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Parametric Specific Fuel Consumption Analysis of the PW120A Turboprop Engine

Executive Summary

The recent volatility in the price of fuel, increasing public concern over the impact of aviation on the environment, particularly CO_2 emissions and more currently, the economic downturn are driving factors for airlines to review and where possible, further optimize their flight operations by reducing fuel burn and associated emissions.

The Pratt & Whitney Canada PW100-series turboprop engines have now been in service for a quarter century and continue to have strong commercial success in the regional aircraft market, a testament to the efficiency and reliability of the original design.

Using a validated thermodynamic model of the PW120A turboprop developed by Specific Range Solutions Ltd., this paper evaluates the sensitivity of the Equivalent Specific Fuel Consumption (ESFC) of the engine in the cruise condition as a function of various operational parameters such as throttle setting, aircraft altitude, static air temperature (SAT) and bleed air function. The effects of compressor fouling and turbine wear on performance are also assessed.

The conclusions of the analysis, which are consistent with known turboprop characteristics, are as follows:

1. The engine fuel efficiency improves slightly, i.e. ESFC decreases slightly, as the cruise power setting is increased. However, the lowest fuel burn rate is achieved at the Long Range Cruise setting.
2. The highest engine fuel efficiency, i.e. the minimum ESFC, will be achieved at the highest permitted operational altitude based on ISA conditions.
3. Warmer temperatures aloft are detrimental to ESFC and the converse is also true, cooler temperatures aloft are favourable to ESFC.
4. Minimizing the external bleed air mass flow will improve engine fuel efficiency, i.e. decrease ESFC. However, a minimum amount of bleed flow is required to satisfy passenger and crew fresh air flow and pressurization requirements.
5. Engine fuel efficiency is maintained by avoiding compressor fouling conditions and by ensuring turbine wear is minimized.

Ultimately, this model could form part of an analytical toolbox that operators could employ to further optimize their flight operations.

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Parametric Specific Fuel Consumption Analysis of the PW120A Turboprop Engine

1.0 Introduction

The recent volatility in the price of fuel, increasing public concern over the impact of aviation on the environment, particularly CO_2 emissions and more currently, the economic downturn are driving factors for airlines to review and where possible, further optimize their flight operations by reducing fuel burn and associated emissions.

The Pratt & Whitney Canada PW100-series turboprop engines have now been in service for a quarter century and continue to have strong commercial success in the regional aircraft market, a testament to the efficiency and reliability of the original design.

Using a thermodynamic model of the turboprop developed by Specific Range Solutions Ltd, this paper evaluates the sensitivity of the Equivalent Specific Fuel Consumption (ESFC) of the PW120A engine as installed on the Dash 8-100 (Q100) aircraft as a function of various operational parameters such as throttle setting, aircraft altitude, static air temperature (SAT) and bleed air function. The effects of compressor fouling and turbine wear on performance are also assessed. The model was validated for take-off and cruise conditions using recorded flight data generously provided by a Dash 8-100 operator.

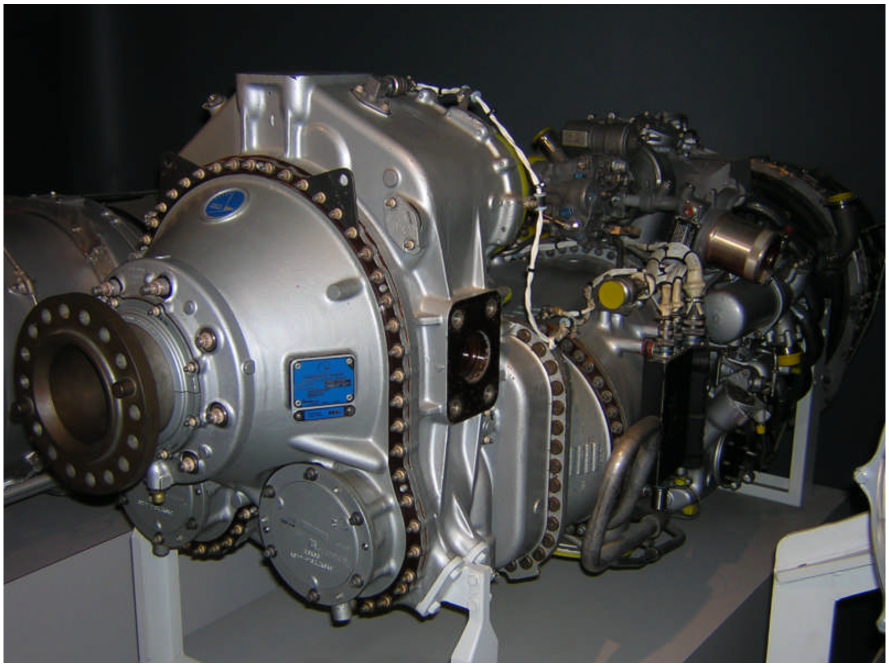

Figure 1.1 – Photo of a PW120 Turboprop Engine

2.0 Model Development

The PW120A is installed on both the Bombardier Aerospace Dash 8-100 (Q100) and the Avions de Transport Régional ATR 42. Both aircraft applications have been highly successful due to the inherent propulsion efficiency, η_p of the turboprop configuration i.e. a large diameter propeller imparting a relatively low velocity to a large mass of air and the energy conversion efficiency, η_e of the engine design itself. This PW120A model is based on installation on a Dash 8-100 aircraft and therefore the operational parameters are representative of the performance envelope of that aircraft. Model validation is based on recorded data from a Dash 8-100 in-service flight.

