An Altitude Test Facility for Large Turbofan Engines

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The altitude test facility at NGTE has been progressively developed over many years and now includes a test cell capable of testing large turbofan engines over a wide range of simulated flight conditions. The cell enables measurements to be made during rapid engine transients as well as at steady state conditions. Icing, freezing fog and tropical rain conditions can also be simulated. The cell is described and its basic test capability outlined. The methods used to measure the main engine performance parameters and the techniques for calibrating the measurement systems and defining their degrees of precision are described.

Introduction

THE emergence during the 1960's of the large high-bypass multishaft turbofan as the preferred powerplant for a new generation of subsonic jet transport aircraft made it necessary to consider how such engines could be tested under representative altitude conditions for development, certification—including behaviour in icing conditions—and performance guarantee demonstrations.

A large altitude test facility complex was available at the National Gas Turbine Establishment, Pyestock and the problem was to decide how the existing plant could be extended and adapted to meet the new requirements. Financial considerations were naturally of great importance and a major objective was to achieve a satisfactory compromise between test capability and capital cost.

A solution was found which met all the design objectives and which has satisfactorily proved itself in operation. This paper describes how this was achieved. The problems encountered are enumerated and reasons given for the various design choices.

Background to Test Cell Design

When the test facility requirements for the new generation of engines were first considered project design studies were in progress on a family of turbofans covering a wide range of thrust and air swallowing capacity. The largest was a 50,000 lb thrust engine having an airflow of 1850 lb/sec at takeoff and it was decided to use this as the basis for an investigation into the flight conditions that could be covered using existing compressor/exhauster plant.

It was assumed that there would be no requirement for tests with the engine inlet pressure above standard sea-level ambient so that all the exhauster plant would be available for suction duty. This implies that there is a minimum altitude below which testing is not possible, the minimum being determined by the pressure loss in the air inlet system. A reasonable design target for the over-all inlet loss at maximum throughout was thought to be 4½ psi, giving a maximum total pressure at the engine inlet of 10 psia. This defines a lower boundary to the simulated flight envelope which runs from roughly 13,000 ft at Mach No. 0.4 to 21,000 ft at Mach No. 0.9. This boundary approximates closely to a line of constant engine airflow demand. The precise level of airflow depends on the engine thermodynamics, but the 50,000 lb thrust engine previously referred to required 1400 lb/sec at an inlet pressure of 10 psia when operating at maximum continuous rating. This flow was therefore adopted as a convenient design value for the cooler and inlet system.

Air Drying

It soon became evident that the dominant problem was to define the most cost-effective way of drying and cooling the large airflows involved. The Altitude Test Facility already possessed a large absorption drier unit using silica gel as the dessicant, but its air throughput capacity was appreciably less than that required. An obvious possibility was to increase the capacity of the existing drier, but this would have required a very long length of large diameter ducting to transport the dry air to the cell location, thereby adding considerably to the cost. An alternative solution was to provide a completely new absorption drier close to the cell, but this would have been even more expensive. Various combinations of these two proposals were examined, including the possibility of using a mixture of dry air and moist atmospheric air, but all were rejected primarily on the grounds of cost. The scheme finally chosen combined the two functions of drying and cooling; the factors governing this choice are described in the following paragraphs.

Air Cooling

The Altitude Test Facility already contained a plant for the continuous production of cold air by expanding dry high pressure air in a turbine, but its capacity was insufficient to meet the demands of large turbofan engines.

It was obvious that the capital cost of equipment to give a continuous supply of cold air on the scale required was so high that it could not seriously be contemplated. Attention was therefore turned to intermittent or storage systems in which a refrigeration system of relatively small size is run for several hours to reduce the temperature of a secondary medium which is subsequently used as a heat sink during engine testing periods of shorter duration.

Several alternative schemes were considered. The one finally selected employs aqueous ammonia (33% solution) as the heat transfer medium, the cold store being cooled by a conventional vapour compression refrigeration system using Freon 22 as the refrigerant.

Choice of Cooler Design Parameters

Thermal Loading

The air temperature required at the engine inlet depends only on the flight Mach number and altitude being simulated, whilst the airflow depends on the engine characteristics and the power lever setting. Figure 1 presents data for

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a 50,000 lb takeoff thrust high-bypass turofan operating at continuous power; from this the amount of heat to be removed from the air before it enters the test cell can be calculated for any chosen flight condition. Such calculations show that at a fixed flight Mach number the heat extraction rate at first increases with altitude, then passes through a maximum and subsequently decreases. Over the Mach number range 0.4 to 0.9 the locus of the maxima approximates closely to a line of constant airflow, the magnitude of which depends on the temperature of the air entering the cooler. The variation with flight Mach number of the maximum rate of heat extraction required to simulate ISA conditions is shown plotted in Fig. 2 for ambient temperatures of 15°C and 40°C (59°F and 104°F). Corresponding altitudes are indicated on the curves; reference to Fig. 1 shows that the airflows are in the region of 800 lb/sec and 1100 lb/sec for the 15°C and 40°C curves, respectively. Figure 2 shows that up to a Mach number of about 0.5 the maximum rate of heat extraction is only marginally affected by flight speed, but thereafter it decreases with increasing speed. Changing the inlet air temperature from 15°C to 40°C (59°F to 104°F) increases the heat extraction rate by more than 50% illustrating the marked effect the choice of design air temperature has on cooler size.

