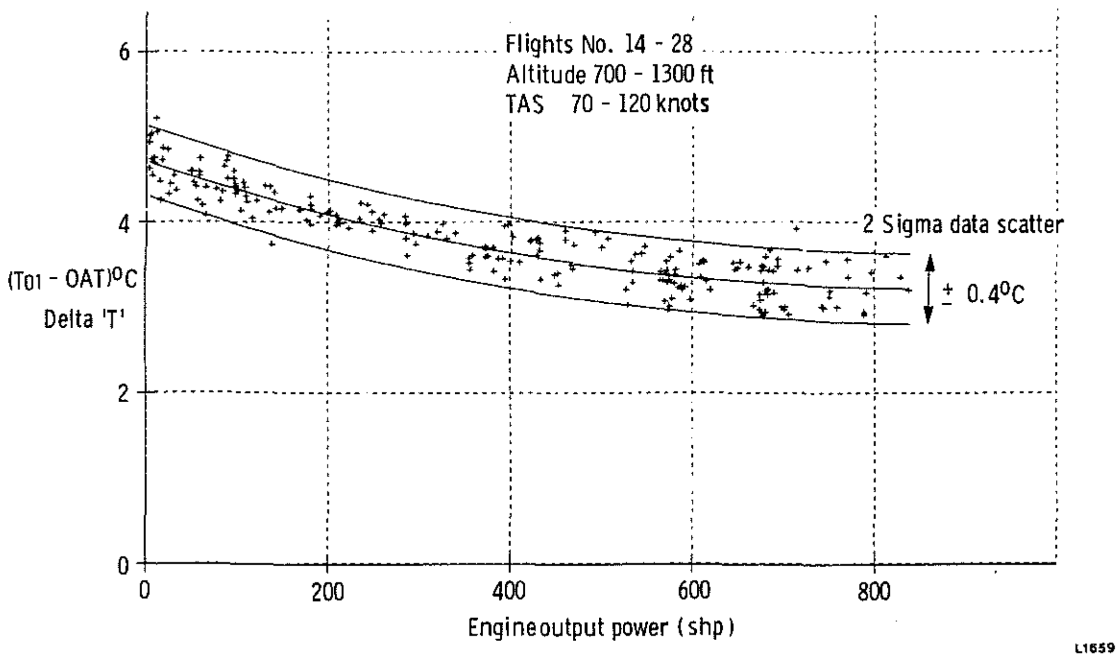


Fig.8. Plot of intake Delta 'T' against engine power

This showed that the sum of the engine and measurement uncertainties, or repeatabilities, was not greater than ±0.4°C. Repeatabilities quoted in Fig.4 were ±0.25°C for both T01 and OAT. These results were very encouraging and gave a high level of confidence to conclusions drawn from the tests.

Pressure measurements in the intake were taken to quantify pressure distortion profiles at the engine inlet plane and the total pressure recovery of the aircraft intake. Fig.7c shows a typical profile at 100 kts. This type of analysis showed that throughout the flight envelope, the pressure profiles obtain agreed very closely with model testing previously undertaken.

Data from the PITOT total pressure sensor was used with the mean PoI reading to calculate the intake pressure recovery. Fig.9 shows these recovery factors measured over a wide aircraft speed range. These results again gave good correlation with model testing.