All the PW100-series engines, including the PW120A have a twin-spool design with a free power turbine connected to a gearbox, which drives a propeller. The total PW120A installation can be best described as very high bypass-ratio *unducted* geared turbofan. The low pressure (LP) centrifugal compressor is connected via a shaft to a single stage axial low pressure turbine. The high pressure (HP) centrifugal compressor is connected via a shaft to a single stage axial HP turbine with cooled blades. The air/fuel combustion occurs an annular reverse flow combustor.

The approach employed in this analysis was to use classic thermodynamic cycle calculations as described in Chapter 2 "Shaft power cycles" of Ref. [1] to enable engine performance estimation. The LP and HP spools were modelled separately to enable more accurate accounting of the accessory drive load off the HP shaft and external bleed air drawn from the LP port.

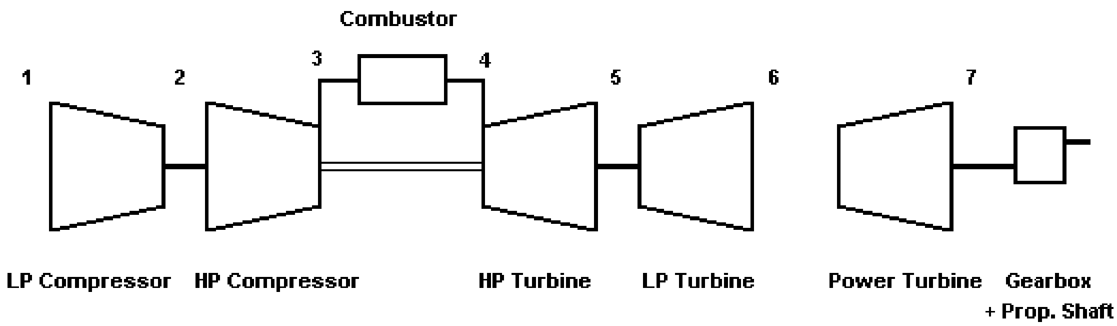

Figure 2.1 – PW120A Schematic with Station Numbers

Station	Location
1	LP Compressor Inlet
2	LP Compressor Outlet
3	HP Compressor Outlet
4	Combustor Outlet
5	HP Turbine Outlet
6	LP Turbine Outlet
7	Power Turbine Outlet

The power equations for the LP spool, the HP spool and the power turbine are presented below based on accessory power drawn from the HP spool and external bleed air extracted from the LP port.

<u>*LP Spool Power Equation*</u>:

$$m_a * C_{pa} * (T_{02} - T_{01}) = (m_a - m_{bld}) * C_{pg} * (T_{05} - T_{06}) * \eta_m \quad [2.1]$$

where:

C_{pa} = Specific Heat of Air (1.005 kJ/kg K)

C_{pg} = Specific Heat of Exhaust Gases (1.148 kJ/kg K)

m_a = Compressor Air Mass Flow (kg/s)

m_{bld} = External Bleed Air Mass Flow (kg/s)

T_{0x} = Station Air/Gas Stagnation Temperature (K)

η_m = Shaft Mechanical Efficiency (0.98)

HP Spool Power Equation:

$$(m_a - m_{bld}) * C_{pa} * (T_{03} - T_{02}) + P_{acc} = (m_a - m_{bld}) * C_{pg} * (T_{04} - T_{05}) * \eta_m \qquad [2.2]$$

where:

P_{acc} = Accessory Drive Power Requirement (22.4 kW @ Max.Take-Off)

Power Turbine Equation:

$$P_{tp} = (m_a - m_{bld}) * C_{pg} * (T_{06} - T_{07}) * \eta_m \qquad [2.3]$$

where:

P_{tp} = Power Turbine Shaft Output Power (kW)

In order to begin developing the model, PW120A performance specification data were required. The following design data were obtained from publications found in the public domain.