Minimum Temperature

A minimum required engine air inlet temperature has to be specified since this affects the choice of the heat transfer medium and determines the capacity of the cold store. The minimum temperature depends on the minimum Mach number and the altitude at which it will occur, both parameters being determined by the aircraft flight envelope. The condition chosen was a Mach number of 0.4 at an altitude of 30,000 ft, which for an ISA standard day corresponds to total temperature of −37°C (−35°F). Figure 2 shows that this condition imposes a heat extraction load on the cooling system which is close to the maximum.

Pressure Loss

For a given flight Mach number and engine throttle setting the lowest test altitude is governed by the pressure loss in the inlet system. For design purposes the loss across the cooler was set at 3 psi when passing the design airflow of 1,400 lb/sec.

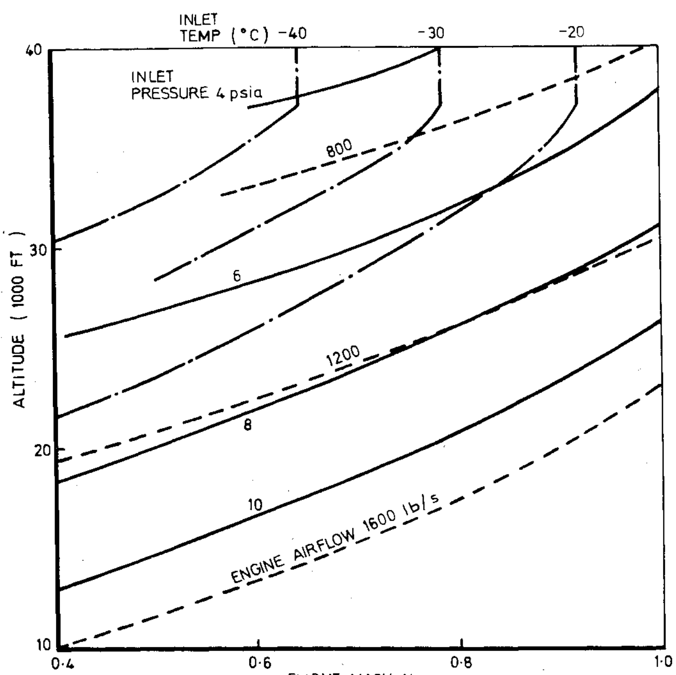


Fig. 1 Test conditions for large turbofan.

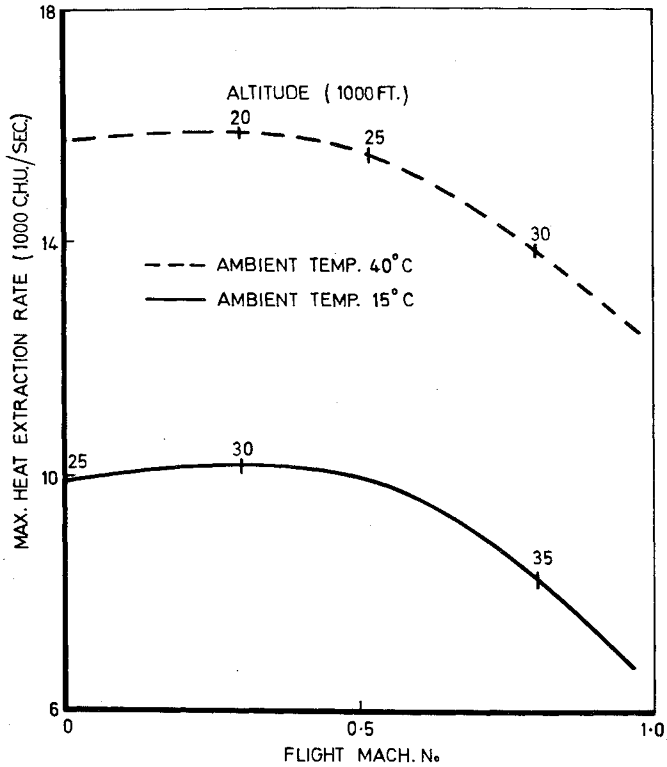


Fig. 2 Air cooler thermal loading.

Test Duration

To minimize capital costs a limit had to be set to the cooling potential and this meant defining the shortest acceptable duration for a test requiring maximum cooling load. After much discussion it was decided that the absolute minimum duration would be 30 min.

