AIAA–2002–2922
High Altitude Small Engine Test Techniques at the NASA Glenn Propulsion Systems Lab

Raymond Castner
NASA Glenn Research Center
Cleveland, OH

John Wyzykowski and Santo Chiapetta
Pratt & Whitney
Canada

22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference
June 24–26, 2002 / St. Louis, MO

HIGH ALTITUDE SMALL ENGINE TEST TECHNIQUES AT THE NASA GLENN PROPULSION SYSTEMS LAB

Raymond Castner
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

John Wyzykowski and Santo Chiapetta
Pratt & Whitney
Canada

Abstract

A High Altitude Test was performed in the Propulsion Systems Lab (PSL) at the NASA Glenn Research Center using a Pratt and Whitney Canada PW545 jet engine. This engine was tested to develop a high-altitude database on small, high-bypass ratio, engine performance and operability. Industry is interested in the use of high-bypass engines for Uninhabited Aerial Vehicles (UAV's) to perform high altitude surveillance. The tests were a combined effort between Pratt & Whitney Canada (PWC) and NASA Glenn Research Center. A large portion of this test activity was to collect performance data with a highly instrumented low-pressure turbine. Low-pressure turbine aerodynamic performance at low Reynolds numbers was collected and compared to analytical models developed by NASA and PWC.

This report describes the test techniques implemented to obtain high accuracy turbine performance data in an altitude test facility, including high accuracy airflow at high altitudes, very low mass flow, and low air temperatures.

Major accomplishments from this test activity were to collect accurate and repeatable turbine performance data at high altitudes to within 1 percent. Data were collected at 19,800m, 16,750m, and 13,700m providing documentation of diminishing LPT performance with reductions in Reynolds number in an actual engine flight environment. The test provided a unique database for the development of engine analysis codes to be used for future LPT performance improvements.

Introduction

The PW545 engine was tested to develop a high-altitude database on small, high-bypass ratio, engine performance and operability. Industry is interested in the use of high-bypass engines for Uninhabited Aerial Vehicles (UAV's) to perform high altitude surveillance. The tests are a combined effort between Pratt & Whitney Canada (PWC) and NASA Glenn Research Center. The testing was conducted in two test entries, designated Phase 1 and Phase 2 respectively. The Phase 1 test objective was to obtain engine performance and operability data to the maximum altitude that the basic engine would operate safely, with minor modifications to the electronic control and fuel system. The engine was modified as dictated by the Phase 1 entry, and tested to maximize performance and confirm engine operability to a minimum altitude of 19,800 meters in the Phase 2 test entry.

A large portion of this test activity was to collect aerodynamic performance data on the low-pressure turbine. Turbine aerodynamic performance at low Reynolds numbers was collected and compared to analytical models developed by NASA and PWC.

High Altitude Test

The PW545 High Altitude Test was performed in the NASA Glenn Research Center Propulsion Systems Laboratory, Cell #4. Test hardware and auxiliary subsystems descriptions are documented in this section. An overall installation drawing of the test engine is shown in Figure 2.

Propulsion Systems Laboratory

The PW545 High Altitude Baseline Test took place in the Propulsion Systems Laboratory (PSL) Cell 4.[1] The test engine, a PW545 turbofan, was hard-mounted via engine stand to a single-axis thrust stand. NASA inlet ducting was used with the exception of a PWC supplied bell mouth and station 2 duct. Existing exhaust collector hardware was used without modification. Central service turbo-expanders were used for every test run to supply cold inlet air.

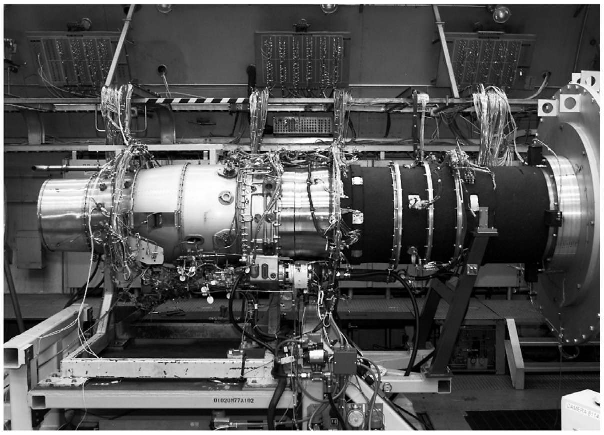


Figure 1.—Installation photo.