Parameter	Value	Reference
Max. Take-Off Power (SL to 27.9^{o}C)	1 491 kW (2,000 shp) 1 566 ekW (2,100 eshp)	Ref. [2] & Ref. [3] Ref. [3]
Overall Pressure Ratio @ Max. TO	12.14	Ref. [2]
Compressor Flow @ Max. TO	6.7 kg/sec (14.8 lb/sec)	Ref. [2]
ESFC @ Max. TO	0.286 kg/ekW h (0.470 lb/ehp h) 0.295 kg/ekW h (0.485 lb/ehp h)	Ref. [2] Ref. [3]
Max. Cruise Power (SL, ISA)	1 231 kW (1,651 shp) 1 295 ekW (1,737 eshp)	Ref. [3] Ref. [3]
Max. Cruise Turbine Inlet Temperature (25,000 ft, 350 mph)	1 093 ^{o}C (2 000 ^{o}F)	Ref. [4]
Norm Take-Off Power (SL to 28^{o}C)	1 342 kW (1 800 shp)	Ref. [5]

Table 2.1 – Published Cycle Parameter Data

No other published specification or performance data at either the engine or component level was found i.e. no compressor or turbine efficiency characteristics. The turbine inlet temperature (TIT) at the Maximum Power Take-Off condition was also unknown, but it was assumed by the author to be 100^{o}C greater than the Maximum Cruise TIT.

The following constants were defined in the performance model. Their values were selected based on typical design values published in Ref. [1]. In the model development process, the polytropic efficiency, η_∞ common to both the compressor and turbine stages was adjusted to generate the required mass flow. The pressure ratios for the LP and HP compressors were calculated based on an equal amount of compression work shared between the two compressors and not taking into account any imposed loads.

Parameter	Value
Intake Isentropic Efficiency, η_{in}	0.95
Shaft Mechanical Efficiency, η_m	0.98
Combustion Chamber Pressure Loss, Δ_{cc}	0.06
Combustion Efficiency, η_c	0.99
Exhaust Isentropic Efficiency, η_{ex}	0.95
Internal Cooling Bleed Fraction, β_i	0.043
Polytropic Efficiency, η_∞	Function of mass flow.

Table 2.2 – Constant Parameters

Calculation of the fuel fraction based on the stagnation temperature T03 upstream of the combustor and T04 (TIT) downstream of the combustor was based on enthalpy values and equivalent caloric values (ECV) listed in Ref. [6].

The accessory drive power requirement for the fuel pump, starter/generator, alternator, hydraulic pump and oil pumps was estimated to be 22.4 kW (30 hp) at the Maximum Take-Off Power condition (6.7 kg/sec).

For external bleed calculations, the bleed flow rate per engine was estimated and is listed in the following table. The minimum mass flow rate was based on a minimum fresh air flow requirement rate of 0.55 lb/min per occupant for 40 passengers and crew per the Dash 8-100 with the normal and maximum bleed flow rates being double and triple the minimum rate, respectively. The maximum rate maintains margin over the LP port maximum available core air flow.

ECS Flow Demand	Bleed Flow, SL (kg/s)	Bleed Flow, FL250 (kg/s)
Min	0.100	0.086
Norm	0.200	0.172
Max	0.300	0.258

Table 2.3 – Bleed Flow as a Function of Setting and Aircraft Altitude

Residual thrust was calculated by multiplying the mass flow at the free turbine exit times its relative velocity out the exhaust nozzle. The thrust (N) was converted into power (kW) by dividing by 8.5 which is a propeller constant at static conditions. The residual thrust converted to power represents just a small fraction of the shaft power under static conditions (~ 5%).

A set of baseline engine performance settings based on a given shaft power were defined based on the three listed cycle parameters TIT, compressor mass flow and pressure ratio and were at Sea Level ISA conditions without external bleed air.

Performance Setting	Shaft Power (kW)	Turbine Inlet Temp (K)	Comp. Mass Flow (kg/s)	Pressure Ratio
Maximum Take-Off	1 491	1 466 (1 193^{o}C)*	6.70	12.14
Normal Take-Off	1 342	1 416 (1 143^{o}C)*	6.10*	11.0*
Maximum Cruise	1 231	1 366 (1 093^{o}C)	5.50*	10.0*
Normal Cruise	1 166*	1 341 (1 068^{o}C)*	4.95*	9.5*
Long Range Cruise	1 101*	1 316 (1 043^{o}C)*	4.40*	9.0*

Table 2.4 – Engine Performance Cases with Associated Cycle Parameters (SL ISA, No Ext. Bleed, * indicates author-estimated value)

3.0 Model Validation

The model was validated against the published data for Equivalent SFC at Maximum Take-Off under Sea Level ISA conditions without external bleed air. Equivalent SFC is the sum of the shaft power and the power derived from the gas turbine exhaust thrust.

Configuration	ESFC (kg/ekW h)	Model Error (%)
Maximum Take-Off Ref. [2]	0.286	12.9
Maximum Take-Off Ref. [3]	0.295	9.5
Maximum Take-Off Model	0.323	N/A

Table 3.1 – Published versus Model Max. Take-Off ESFC (SL ISA, No Ext. Bleed)

The model result was in reasonable agreement with the published data with between 9.5% and 12.9% of error depending on the reference for ESFC.