The effects of ambient day temperature and humidity on test duration were examined for two extreme flight conditions, representing stand-off and cruise, using the airflow requirements of the datum engine given in Fig. 1. For this exercise the cold store was sized so that a 30-min test could be run at conditions simulating a flight Mach number of 0.45 at 27,500 ft ISA conditions with a day temperature of 15°C (60°F) and a relative humidity of 100%. This required heat to be removed from the incoming air at the rate of 15,700 CHU/sec (28,200 Btu/sec). The results are given in Fig. 3 which shows that at a condition requiring very cold air (Mach number 0.45; 27,500 ft;) the rate of change of test duration with ambient temperature is about twice as great as at a less arduous condition (Mach number 0.85; 30,000 ft). At the datum day temperature (60°F) the maximum test duration varies only to the extent of about 30% over the required test envelope. Atmospheric humidity has a relatively small effect.

Even the relatively modest performance target represented by Fig. 3 was considered over-generous and the cold store size was finally defined arbitrarily as that required to abstract the heat equivalent of cooling 800 lb/sec of air initially at 7°C (45°F) and 100% relative humidity to −37°C (−35°F) for 30 min. This corresponds to approximately 6200 tons of refrigeration.

Description of Cell Layout

A schematic drawing of the cell is given in Fig. 4. Air is drawn directly from atmosphere into the cooler, through a

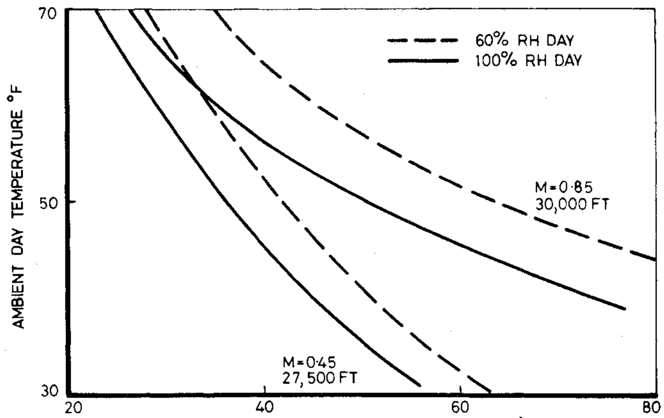


Fig. 3 Calculated test duration.

valve for pressure control and thence via an airflow measuring section to the engine. The engine exhaust is diffused, cooled by water sprays and passed to the plant exhausters which pump the gases back to atmosphere. An inbleed valve in the exhaust duct permits separate control of cell pressure and engine inlet total pressure. Both valves can be set to operate on either manual or automatic control, the latter facility enabling rapid transients to be accommodated. Figure 5 shows a general view of the cell layout.

Air Cooler

The thermodynamic design of the air cooler was undertaken by the National Engineering Laboratory, East Kilbride, Scotland. It is a gas-over-tube type constructed in modular form, the coolant flow path being so arranged that the cold aqueous ammonia makes several passes across the airflow. The moisture present in the incoming air is deposited as frost on the cooler tubes.

The 33 separate modules which make up the cooler are divided for control purposes into three sections each having its own ammonia circulating pump and coolant blending arrangement to control the coolant supply temperature automatically to a predetermined value. Final trimming to achieve the desired air temperature is carried out manually.

The cold aqueous ammonia is supplied from a large tank containing 500 tons of liquid, the normal holding temperature being −50°C (−58°F). At the conclusion of a test the cold store temperature is in the region of −15°C (5°F) and from this condition it takes about 24 hr to regenerate to −50°C.

A computer program predicting the cooler performance was developed by J. R. Singham and D. B. Spalding of Imperial College, London University as described in Ref. 1 and this was used to examine the influence of the main operating parameters and determine the best method of control.

Inlet Pressure Control Valve

The inlet valve which regulates the engine face total pressure must have a high degree of sensitivity, accuracy of control, rapid response rate and create the minimum flow distortion. A single butterfly or gate-type valve cannot meet these requirements, so a louvre-type valve was chosen having three pairs of vanes spanning a duct 12 ft square. The vanes are connected by a linkage and operated by a single hydraulic actuator which can position the vanes to within ±0.1° over an open/shut range of 70°. Figure 6 shows a photograph of the valve in the closed position.

When partly open the valve produces a grossly nonuniform flow distribution because adjacent flow passages are alternately convergent and divergent. At pressure ratios above the critical shock waves further add to the flow irregularities. To determine the extent to which smoothing devices could improve the distribution an extensive program of tests was undertaken using a one-twelfth scale model of the entire cell inlet system, including the cooler. An arrangement was finally arrived at which when applied full-scale gave a substantially flat distribution at the engine face. It required the use of gauzes spaced at intervals in the 103 in. diam duct upstream of the air-meter with a further gauze immediately downstream. The over-all pressure loss measured from the cooler outlet to the engine face is 1.7 psi at an airflow of 1000 lb/sec.