PW545 Test Engine

The test engine was a Pratt & Whitney Canada PW545 high-bypass ratio turbofan engine. This engine type is certified on the Cessna Citation Excel aircraft. The same test engine was used for both test phases, and was an experimental development engine serial number 5402 build 35 and build 36. This engine was built, instrumented, and acceptance tested in a sea level test facility in Mississauga, Ontario.

Changes made to the engine for both phases of testing included modification to EEC logic and fuel control to accommodate the low fuel flow requirements at very high altitudes.[2] Oil system modifications were made to provide a lower oil system temperature and pressure at high altitudes. Several EEC logic changes were utilized during testing to allow operation over 19,800 meters, and to change the engine acceleration and bleed scheduling. Bleed valve scheduling was altered to prevent surging at altitudes above 18,200 meters. Acceleration limiting prevented a fuel-scheduling over-shoot upon rapid decelerations.

The engine burner drain valve had to be capped-off during testing to prevent inadvertent opening during testing at high altitudes. Forced cooling of the engine starter/generator was required to prevent over-temperatures while generating over 7.5 kilowatt extraction levels.

Engine Stand and Inlet Ducting

Pratt & Whitney Canada provided the engine stand used for both the phase 1 and phase 2 test entries. The stand supported the test engine from the port side by means of a two-point yoke on the forward end, and a flange-supporting ring on the back end.

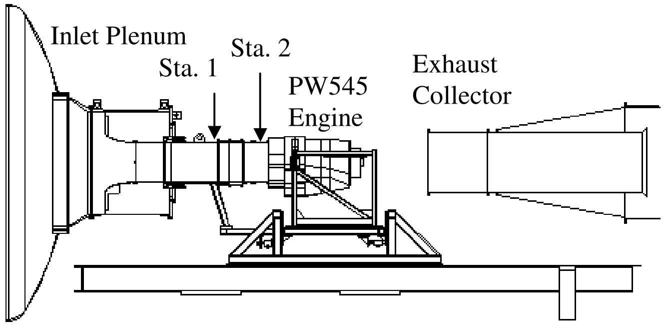


Figure 2.—Installation diagram.

The inlet ducting utilized for these tests was new except for the station 2.0-distortion duct, and the inlet bell mouth, both of which were supplied by PWC. The following sections provide information regarding each inlet section.

The station 1.0 instrumentation duct provided mounting for four boundary layer rakes, one cross-duct rake, and wall static instrumentation ports. The forward edge of the duct was the metric break location for the entire inlet assembly.

During phase 1 testing, it was noted that the boundary layer rakes did not fully penetrate into the fully developed flow field. The additional cross-duct rake was added during phase 2, to verify the pressure profile across the inlet duct. The phase 2 entry also added six thermocouple rakes with 12 elements each at station 1.0 to gather a more detailed temperature profile. Detailed results of the station 1.0 measurements are discussed later in this report.

The station 2.0 duct mounted directly to the engine compressor inlet case flange. For this test entry, four boundary layer rakes were installed to record total pressure and airflow at station 2.0.

Both entries used a single-axis thrust stand, designed and fabricated for these tests. The metric bed was designed to accommodate the PWC engine stand, and also support the inlet ducting from an "H" frame assembly bolted to the front of the live bed. One measurement and one calibration load cell were included on the stand. Maximum loading on the structure was limited to 2270-kilogram force.

Turbine Measurements

For this test, the Low Pressure Turbine (LPT) was heavily instrumented to investigate the loss of turbine performance at the low Reynolds numbers resulting from operation at high altitude. Over 150 pressures and temperatures were installed in the LPT module at PWC.