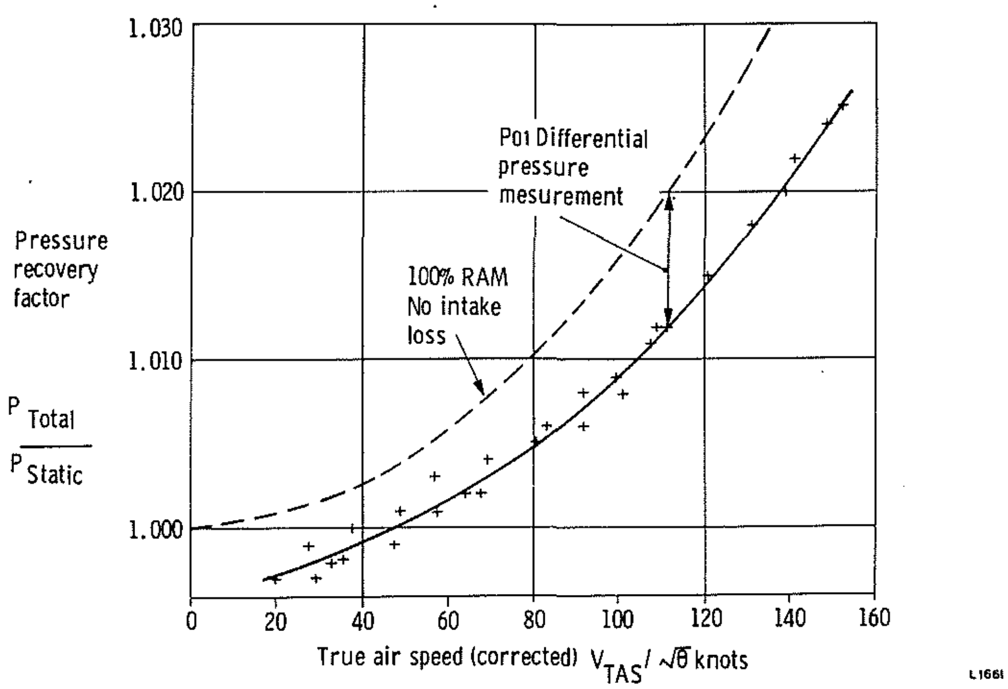


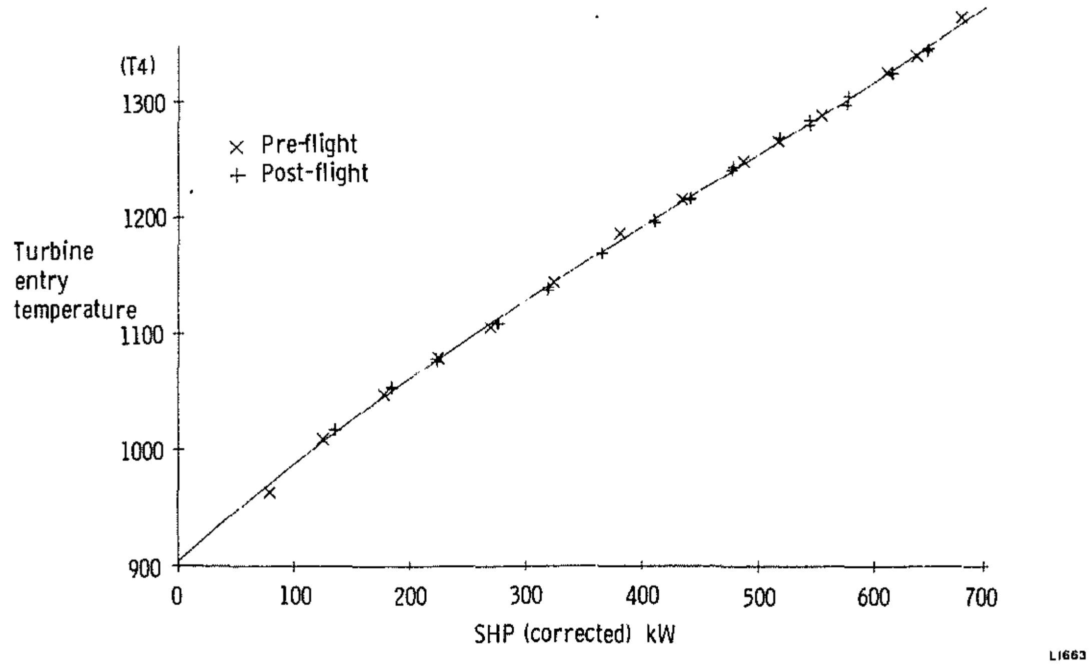
Fig.9. Intake pressure recovery

Accuracy of the pressure data was considered to be well within that predicted by repeated calibrations, i.e. ± 0.5" H_2O. It is reasonable to assume that airflow over the aircraft and PITOT is not very stable below about 60 kts. However, at the higher forward speeds the sum of the intake and measurement uncertainties was less than ± 0.2" H_2O.

This enabled many useful pressure profile plots to be obtained, similar to Fig.7c, with the aircraft operating in all relevant flight modes.

Thermodynamic analysis of engine performance between planes 1 and 8 was carried out on data recorded in these flight modes. To illustrate the results of these analysis techniques, typical computer generated plots are shown on Figs.10 and 11.

The first two graphs, Fig.10, show two critical parameters plotted against output power (SHP). These parameters are Turbine Entry Temperature (TET), which is derived from compressor outlet conditions (T3, P3) and fuel flow, (WF), and HP Rotor Speed (NH), a direct measurement. Data from a preflight and post-flight test bed engine calibration is plotted in Fig.10. This analysis was presented to demonstrate that the engine performance did not change over the period of the flight trials. Close inspection of the results shows this to be well proven. TET scatter about a best curve fit for both runs is generally less than 5°C with the occasional point showing a 10°C deviation. Similarly with rotor speed, the maximum deviation is $\pm 0.5\%$.