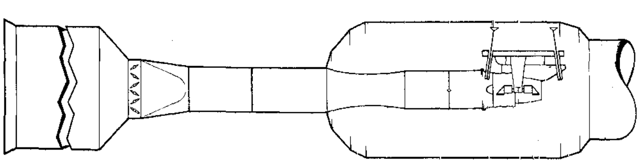


Fig. 4 General arrangement of test cell.

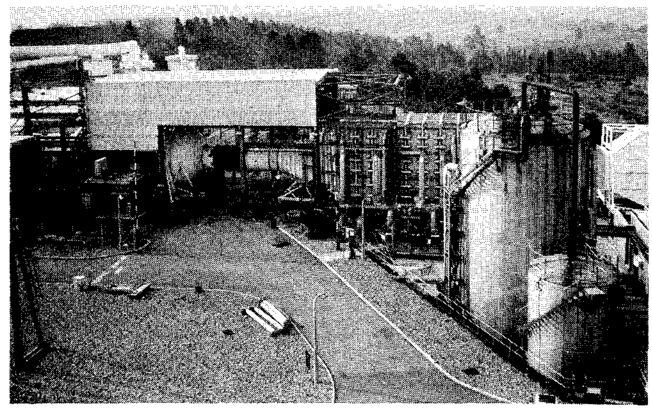


Fig. 5 General view of cell layout.

Inlet Ductwork

The airflow to the engine is measured with a venturi-type air-meter having an inlet flare and throat section moulded in fibreglass reinforced plastic, a material which enables the desired contour and surface finish to be achieved easily and simply. Six total pressure probes, wall static taps and thermocouples, the so-called "permanent" instrumentation, measure the flow conditions in the meter throat, which has a diameter of 80 in. For calibration purposes a removable 60 point total pressure rake is installed downstream of the permanent instrumentation, and this enables the relationship between the mean given by the six permanent total pressure probes and the mean defined by the 60 point rake to be established.

A slip joint is installed 28 in. upstream of the engine entry plane in the 93 in. diam inlet duct to isolate the thrust frame from the mechanical loads that would otherwise be imposed on it by the ductwork. The two halves of the slip joint are separated by a small radial gap, nominally 0.050 in., using eight radial spokes to maintain the clearance and prevent contact between the two parts. The spokes are each 24 in. long and 0.125 in. diam, and they centralize the two parts of the slip joint without imposing any significant restraint on small axial movements.

Allowance is made for the leakage of air through the slip joint when computing the engine thrust. Leakage may be either outwards (from duct to cell) or inwards depending on the flight condition being simulated.

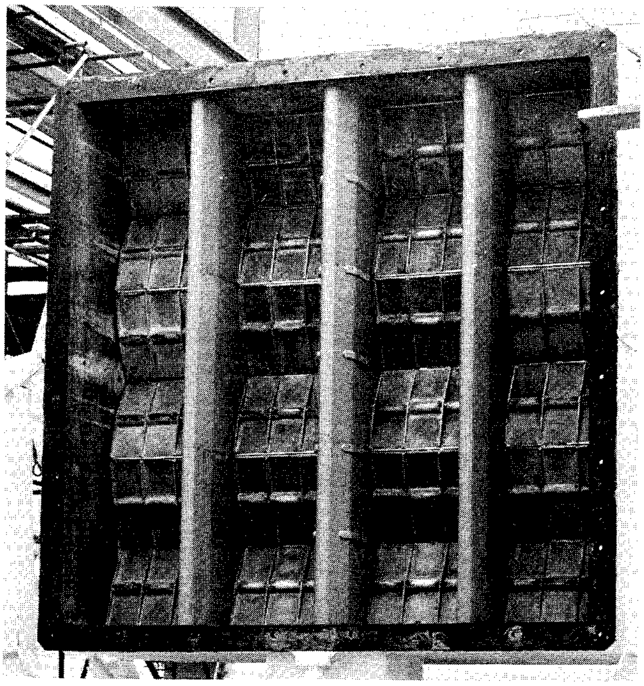


Fig. 6 Inlet air control valve.

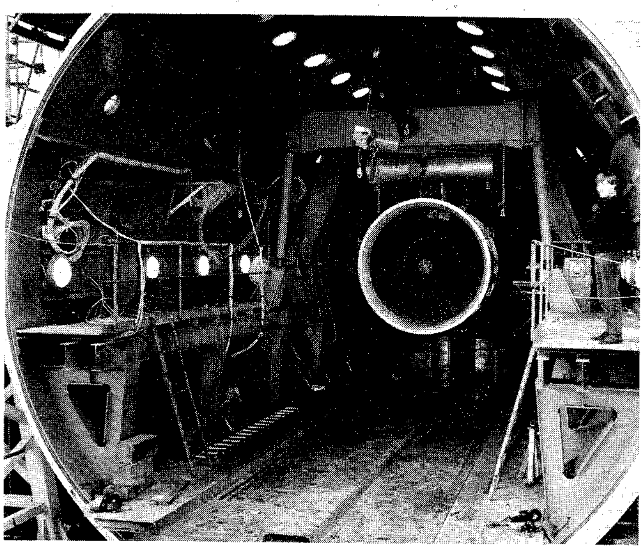


Fig. 7 Test chamber with end dome removed.