Data from a Digital Flight Data Recorder (DFDR) were provided by an interested Dash 8-100 operator to Specific Range Solutions Ltd. This data was crucial for validating the model. The data, sampled at 1 Hz, is from a typical commercial flight from taxi-out to taxi-in. Two points in flight were used to validate the PW120A thermodynamic model, take-off at a time of 13:06:51 *UTC* and cruise at a time of 13:51:11 *UTC*. The model utilized the normal take-off and normal cruise settings defined in Table 2.4. The model also accounted for external bleed air drawn from the LP port taken at the Norm setting. Shaft power for the flight data was calculated as follows.

Aircraft Output Shaft Power Equation:

$$Shaft\ Power = TRQ \times [\ NP / 1200\ ] \times 1\,491\ kW \qquad [2.4]$$

where:

TRQ = Measured Gearbox Torque (%)

NP = Propeller Speed (RPM)

Please note that the effect of the propeller on the free stream velocity upstream of the intake was not taken into account in the model.

Configuration	Shaft Power (kW)	Model Error (%)	Fuel Flow (kg/h)	Model Error (%)	SFC (kg/kW-h)	Model Error (%)
Norm. TO Eng. 1	1 358	7.1	437.6	10.2	0.322	3.1
Norm. TO Eng. 2	1 391	4.5	456.2	5.7	0.328	1.2
Norm. TO Model	1 454	N/A	482.2	N/A	0.332	N/A

Table 3.2 – Flight versus Model Data Norm Take-Off (PALT = -288 ft, SAT = -3.5°C, KIAS = 96.9, Norm. LP Bleed)

Configuration	Shaft Power (kW)	Model Error (%)	Fuel Flow (kg/h)	Model Error (%)	SFC (kg/kW-h)	Model Error (%)
Norm. Cruise Eng. 1	928.7	-0.2	266.4	8.7	0.287	8.7
Norm. Cruise Eng. 2	930.4	-0.4	281.1	3.0	0.302	3.3
Norm. Cruise Model	926.9	N/A	289.6	N/A	0.312	N/A

Table 3.3 – Flight versus Model Data Norm Cruise (PALT = 15 616 ft, SAT = -23.5°C, KIAS = 198.7, Norm. LP Bleed)

The model results are encouraging in that the shaft power, fuel flows and SFC are within 10% of the recorded flight data. The shaft power in Norm. Cruise has been accurately estimated. The main likely reasons for the errors are presented below:

- model of engine may be too simplified e.g. assumption of equivalent polytropic efficiency, η_∞ for both compressor and turbine stages;
- actual take-off power setting may not correspond to the normal take-off setting;
- typical variance in engine power and fuel flow between the engines due to different engine condition;
- accuracy of modelling of cooling bleed flow;
- accuracy of the measured propeller speed (NP), gearbox torque (%) and fuel flow values;
- precision in calculating exhaust thrust.

Overall however, the PW120A model appears to be reasonably accurate for the purposes of performing the various parametric analyses. The model did not account for turboprop installation losses.

4.0 Model Parametric Analysis

4.1 Impact of Cruise Power Setting

The output power, fuel flow and ESFC were calculated for three difference cruise power settings at 25,000 ft ISA conditions with Normal LP bleed. The increase in fuel flow is clear with increasing power setting. Interestingly, the ESFC does improve i.e. decreases slightly with increasing power. This behaviour is expected as the engine approaches its design point and is consistent with Fig. 9.11 in Ref. [1].

The engine fuel efficiency improves slightly, i.e. ESFC decreases slightly, as the cruise power setting is increased. However, the lowest fuel burn rate is achieved at the Long Range Cruise setting.

Cruise Setting	True Air Speed (km/h)	Shaft Power (kW)	Thrust Power (kW)	Fuel Flow (kg/h)	ESFC (kg/ekW h)	Delta ESFC (%)
Long Range	440	693.7	13.3	215.3	0.304	0.3
Normal	465	798.5	21.1	248.4	0.303	0.0
Maximum	490	902.3	30.7	282.7	0.303	0.0

Table 4.1 – Power, Fuel Flow & ESFC vs. Cruise Power Setting (25,000 ft, ISA, Norm. LP Bleed)