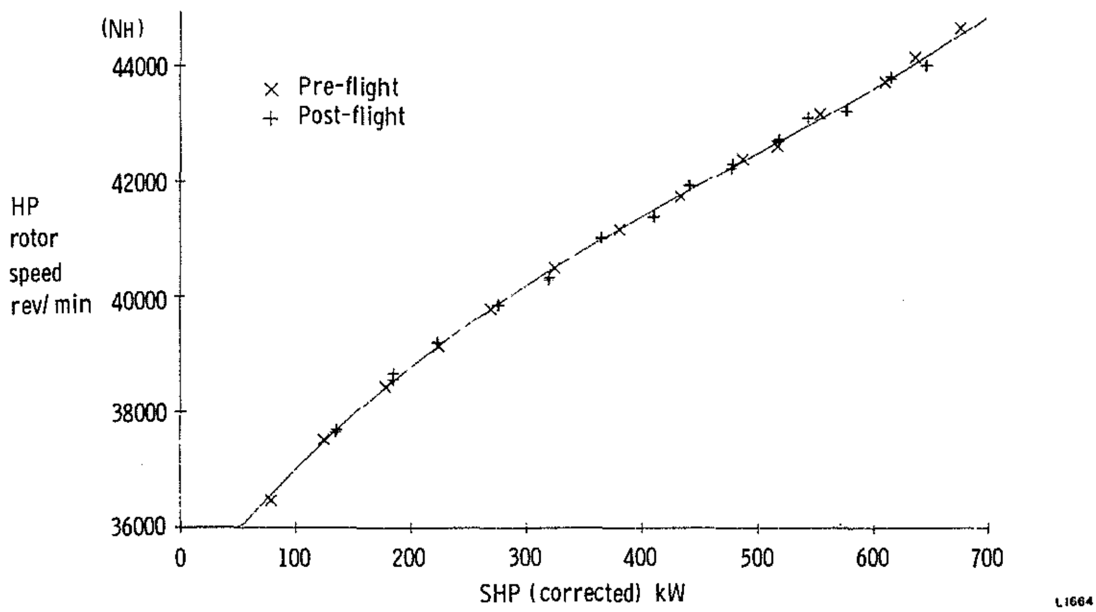
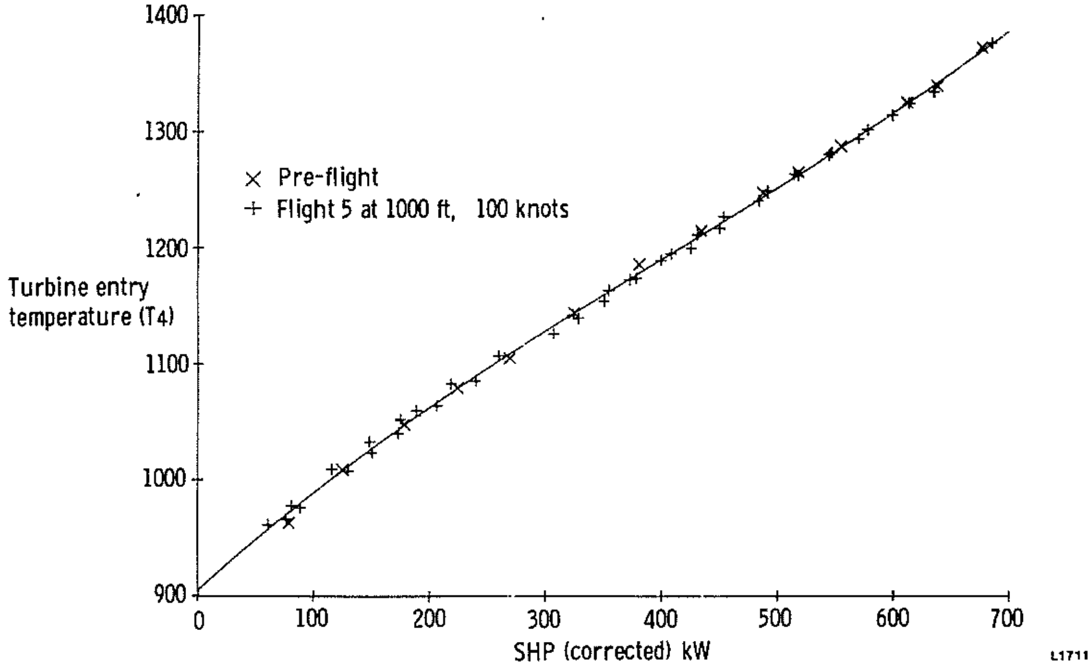