A sealed flexible joint is provided in the inlet duct some distance upstream of the slip joint to accommodate relative movements between the engine axis and the fixed inlet ducting. The section of inlet duct on the upstream side of the slip joint is restrained in an axial direction by two tie bars anchored to the fixed ducting; it is supported from the cell roof by constant load devices so that no vertical load can be transmitted to the engine through the slip joint.

Engine Mounting

The test chamber is 44 ft long and 25 ft diam. The upstream domed end is mounted in a wheeled carriage so that when the inlet ducting is removed it can be pulled back leaving the full diameter of the cell available for access during engine installation. Figure 7 shows the test chamber with the front dome removed.

The engine is hung by its pylon from a massive mounting frame which is freely suspended from the roof by four thin flexure rods. The ends of the rods are rigidly clamped to avoid the hysteresis due to stiction which is inevitable with pivotted suspensions. The front pair of rods carry the frame through a rocking beam thus providing virtually a three-point suspension and thereby eliminating the effects of cell distortion due to thermal or pressure loads. Lateral movement of the frame is prevented by four radius rods attached to the side of the cell; two of the rods incorporate spring loading devices to nullify the effects of differential expansion. The stiffness of the complete system is very low, being of the order of 8 lb/0.001 in. deflection. The resultant load on the mounting frame is measured by two 20,000 lb load cells, one mounted on either side of the test cell on the engine horizontal center-line. The system operates with virtually zero displacement, the maximum deflection of the load cells being only 0.030 in. at full load. At some conditions the resultant load is negative, that is it acts in the drag sense, so to simplify force measurement a preload is applied to the frame by two pneumatic jacks. The preload is measured on two separate load cells. Provision is made for calibrating all the load cells in situ against two high quality reference load cells which are periodically calibrated against a National Standard.

Equipment for Icing Tests

The cell has the usual facilities to enable engine operation in wet icing conditions to be studied and the effectiveness of anti-icing equipment evaluated. These include a water spray rake with its associated supply and metering equipment, and steam injector manifolds for increasing the humidity of the engine air supply should this be necessary. The rake consists of an array of 242 air assisted atomisers of a type specially developed and calibrated for this application, which is installed when required in the inlet duct 10 ft upstream of the engine face. Closed circuit TV channels with stroboscopic lighting and film cameras enable observations of ice formation on engine blades and components to be made and recorded whilst testing is in progress.

The inherent versatility of the system has led to its use as an icing tunnel and free jet tests of full-scale aircraft com-

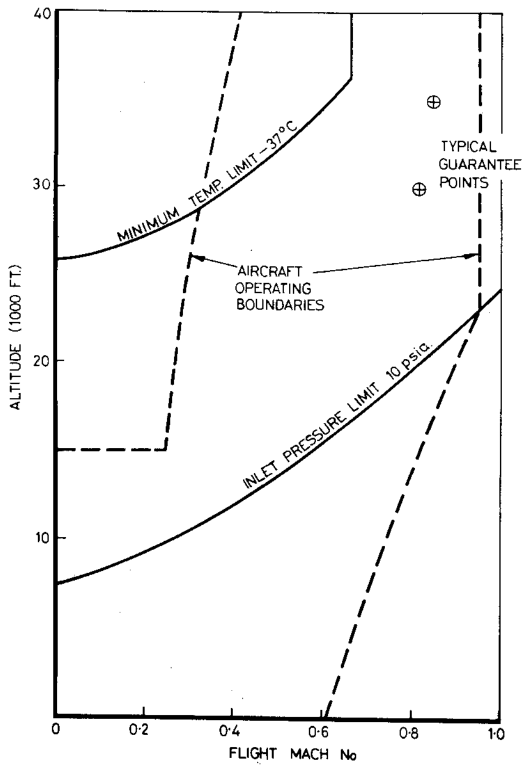


Fig. 8 Test envelope for RB211 engine.