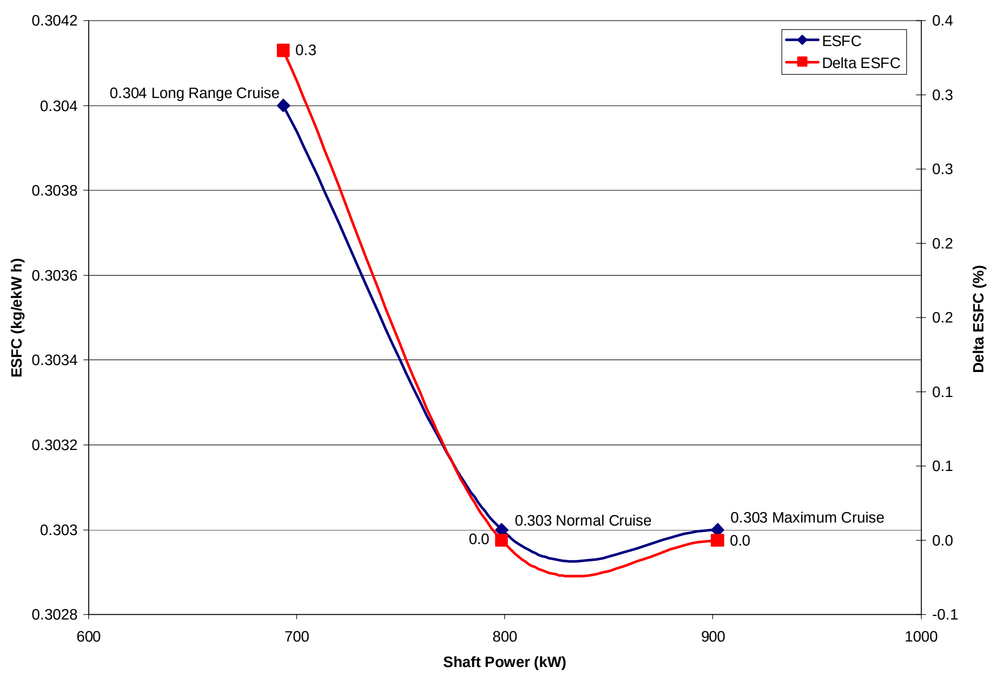

Figure 4.1 – ESFC vs. Cruise Power Setting (25,000 ft, ISA, Norm. LP Bleed)

4.2 Impact of Altitude

The output power, fuel flow and ESFC were calculated for five different altitudes at Max. Cruise Power, ISA conditions with Normal LP bleed. The ESFC decreases with increasing altitude due to the decreasing temperature. This is because the ambient temperature has a direct impact on the specific work of the working fluid across the power turbine. The power output and fuel flow decrease because of the decreasing air density due to decreasing air pressure.

The highest engine fuel efficiency, i.e. the minimum ESFC, will be achieved at the highest permitted operational altitude under ISA conditions.

Altitude (ft)	SAT (deg. C)	Shaft Power (kW)	Thrust Power (kW)	Fuel Flow (kg/h)	ESFC (kg/ekW h)	Delta ESFC (%)
13,000	-10.7	1,023.8	21.7	329.8	0.315	4.0
16,000	-16.7	997.7	23.7	318.2	0.312	3.0
19,000	-22.6	967.8	25.9	306.6	0.309	2.0
22,000	-28.6	936.0	28.1	294.6	0.306	1.0
25,000	-34.5	902.3	30.7	282.7	0.303	0.0

Table 4.2 – Power, Fuel Flow & ESFC vs. Altitude (Max. Cruise Power, ISA, Norm. LP Bleed)

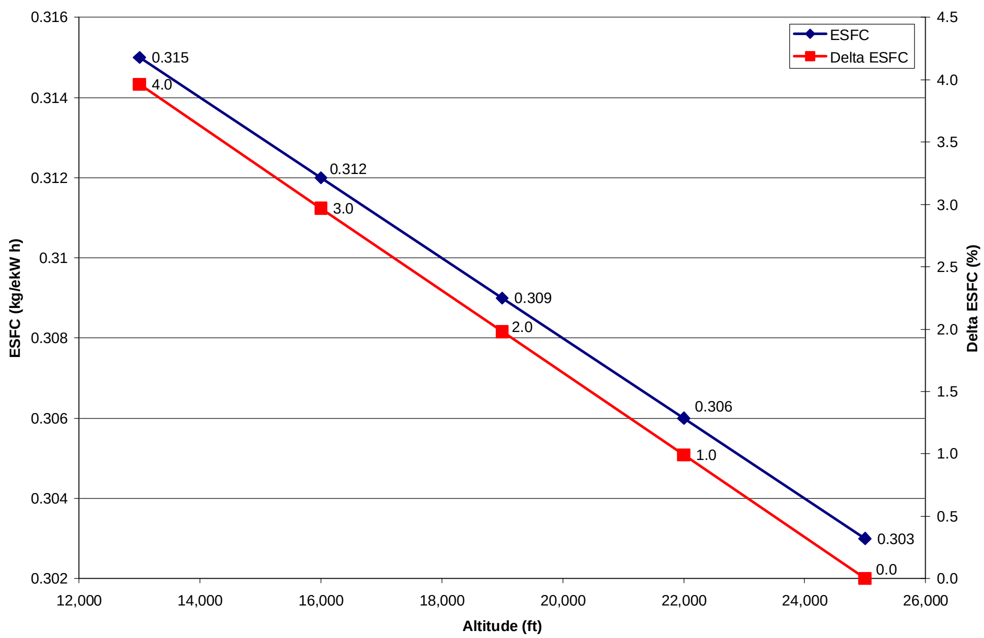

Figure 4.2 – ESFC vs. Altitude (Max. Cruise Power, ISA, Norm. LP Bleed)