Test Techniques and Lessons Learned

Engine Airflow

High accuracy airflow measurement was required at high altitude and low inlet velocities. These measurements have unique pressure measurement issues. The PW545 engine required measurement of 5 kg/sec at 7.8 kPa inlet pressure where the difference between total pressure and static pressure in the inlet duct was very small. This problem was further complicated by the large duct diameter for the small airflows.

As the PW545 was tested in PSL twice, improvements in airflow measurement were obtained based on experience. For the first test, the airflow measurement system was only accurate to approximately 3 percent. This measurement assumed uniform one-dimensional flow and complete coverage of the boundary layer measurement by the four boundary layer rakes. Improvements in the measurement system improved its accuracy to better than 1 percent. Another major issue involved the measurement of the pressure profile in the inlet duct.

The PW 545 inlet configuration is shown in the figure below:

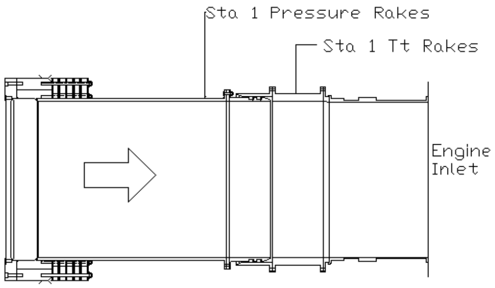


Figure 3.—Inlet configuration.

The station 1 inlet pressure rakes were located 99 cm upstream of the PW545 engine inlet, and the station 1 temperature rakes were located 56 cm upstream of the engine inlet.

The station 1 pressure rakes were installed in the inlet ducting as shown in figure 4.

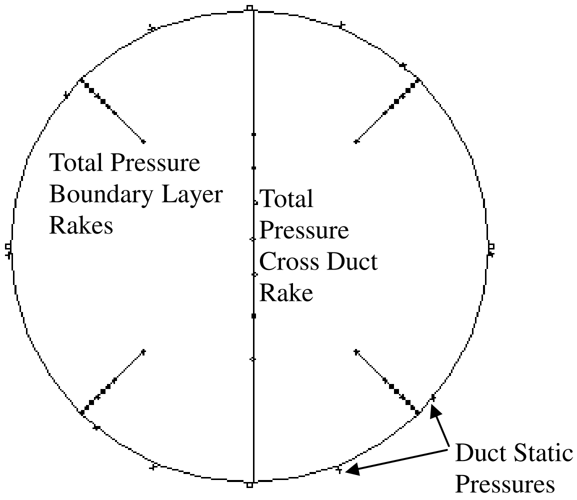


Figure 4.—Station 1.0.

The rakes at the 45,135, 225, and 335-degree locations are 8 element boundary layer rakes per NASA CF-658614-4. The vertical rake that crosses the duct is a 7-element pressure rake per Pratt & Whitney Canada drawing EFD-99979. Static pressure for station 1.0-airflow is measured with a static pressure measurement located 10 degrees to the side of each boundary layer rake.

The total temperature rakes were an array of 6 rakes, per PWC drawing PWC-43415. Each rake was 23.5 cm long with 12 shielded total temperature probes on each rake – for a total of 72 measurements. The rakes were equally spaced around the duct at 60-degree increments.

Table 1.—Probe Positions for Inlet Rakes

PWC-43415		EFD-99979		CF-658614-4	
Shielded Total Temperature Rake		Total Pressure Rake		Boundary Layer Rake	
Probe	Location, cm	Probe	Location, cm	Probe	Location, cm
1	1.35	1	6.21	1	0.18
2	3.20	2	15.90	2	0.58
3	5.16	3	25.59	3	1.14
4	7.24	4	35.28 *	4	1.70
5	9.47	5	44.97	5	2.26
6	11.89	6	54.66	6	2.82
7	14.50	7	64.35	7	3.38
8	15.95	* Center of duct		8	6.21
9	17.55				
10	19.15				
11	20.96				
12	22.99				