Fig.10 Comparison of critical measurements taken on the test-bed before and after flight trials



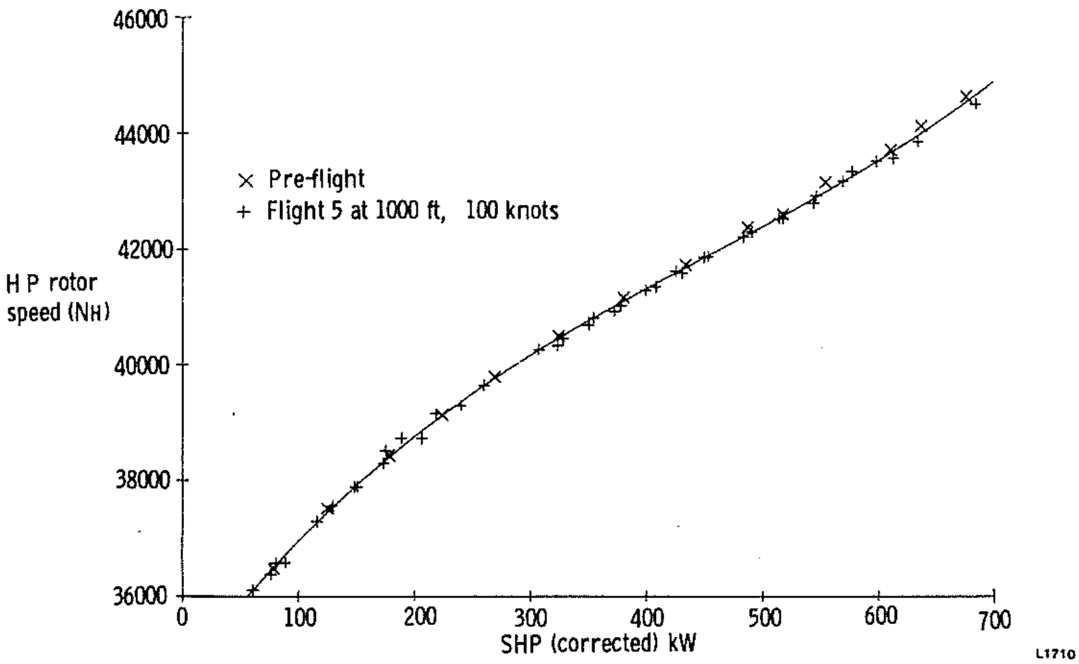


Fig.11 Comparison of critical measurements taken on the test-bed and during flight trials

Fig.11 presents results in a similar manner but compares the pre-flight test bed calibration with one of the flight engine calibration. Constant altitude and forward speed was maintained whilst test points were recorded over the engine power range, the second engine automatically compensating for the aircraft power requirements.

Conclusions from this flight data are similar to those of Fig.10 in that they clearly demonstrate no change in the engine characteristics when it is transferred from a test bed to an aircraft installation.

8.0 POST TRIALS CONCLUSIONS

In conclusion these flight trials set a notoriously difficult measurement task requiring the small difference of two large quantities to be measured. Although high absolute accuracy of the measurement system was desirable, the prime requirement was to achieve a very high level of repeatability.

The task was a significant challenge to the measurement 'state of the art' using available equipment to its best advantage. Configuration of the engine mounted sensors proved very satisfactory with minimal unserviceability. Novel adaptations to the design of EUMS recording system showed it to be capable of much more than routine service aircraft operation.

Data listed in Fig.4 shows a very high level of repeatability of each parameter for the total measurement system. Although this was based on design and calibration data, the test results presented fully justifies these conclusions.

Individual measurements such as intake pressures and temperatures produced data scatter significantly less than that predicted.

For the engine thermodynamic analysis, some parameters, such as TET, had to be derived from a number of measured parameters and correct to ISA conditions using ambient temperatures and pressures. Since the TET data scatter for repeated tests was generally less than 5°C, it was considered that a very satisfactory system design had been produced.

On completion of the trials it was concluded that the measurement system and supporting ground based software played a major part in the overall success of the task. This enabled a detailed understanding of the behavioural pattern of the Gem engine in the Lynx to be obtained.

From the measurement systems aspect, valuable experience was gained in recording and handling large quantities of flight data. We would therefore not hesitate in repeating this type of installation measurement for a new engine application or any other special in-flight measurements.

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