4.3 Impact of Static Air Temperature

The output power, fuel flow and ESFC were calculated for five different external temperatures (ISA-20^{o}C, ISA-10^{o}C, ISA, ISA+10^{o}C and ISA+20^{o}C) at Max. Cruise Power and 25,000 ft with Normal LP bleed. Power and fuel flow decrease with increasing static air temperature (SAT) and the ESFC increases with increasing SAT. The converse is also true for colder values of SAT. The explanation is previously discussed in paragraph 4.2.

Warmer temperatures aloft are detrimental to ESFC and the converse is also true, cooler temperatures aloft are favourable to ESFC.

Delta ISA (SAT)	Shaft Power (kW)	Thrust Power (kW)	Fuel Flow (kg/h)	ESFC (kg/ekW h)	Delta ESFC (%)
-20 C (-54.5 C)	1,032.9	36.0	309.8	0.290	-4.3
-10 C (-44.5 C)	965.9	33.2	295.9	0.296	-2.3
0 C (-34.5 C)	902.3	30.7	282.7	0.303	0.0
+10 C (-24.5 C)	841.7	28.4	270.1	0.310	2.3
+20 C (-14.5 C)	783.8	26.3	258.1	0.319	5.3

Table 4.3 – Power, Fuel Flow & ESFC vs. Delta ISA/SAT (Max. Cruise Power, 25,000 ft, Norm. LP Bleed)

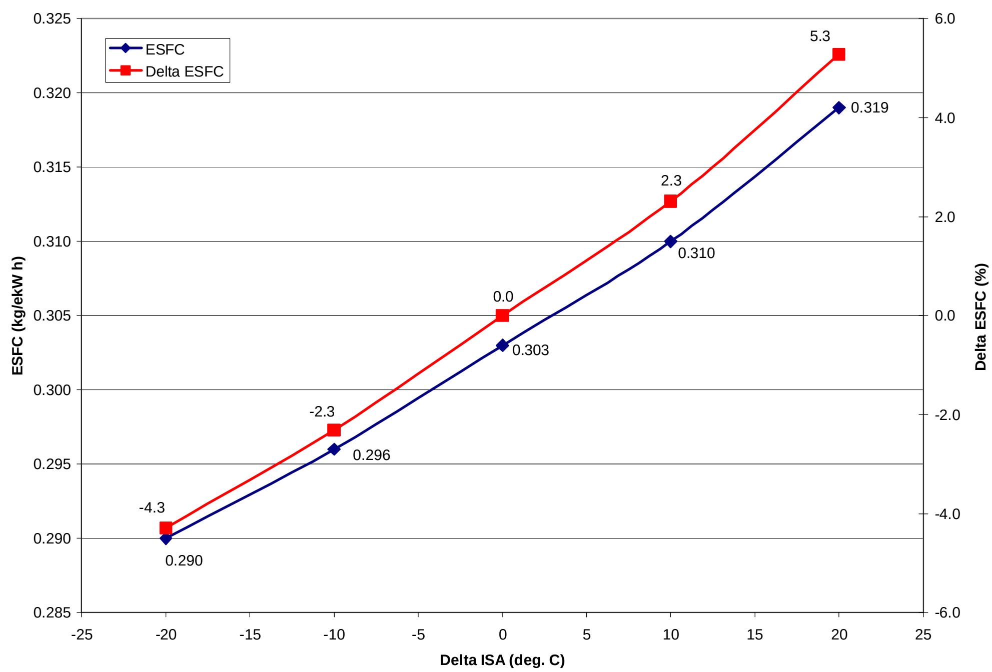

Figure 4.3 – ESFC vs. Delta ISA/SAT (Max. Cruise Power, 25,000 ft, Norm. LP Bleed)

4.4 Impact of External Bleed Air

The output power, fuel flow and ESFC were calculated for four different bleed air settings at Max. Cruise Power, 25,000 ft ISA conditions. Under cruise conditions, air would be normally bled from the Low Pressure (LP) compressor stage and this is how the external bleed air was modeled.

Power output and fuel flow decrease with increasing bleed air flow which is understandable as the mass flow passing through the combustor is reduced. However, work is required to compress the bleed air in the LP stage and this is reflected in the higher ESFC. Air bled from the HP port would have an even larger impact on ESFC. The Minimum setting was selected as the baseline

Minimizing the external bleed air mass flow will improve engine fuel efficiency, i.e. decrease ESFC. However, a minimum amount of bleed flow is required to satisfy passenger and crew fresh air flow and pressurization requirements.