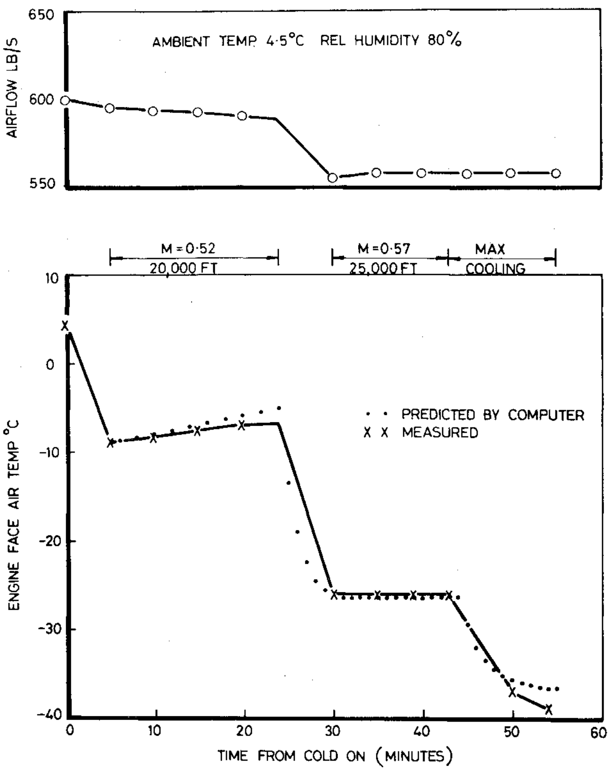


Fig. 9 Cooler performance.

ponents have been undertaken. These are described in a later Section.

Cell Performance Capability

The test boundaries cannot be defined uniquely in terms of alititude and flight Mach number because of the interaction between the engine, cell and exhauster plant characteristics. Three main boundary limits are set by: 1) the lowest achievable inlet air temperature (design figure −37°C (−35°F); 2) the highest achievable inlet air pressure (design figure 10 psia); and, 3) the pressure ratio/flow characteristics of the exhausters.

The limits calculated using the design values quoted above and the airflow demand of the Rolls-Royce RB211 engine are shown in Fig. 8.

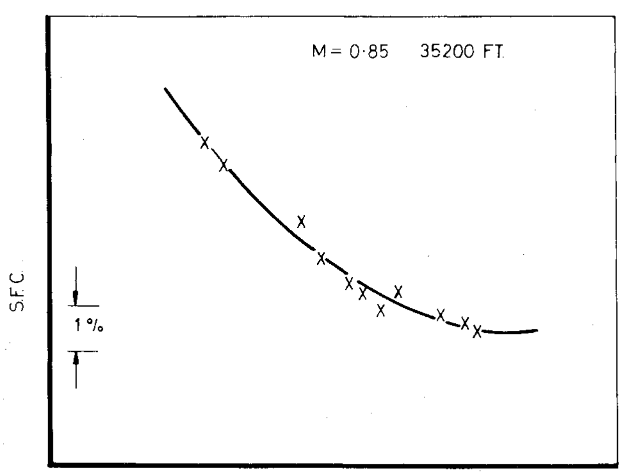


Fig. 10 Random errors in sfc measurement.

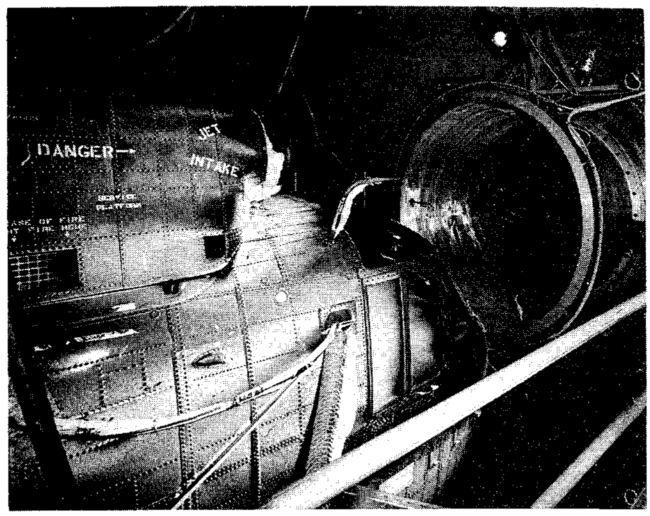


Fig. 11 Helicopter icing test.

Performance of Air Cooler

During the cell commissioning trials tests were made to check the thermal performance of the cooler, its response to changes in airflow and outlet temperature demand, and its flexibility when operating in various alternative modes.

To attain the most effective utilization of the total supply of "stored cold," it was originally intended that the first fill of coolant would be collected in a separate tank rather than be returned to the cold store. On conclusion of a test the warm coolant would be passed through the cooler to defrost the tubes. After a few tests it became clear that this procedure subjected the engine to an undesirably rapid temperature transient and it was therefore decided that it would be preferable to induce a flow of air at ambient temperature through the cooler before starting the coolant flow. This has since been adopted as standard practice.