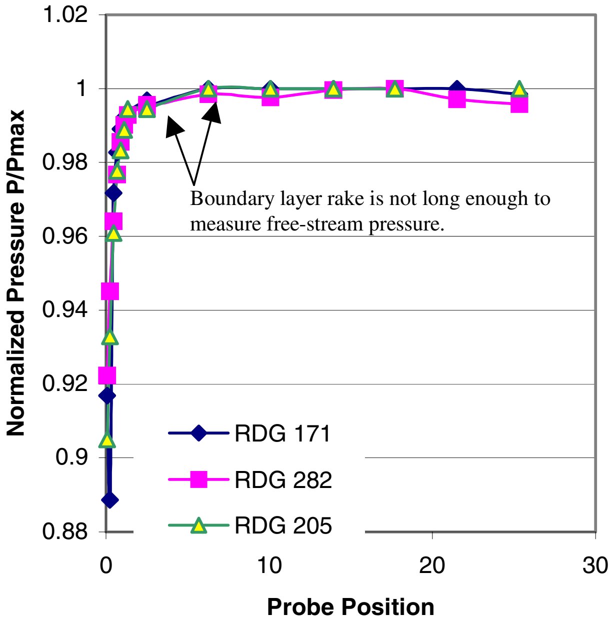
For the PW545 Phase 1 test, only the four 8-element boundary layer pressure rakes were used to calculate airflow. For the Phase 2 test, the 7-element pressure rake across the duct was added. Airflow was calculated using an equal area integration of all pressure measurements across the duct. The following table shows the difference in airflow calculations using the two methods of measurement:

RDG #	282	171	205
WA1T (kg/sec)	5.63	32.90	9.44
WA1 (kg/sec)	5.58	32.75	9.42
% Error	0.89	0.46	0.21

Reading 282 was Mach 0.7 at 19,800 m
Reading 205 was Mach 0.7 at 16,750 m
Reading 171 was Mach 0.7 at 13,700 m

WA1T is the airflow measurement in kg/sec integrating airflow with both the boundary layer rakes and the 7-element pressure rake. WA1 is the airflow measurement with only the boundary layer rakes.

The error is worst at the high altitude, low airflow condition of reading 282, but the error is largely due to the insufficient measurement of the boundary layer in the duct, shown in figure 5.



Boundary layer rake is not long enough to measure free-stream pressure.

Figure 5.—Station 1.0 inlet flow profile.

Past practice in PSL has been to design boundary layer rakes that are long enough for the tip to capture the free-stream pressure. Airflow was calculated from the boundary layer rakes only. The design of the rakes is typically based on boundary layer thickness calculations.

For this test, the boundary layer rakes did not capture the full boundary layer thickness. For a situation where a high accuracy calculation of airflow is a requirement, it is recommended to install a pressure rake to span the entire flow and accurately collect the pressure variation across the duct. From the figure, the variation does not look significant, but the error in airflow indicates there can be nearly 1 percent error if the proper profile is not captured and used in the airflow calculation. A longer boundary layer rake could also be used to be sure the free-stream pressure is measured. In this test, the rakes were not long enough to be in the free-stream flow.

Cold Air Operations

For this test activity, collection of engine performance and turbine performance required matching of the proper air temperature at flight conditions. These temperatures ranged from –22 °C to –45 °C. Cold air is achieved in PSL through the use of turbo expanders, which extract work from the compressed air supply with a hydraulic power brake. The turbo expanders are capable of providing air at –62 °C. However, cold air operations in a large altitude facility can be complicated. From the Phase I test activity, it was determined that air dew point must be measured throughout the air supply system, so an additional sensor was added directly upstream of the engine bell mouth inlet. An existing sensor was located at the output of the turbo expanders.

Readings indicated that the dew point of the air in the engine bell mouth was often only –32 °C, while the air exiting the turbo expanders was –45 °F. Since the desired test conditions were often –36 and sometimes –45 °F, this test experienced serious problems with ice buildup on the pressure probes used to measure airflow. Since accurate measurement of airflow was critical to the computation of LPT performance, this was a problem. Often, test conditions were run at conditions 5 to 10 °C above the desired temperature to stay above the inlet dew point.