Bleed Setting	Bleed Flow (kg/s)	Shaft Power (kW)	Thrust Power (kW)	Fuel Flow (kg/h)	ESFC (kg/ekW h)	Delta ESFC (%)
No Bleed	0.000	972.1	36.4	296.3	0.294	-1.3
Minimum	0.086	937.2	33.5	289.5	0.298	0.0
Normal	0.172	902.3	30.7	282.7	0.303	1.7
Maximum	0.258	865.8	27.9	275.6	0.308	3.4

Table 4.4 – Power, Fuel Flow & ESFC vs. LP Bleed Air (Max. Cruise Power, 25,000 ft, ISA)

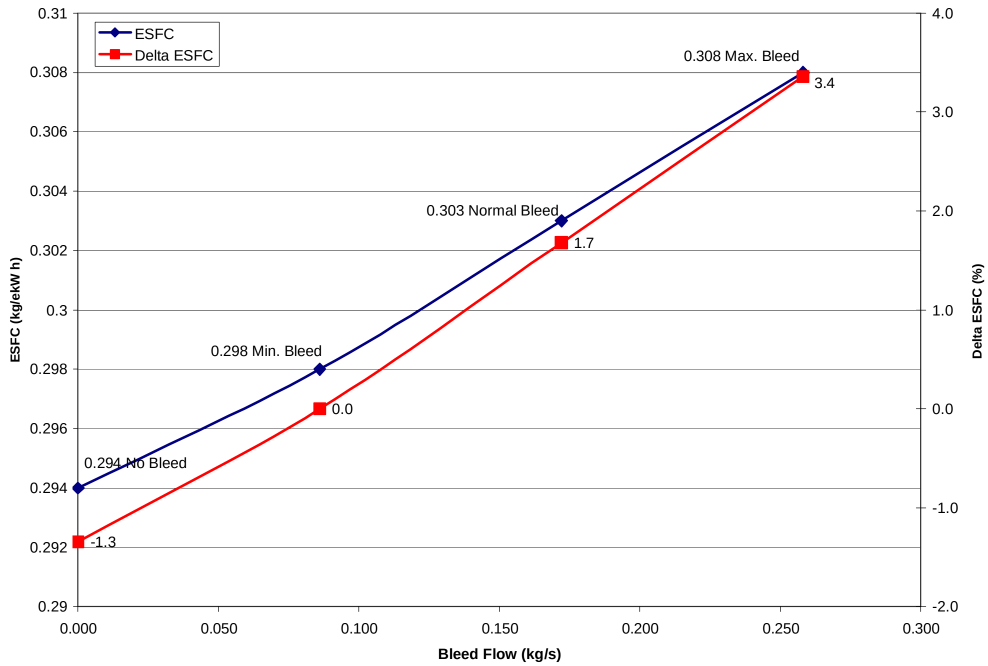

Figure 4.4 – ESFC vs. LP Bleed Air (Max. Cruise Power, 25,000 ft, ISA)

4.5 Impact of Compressor Fouling and Turbine Wear

The effect of compressor fouling and turbine wear were evaluated individually and also in a combined manner. Levels of compressor wear were incorporated into the model by decreasing the polytropic efficiency, η_∞, of both the LP and HP spools by 1% and 2%. Turbine wear was simulated by model by decreasing the polytropic efficiency, η_∞, of the LP, HP and power turbine stages by 1% and 2%. Combined fouling and wear conditions were also calculated.

It should be noted that these reductions in polytropic efficiencies were not linked to a specific physical condition for the compressor or turbine. This was an abstraction established to perform this sensitivity analysis. Further study is required to correlate component efficiency and physical state.

In regards to compressor fouling, power output and fuel flow decrease because of frictional effects, and therefore ESFC increases. In the case of turbine wear, fuel flow remains constant and power output drops, ESFC increases due to the negative impact on specific work.

Engine fuel efficiency is maintained by avoiding compressor fouling conditions and by ensuring turbine wear is minimized.

Fouling & Wear Condition	Delta Efficiency (%)	Shaft Power (kW)	Thrust Power (kW)	Fuel Flow (kg/h)	ESFC (kg/ekW h)	Delta ESFC (%)
Baseline	0	902.3	30.7	282.7	0.303	0.0
Comp. Fouling (-1%)	-1	887.4	30.7	281.4	0.307	1.3
Comp. Fouling (-2%)	-2	871.5	30.7	280.4	0.310	2.3
Turb. Wear (-1%)	-1	887.3	31.1	282.7	0.308	1.7
Turb. Wear (-2%)	-2	871.6	31.5	282.7	0.313	3.3
Combined Loss. (-1%)	-1	872.4	31.1	281.4	0.311	2.6
Combined Loss. (-2%)	-2	840.8	31.5	279.9	0.321	5.9