The results from a commissioning trial are shown in Fig. 9. The order in which the tests were run had no special significance and was not intended to represent an engine test schedule. The test conditions were chosen to provide the cooler with a fairly arduous duty suitable for checking its thermal performance and ease of control. The first part of the test simulated conditions encountered by an aircraft holding at 20,000 ft, 230 knots EAS in an ambient temperature of −20°C (−4°F), the corresponding engine inlet temperature being −6°C (21°F). Coolant was passed only through the first section of the cooler at a rate of 1000 gal/min. After 24 min the altitude was increased to 25,000 ft and the engine inlet temperature reduced correspondingly to −26°C (−15°F). All the cooler sections were used and the coolant flow increased to 1500 gal/min. After 45 min the coolant flow was increased to 3000 gal/min to provide maximum cooling. The test was terminated after 54 min when the cold store became exhausted. Control was at all times precise and no difficulty was experienced in maintaining the air temperature to within ±¾°C(±1.3°F).

Also shown in Fig. 9 are the air temperatures predicted by the computer program using the measured ambient air conditions and coolant inlet temperatures. Measured and predicted values agree closely for steady-state conditions; insufficient measurements were made during the transient periods for valid comparison.

Instrumentation and Data Acquisition

Steady-State Measurements

The steady-state instrumentation system used for performance measurement has conventional facilities for measuring 300 individual pressures and 200 temperatures and such quantities as shaft speed, fuel flow, thrust, angular and linear displacements, areas, etc. Separate transducers are used to record the output from each individual pressure sensor, a feature which is standard practice in the NGTE Altitude Test Facility. This arrangement has several advantages over systems employing pressure switching (scanning valves): the scan time is very much shorter, lower quality (and hence cheaper) transducers can be used, and it is more flexible in that transducers can be selected to match the pressure ranges required.

The pressure transducers are housed in temperature controlled cabinets in groups of 100. Their outputs are fed through analogue/digital converters to a central data processor, processed in real time and output to a line printer. Selected items are displayed in digital form in the cell control room to enable the required test conditions to be set up rapidly.

When a data point is called up the computer scans the outputs of all transducers in a predetermined sequence, those from the load cells measuring thrust being scanned 50 times. This entire scanning sequence is repeated 5 times and the output print is the arithmetic mean of the 5 scans (250 for the load cells).

Transient Measurements

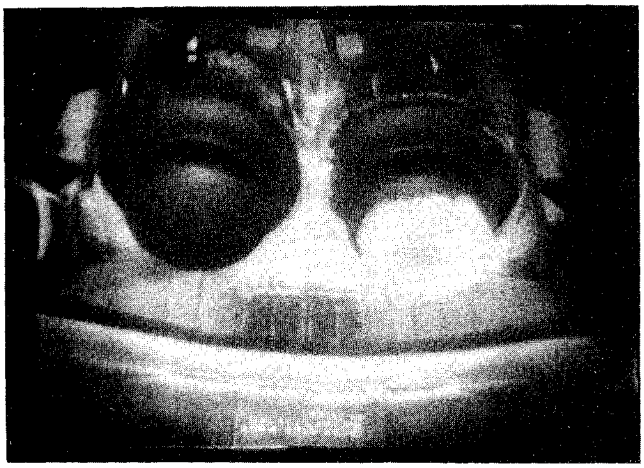
Facilities are available for recording a limited number of time variant quantities on magnetic tape for subsequent off-line analysis. Chart recorders are used to provide an output for direct visual observations and from these recordings quantitative data can be obtained if required.

Calibration

Means are provided for calibrating the steady-state system by applying reference pressures generated by a standard dead weight tester for pressures greater than atmospheric or by a vacuum pump controlled by a regulator and monitored by an accurately calibrated, sensitive electromanometer for pressures less than atmospheric. During this process the computer is used to acquire and process the output from each transducer. Straight line fits relating applied pressure to digital output are computed using the method of least squares and the equations defining these lines are stored in the computer for use during test running.

The systems measuring temperature and other quantities giving rise to electrical output are calibrated in an analogous way by injecting known emf's or frequencies into the appropriate circuits.

Thrust calibration involves the calibration of four load cells, two measuring the force acting in the "thrust" sense and two that in the "drag" sense. Load is applied directly to the thrust load cells through the engine mounting frame by two hydraulic jacks and measured by high quality load cells which are periodically calibrated against a National Standard. Quadratic curve fits are obtained by a similar procedure to that used for the pressure transducers and the data stored for use on-line.