The dew point is attributed to ambient air leakage into the facility inlet piping, which is a complex system with many valves and joints. For future programs requiring cold temperature operations, detailed monitoring of dew point will be essential. Also essential, will be the reduction or elimination of all ambient air leakage into the facility air supply system, which runs at sub ambient pressures.

In anticipation of this problem, a nitrogen purge system was installed on the station 1 airflow measurement probe tubing. This system would isolate the measurement transducers and blow nitrogen backwards through the tubing and out the pressure probe into the duct. This system was found to be ineffective, as the probe tips froze anyway; or froze immediately after the purge was turned off. The system often caused nitrogen to be trapped behind the ice and cause high-pressure readings. One recommendation for cold air operations might be to design heated airflow measurement probes, to prevent ice buildup or to melt ice buildup.

Temperature Distortion

For detailed engine performance calculations, the temperature in the inlet duct must be known with a high level of accuracy. For the phase I test activity, the engine inlet only had two temperature sensors, located at a 7 cm immersion depth from the duct wall, at the top and bottom of the duct. Due to the temperature difference between these sensors during testing, it was difficult to ascertain the temperature distortion in the duct and it's effect on airflow and engine operation.
As an improvement for the phase 2 test activity, the engine inlet had six rakes with 12 temperature elements each in the engine inlet. Temperature distortion levels are plotted:

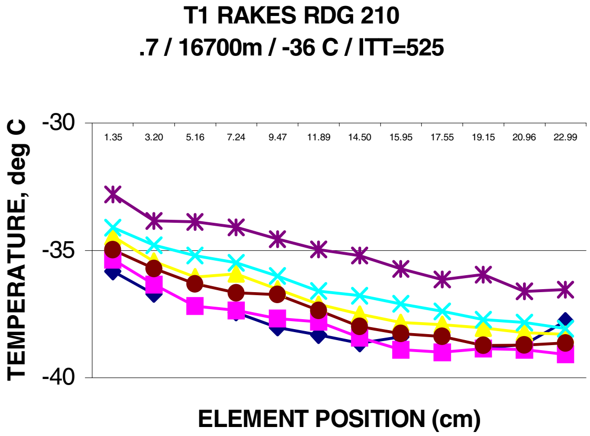


Figure 6.—Inlet temperature profile.

Temperature distortion levels were on the order of 6 °C for the –36° test conditions. This effect appears to be due to heat transfer through the duct wall to the warm test cell, and occurred even with insulation on the inlet ducting. Plots show that the distortion increases for lower test temperatures. This effect is difficult to control, but should be carefully measured and documented as temperature distortions have a great effect on engine performance and stall margin.

Surge Monitoring

On-line surge monitoring was accomplished using a dynamic data acquisition system. Compressor outlet pressure, P3, was displayed on a scrolling plot during the test. Engine instabilities and the onset of surge could be observed by monitoring this display. The PW545 Electronic Engine Control (EEC) handled all engine surges smoothly, and surges at 19,800 m were not severe due to the low engine loading at this high altitude condition.

Conclusions

This report summarizes the techniques used to collect engine airflow data, which was critical to determine the low-pressure turbine performance at high altitude test conditions. The test collected data at 19,800m, 16,750m, and 13,700m and provided documentation of diminishing LPT performance with reductions in Reynolds number in an actual engine flight environment[3]. This activity also provided a database for the development of engine analysis codes to be used for future LPT performance improvements.

Acknowledgments

The authors would like to acknowledge the work of Joyel Kerl, John Leone, Pam Poljak, Pete Pachlhofer, Rick Sorge, Mike Abdelwahab, and the entire staff at the Propulsion Systems Laboratory at the NASA Glenn Research Center.

References

1. NASA Lewis Propulsion Systems Laboratory Customer Guide Manual, R. Soeder, NASA TM–106569, 1994.
2. Development and Testing of a Commercial Turbofan Engine for High Altitude UAV applications, M. Weinberg and J. Wyzykowski, SAE paper 2001–01–2972.
3. An Engine Research Program Focused on Low Pressure Turbine Aerodynamic Performance, R. Castner, S. Chiapetta, J. Wyzykowski, and J. Adamczyk, ASME, IGTI paper GT–2002–30004, 2002.