Table 4.5 – Power, Fuel Flow & ESFC vs. Polytropic Eff. Change (Max. Cruise Power, 25,000 ft, ISA, Norm. LP Bleed)

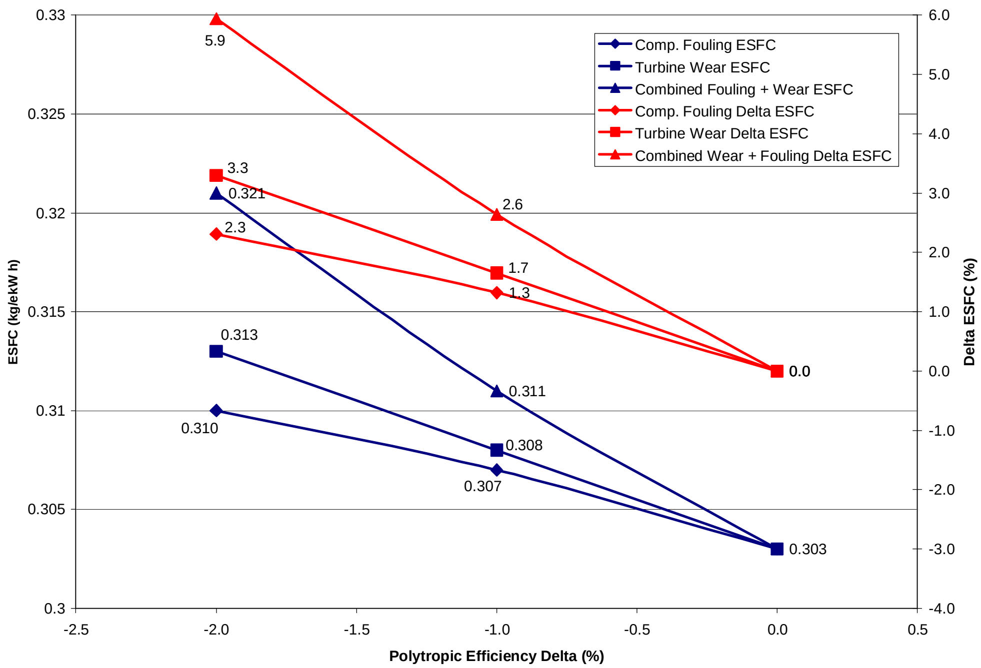

Figure 4.5 – ESFC vs. Polytropic Eff. Change (Max. Cruise Power, 25,000 ft, ISA, Norm. LP Bleed)

5.0 Conclusions

In the cruise flight phase, the impact of throttle setting, aircraft altitude, static air temperature, external bleed flow, compressor fouling and turbine wear have been evaluated using classical thermodynamic techniques and conservative assumptions about gas turbine characteristics. The study confirmed information which is known:

1. The engine fuel efficiency improves slightly, i.e. ESFC decreases slightly, as the cruise power setting is increased. However, the lowest fuel burn rate is achieved at the Long Range Cruise setting.
2. The highest engine fuel efficiency, i.e. the minimum ESFC, will be achieved at the highest permitted operational altitude under ISA conditions.
3. Warmer temperatures aloft are detrimental to ESFC and the converse is also true, cooler temperatures aloft are favourable to ESFC.
4. Minimizing the external bleed air mass flow will improve engine fuel efficiency, i.e. decrease ESFC. However, a minimum amount of bleed flow is required to satisfy passenger and crew fresh air flow and pressurization requirements.
5. Engine fuel efficiency is maintained by avoiding compressor fouling conditions and by ensuring turbine wear is minimized.

6.0 Areas for Further Development

In order to improve the accuracy of the model, the following additional steps are suggested:

1. The model needs to be further optimized around its design points of Max. Cruise and Max. Take-Off with particular attention paid to accurately estimating component level efficiency and internal cooling. The turbine inlet temperatures (TIT) for both cases also need to be verified.
2. The external bleed flow schedule needs to be verified against system specification or flight test data. It is worthwhile to also evaluate impact of air bled from the HP port.
3. Off-design model development is the next priority. This would require a more accurate estimation of the relationships between pressure ratio, TIT, compressor mass flow and stage efficiencies as a function of power setting or gas generator speed. The idle power setting is an important operating point.

4. The accurate accounting of installation effects e.g. propeller and intake effects and a better means of calculating residual thrust power would enable installed performance to be better represented.
5. Ultimately, an aircraft operator is interested in total fuel burn on a particular mission, so the development of an integrated aircraft and engine model to permit evaluation of a complete flight would be useful.

While gas turbine performance software such as GASTURB is readily available, it is hoped that the results of this PW120A simplified model will provide operators of aircraft powered by this engine a better understanding of the engine's fuel efficiency as a function of the operational parameters of throttle setting, altitude, static air temperature, external bleed air, compressor fouling and turbine wear. This model could form part of an analytical toolbox that operators could employ to further optimize their flight operations.

7.0 References

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