

# Flying Test Bed Performance Testing of High-Bypass-Ratio Turbofans

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## ABSTRACT

The commercial turbofan trend of increasing bypass ratio and decreasing fan pressure ratio has seen its latest market entry in Pratt & Whitney's PurePower™ product line, which will power regional aircraft for the Bombardier and Mitsubishi corporations, starting in 2013. The high-bypass-ratio, low-fan-pressure-ratio trend, which is aimed at diminishing noise while increasing propulsive efficiency, combines with contemporary business factors including the escalating cost of testing and limited availability of simulated altitude test sites to pose formidable challenges for engine certification and performance validation. Most fundamentally, high bypass ratio and low fan pressure ratio drive increased gross-to-net thrust ratio and decreased fan temperature rise, magnifying by a factor of two or more the sensitivity of in-flight thrust and low spool efficiency to errors of measurement and assumption, i.e., physical modeling. These configuration-driven challenges come at a time of significantly increased test costs and limited availability of Altitude Test Facilities (ATF).

This paper details the process developed and applied on the PurePower™ Geared Turbofan™ demonstrator engine to address the challenges posed by this combination of engine cycle trends and business conditions. The potential is explored for combining ground-based scale model and rig testing, sea level full-scale testing, and flight testing in the Flying Test Bed (FTB) to achieve in-flight thrust and component performance assessments of the same or better uncertainty as legacy high BPR turbofans achieved in an ATF-based process. In-flight thrust is addressed directly in this paper, and component performance is addressed by considering fan efficiency, which is typically the most

sensitive component parameter in high BPR applications.

## LIST OF ACRONYMS

|       |                                       |
|-------|---------------------------------------|
| AEDC  | Arnold Engineering Development Center |
| AIR   | Aerospace Information Report          |
| AOC   | Air/Oil Cooler                        |
| ATF   | Altitude Test Facility                |
| BPR   | Bypass Ratio                          |
| FTB   | Flying Test Bed                       |
| GLTF  | Ground Level Test Facility            |
| GTF   | Geared Turbofan                       |
| TCS   | Turbulence Control Structure          |
| WBAOC | Air/Oil Cooler Bleed Flow Rate        |

## INTRODUCTION

An Altitude Test Facility, or ATF, can provide exceptional levels of accuracy in determining in-flight thrust and component performance. A well designed facility, such as AEDC or Pratt & Whitney's Willgoos Lab, with a carefully designed installation and test procedure, has demonstrated uncertainties as low as .5 to 1% (Ref 1).

Additionally, the inherent ability of these facilities to provide cooling of air below 0° C and to reach high engine corrected conditions makes them useful for doing engine icing validation and FAR 33 certification for commercial transport engines. Traditionally, a majority of engine manufacturers established engine development programs around this paradigm.

However, several issues have combined to challenge the paradigm:

- The closure of both private and government-operated facilities (Willgoos, Pyestock).
- The increase in schedule pressure and cost of using government run facilities like the Arnold Engineering Development Center in Tullahoma, Tennessee.
- The development of ground-based icing facilities for Large Commercial Engines in Canada, like the GLACIER facility in Manitoba (Ref 2), and GE's Mirabel Facility (Ref 3).

The potential availability of ground-based icing facilities and the limited availability of altitude test facilities have altered the perspective of test planners managing engine validation and certification. Increasingly alternatives are sought to the ATF, particularly for large, high bypass ratio engines, which challenge the flow rate capability of these facilities. The transition away from ATF to a completely ground-based process requires adapting to different methods of validation and certification. The Aerospace Information Report AIR5450 (Ref 4) provides guidance on the means of establishing acceptable levels of uncertainty for in-flight thrust by utilizing a combination of model testing, ground testing, and flight testing in the FTB, a process commonly known as the Ground Level Test Facility (GLTF) Method. A Pratt & Whitney team, led by the authors, set out to define and validate a repeatable process for establishing in-flight thrust and component performance within the uncertainty range achieved by the ATF, but for much reduced cost. This process will be used for the development of the PurePower™ series of Turbofan Engines currently scheduled for certification over the next few years. This methodology was implemented on Geared Turbofan™ Demonstrator testing which was conducted in West Palm Beach, Florida, Plattsburgh, New York, and Toulouse, France during 2008.

## MAIN SECTION

### 1. FUNDAMENTALS OF IN-FLIGHT THRUST AND FAN EFFICIENCY

The equation characterizing net thrust for a turbofan engine with one primary stream and a "Fan" or "Bypass" stream is as follows:

Eq 1.

$$F_{NT} = F_{GT} - F_{Ram} = (C_v \phi W \sqrt{T})_{Fan} + (C_v \phi W \sqrt{T})_{Prim} - W_{Tot} V_0 / g_c$$

where:

$F_{NT}$  = Total Propulsor Net Thrust

$F_{GT}$  = Total Propulsor Gross Thrust

$F_{Ram}$  = Total Propulsor Ram Drag

$C_v$  = Nozzle Velocity Coefficient

$\phi$  = Gross Thrust Parameter for Convergent-Divergent Nozzle

$$= \sqrt{\frac{2\gamma}{\gamma-1} \left[ 1 - \left( \frac{P_{Amb}}{P_T} \right)^{\frac{\gamma-1}{\gamma}} \right]}$$

$W$  = Mass Flow of the Stream

$T$  = Average Total Temperature of the Stream

$V_0$  = Flight Velocity

Total flow is defined as :

$$\text{Eq. 2. } W_{Tot} = W_{Fan Entrance} + W_{Prim Entrance}$$

where for in-flight applications

Eq. 3.

$$W_{Fan Entrance} = (C_D F_{P_{Ideal}} P_A / \sqrt{T})_{Fan Nozzle} + \Sigma W_{Fan Bleed}$$

$$W_{Prim Entrance} = f(\text{HPT Flow Parameter}, P_3, T_3, W_f)$$

In-flight thrust is quoted at a reference condition, so the net thrust as-tested must be adjusted to that reference condition:

$$\text{Eq. 4. } F_{NT, Ref Cond} = f(F_{NT}, P_2, P_{Amb})$$

This adjustment is normally accomplished using the engine computer simulation.