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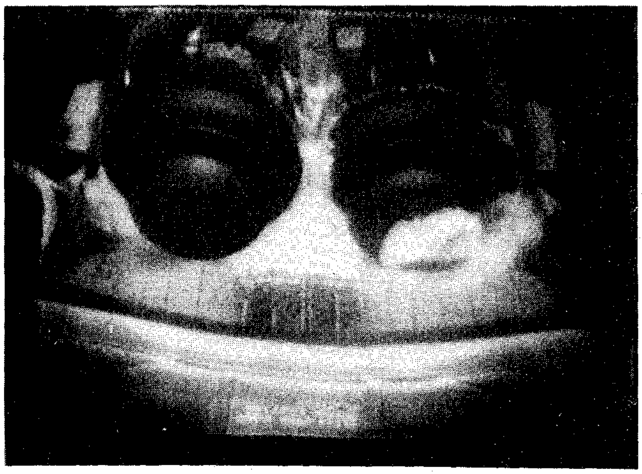

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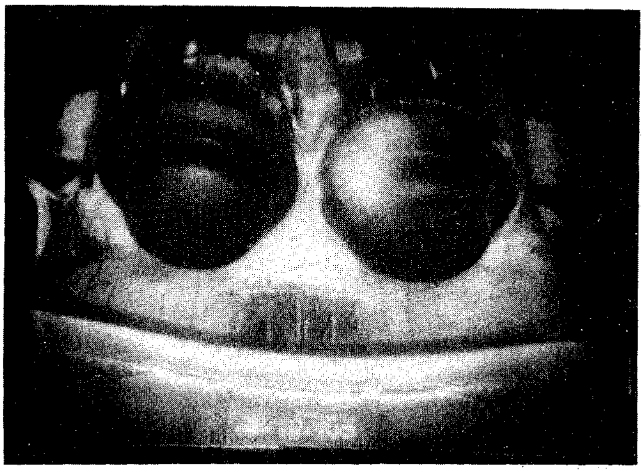

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Fig. 12 High-speed television sequences showing ice ingestion from intake after 30 min at $-5°C$ and 0.7 g/m^3.

Note on Precision of Test Data

One of the most important types of test undertaken in the cell is the demonstration of steady-state performance guarantees. This requires the determination of net thrust and specific fuel consumption with the highest possible degree of precision to yield data for comparison with specification values. The effects of random errors in the test measurements are discussed in a Paper by Yarker and Stanhope[2] and attention drawn to the need to minimise errors in the three quantities which have the greatest influence on the determination of net thrust: air-meter differential pressure, cell pressure and engine inlet pressure. By careful calibration and attention to detail it has proved possible to keep the random error in these measurements below 0.005 psi which, at a typical cruise condition (Mach number 0.85; 35,000 ft), corresponds to a random error in sfc of $\pm 0.2\%$. An example of this is given in Fig. 10 which presents data obtained during tests on three different days. Fitting the best quadratic curve through the 11 points yields a one sigma deviation which corresponds to a tolerance of ±0.2% in cruise sfc.

Systematic error is difficult to establish in the absence of comparable data from the same engine obtained in different test facilities. In the present instance it is believed that the systematic error does not exceed ±1.5%.

Use of the Cell as an Icing Tunnel

Reference was made earlier to the potential of the cell for undertaking icing tests on aircraft components at full-scale. An example is the investigation made to examine ice-shedding from the windscreen and front fuselage of a helicopter with consequent ingestion of pieces of ice by the engines. A description of these trials was given by B. P. Marlow in a Paper presented to the International Helicopter Icing Conference held in Ottawa, Canada, in May 1972.[3]

The tests were required to cover a range of flight speeds between 100 and 200 fps at a pressure altitude of 4000 ft with air temperatures between −2°C and −15°C (28°F and 5°F). The largest free jet blowing nozzle that could be used to meet these conditions with an acceptable operating margin was 100 in. diam and it was, therefore, impossible to immerse the entire helicopter fuselage in the jet flow, although all the areas of interest could be covered. To confirm that the proposed test arrangement would be satisfactory measurements were made using a $1/20$ scale model of the cell installation to compare pressure distributions over the fuselage surface with those measured on the same model in a conventional wind tunnel. Extremely good agreement was obtained and it was concluded that the test arrangement gave a close representation of free flight. No attempt was made to simulate the rotor downwash. The installation is shown in Fig. 11.

Figure 12 is a typical example of the kind of unique visual information that can be obtained using the facility. A sequence of frames taken from a high speed video tape recorded at 100 pictures/sec shows the ingestion during melt-off of a large piece of ice from the front face of the intake. The ability to examine incidents of this kind under controlled conditions has proved of immense value and has enabled satisfactory solutions to be achieved.

Conclusions

A description has been given of the test cell constructed at NGTE to enable trials to be undertaken on large turbofan engines. As well as detailed performance measurements at steady-state conditions, the cell permits studies of engine behaviour during rapid transients. Icing trials can also be carried out to examine the ability of the engine to operate under these conditions and meet the requirements for certification before entry into passenger carrying service. The potential of the cell in regard to the simulation of icing conditions is such that trials of full-scale aircraft components have been undertaken, the most notable being on a helicopter front fuselage complete with its engine intakes. The ability to examine the build up and shedding of ice under closely controlled conditions with video recording equipment has proved of immense value, enabling problem areas to be defined and practical solutions found.

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