Equations 1 through 4 describe the algorithm for calculating in-flight thrust. Inputs to the calculation include measured parameters and empirical relationships for efficiencies. Flight-test-measured parameters include gas path pressures, temperatures, and fuel flow. Empirical relationships include the nozzle efficiencies, commonly expressed as nozzle thrust and

thrust coefficients,  $C_D$  and  $C_V$ . These data, along with analytical representations including the compressible flow functions,  $\phi$  and  $FP_{Ideal}$  as well as other engine system characteristics required to conserve mass flow and quantify system pressure losses, are built into the engine computer simulation, which is used to calculate in-flight thrust using Eq. 1.

Fan rotor efficiency is defined as the ratio of ideal to real temperature rise across the fan rotor:

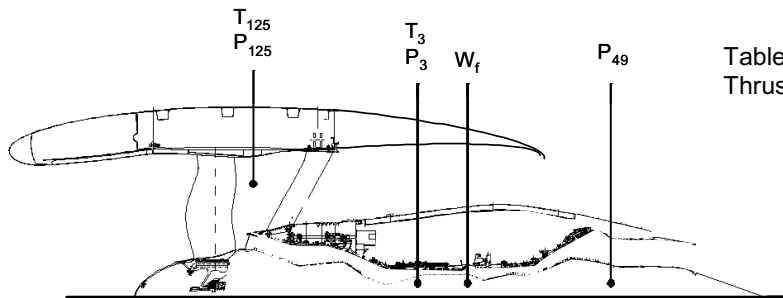
Eq. 5.

$$\eta_{Fan} = \frac{\Delta T_{Ideal}}{\Delta T_{Real}} = \frac{f\left(\frac{P_{FanExit}}{P_{FanInlet}}\right)}{f\left(\frac{T_{FanExit}}{T_{FanInlet}}\right)}$$

The ideal temperature rise across the fan is determined from pressure measurements made at the inlet and exit of the fan and the isentropic relationship, while real temperature rise is determined directly from temperature measurements made at these locations. A common method of data processing uses the technique of scaling the base fan map of the engine computer simulation until the fan exit pressure and temperature predicted by the model match the values measured at test. The fan efficiency that is output by the model as the test result contains the scale factor required to achieve the data match.

## 2. IN-FLIGHT THRUST AND FAN EFFICIENCY DEPENDENCIES

The FTB measurements made for in-flight thrust and fan efficiency on the GTF<sup>TM</sup> Demo flight test are shown in Figure 1.



$T_2$ ,  $P_2$ ,  $P_{Amb}$  from Aircraft Measurement System

Figure 1. Engine schematic indicating gas path and ambient measurements.

A list of the major system characteristics that affect in-flight thrust is given in Table 1. These characteristics are built into the engine computer simulation that performs the in-flight thrust calculation.

Table 1. System Characteristics Affecting In-flight Thrust

| Parameter         | Description                          |
|-------------------|--------------------------------------|
| $C_{VFan}$        | Fan Nozzle Thrust Coefficient        |
| $C_{DFan}$        | Fan Nozzle Flow Coefficient          |
| FEGV $\Delta P/P$ | Fan Exit Guide Vane Pressure Loss    |
| HPT FP            | High Pressure Turbine Flow Parameter |
| $C_{VPrim}$       | Primary Nozzle Thrust Coefficient    |
| WBAOC             | Air/Oil Cooler Bleed Flow            |

Sensitivity analyses conducted at critical points in the flight envelope quantify the relative contributions of each of the measurements and system characteristics to the calculated values of in-flight thrust and fan efficiency. The process of sensitivity analysis, which is performed using the simulation that calculates in-flight thrust, involves running a baseline case with all inputs set to nominal values. Each input, including both measured values and assumed characteristics like  $C_V$  and  $C_D$ , is then varied in turn and the partial derivative of net thrust or fan efficiency with respect to that input is calculated. For the GTF Demo the critical condition is "bucket cruise," the point of minimum TSFC at which a commercial airplane spends the longest time during its mission. The analysis for thrust also includes the effect of adjusting thrust to the reference condition due to the measurement of ambient conditions,  $P_2$ ,  $P_{Amb}$ , and  $T_2$ . Tables 2A and B shows the results of such a sensitivity analysis for the GTF<sup>TM</sup> Demo operating at bucket cruise conditions. For the GTF<sup>TM</sup> Demo the Fan Exit Guide Vane operating point at cruise conditions falls within the operating range of the sea level validation test, so that its influence on in-flight thrust is effectively book-kept by the uncertainty of the fan nozzle thrust and flow coefficients.

Table 2A. Sensitivity Analysis for GTF<sup>TM</sup> Demo In-flight Thrust, Cruise Bucket Conditions.

| Parameter  | $\delta F_{NT}/\delta \text{Parameter}(\%/ \%)$ |
|------------|-------------------------------------------------|
| $C_{VFan}$ | 3.27                                            |
| $P_2$      | -3.07                                           |
| $P_{125}$  | 2.90                                            |
| $C_{DFan}$ | 0.71                                            |
| $A_{18}$   | 0.71                                            |
| $P_{Amb}$  | 0.58                                            |
| $P_{49}$   | 0.41                                            |
| $W_f$      | 0.18                                            |
| $W_{BAOC}$ | -0.03                                           |