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Reynolds Number Effects on the Performance of a Turbofan Engine

MASAO KOZU
3rd Research Center
Technical Research and Development Institute
Japan Defence Agency

SATOSHI YASHIMA
Engineering & Programs Dept.
Aero-engine Division
Ishikawajima-Harima Heavy Industries Co., Ltd.
Tokyo, Japan

ABSTRACT

Reynolds Number effects on the matching performance of a small twin-spool turbofan engine were investigated through the altitude tests of the F3-30 engine which was developed to power the Japan Air Self Defence Force's T-4 intermediate trainer.

Analyzing the test results made it clear that the change of the aerodynamic characteristics of the low pressure turbine due to Reynolds Number effects is as significant as those of fan and compressor, and it caused the difference between the predicted and measured engine performance at high altitudes.

Correlation factors on the Reynolds Number for each of the component characteristics (pressure ratio, airflow and efficiency of fan and compressor, and gas flow and efficiency of low pressure turbine) were obtained, and simulation of the engine performance using these factors coincided well with the test data which were obtained from the altitude tests of the F3-30 at Arnold Engineering Development Center of U.S.Air Force.

NOMENCLATURE

c	Chord length at mid span
Fn	Net thrust
M_0	Flight Mach number
Nf	Fan speed
Ng	Compressor speed
Qc	Compressor corrected air flow
Qf	Fan corrected air flow
Q_{LPT}	Low pressure turbine corrected gas flow (flow function)
Re	Reynolds number
SFC	Specific fuel consumption (=Wf/Fn)
SLS	Sea level static
V	Relative inlet velocity at mid span of the rotor blade
Wf	Fuel flow
η_c	Compressor adiabatic efficiency
η_f	Fan adiabatic efficiency
η_{LPT}	Low pressure turbine adiabatic efficiency
ν	Kinematic viscosity
π_c	Compressor pressure ratio
π_f	Fan pressure ratio

INTRODUCTION

The performance prediction of a turbofan engine is made with computer programs which calculate engine operating points by balancing airflow, work and speed of its components, providing the component performance maps are given.

A typical fan and compressor performance map is shown in Figure 1. Airflow and speed are corrected with the standard inlet temperature (288.15K) and pressure ($1.013 \times 10^5 N/m^2$). The combustor efficiency is given as a map of air-fuel ratio and air loading parameter (Figure 2) which is a function of inlet pressure, temperature, airflow and the typical dimension of the combustor. A typical turbine performance map is shown in Figure 3. This map uses corrected values of gas flow, work and speed. These component maps are obtained from aerodynamic and thermodynamic calculations and/or component rig tests.

Analytical techniques used to balance the component characteristics have been reported in several papers ([1][1], [2], [3]) and further discussion is not the object of this paper.

Using one of the confirmed analytical techniques and the above component maps, the

[1] ***Numbers in brackets designate References at end of paper***

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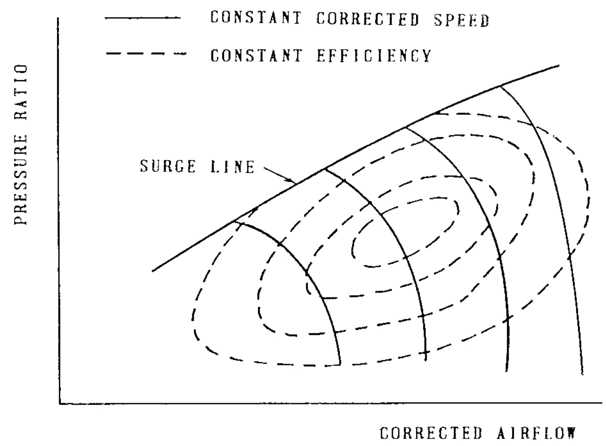

FIGURE 1 SPECIFIC FAN-COMPRESSOR MAP

predicted engine performance agrees well with the measured data at low altitudes (below 30,000ft). However, the difference between the prediction and the measurement is significant at high altitudes, because the component maps are corrected merely with the temperature and pressure; viscosity (i.e. Reynolds Number), which affects the aerodynamic performance of turbomachinary, is not taken into consideration.

The effects of Reynolds Number on turbomachinary have been studied in several papers ([4] -[7]), though the data of these papers are not broken down enough to be applied to the design of specific components. Then, it is necessary to execute component rig tests in order to study the precise Reynolds Number effects on each component. This is a time and cost consuming procedure which might impact the engine development program.

In the development of the F3-30 engine, the component rig tests were not done for the study of the Reynolds Number effects. Engine test data, which were obtained from the altitude test facility (ATF) at the early stage of the engine development, were analyzed to give the Reynolds Number correlation factors of the components. Applying the correlation factors to the component maps, the performance prediction at the mature stage of development improved significantly and the results were reflected on the customer computer deck of the F3-30 engine.

ENGINE DESCRIPTION

The F3-30 is the low bypass ratio turbofan engine which was developed to power the Japan Air Self Defence Force's T-4 intermediate trainer. The full scale development started in 1980 and the qualification tests were successfully completed by March, 1986, and the first production engine was delivered in December, 1987.

The cross section of the F3-30 is shown in Figure 4, and the leading characteristics are shown in Table 1.
Further information on the development program of the F3-30 is available from [8].

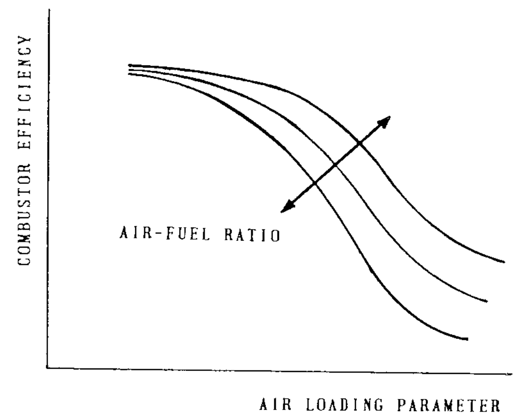

FIGURE 2 SPECIFIC COMBUSTOR MAP

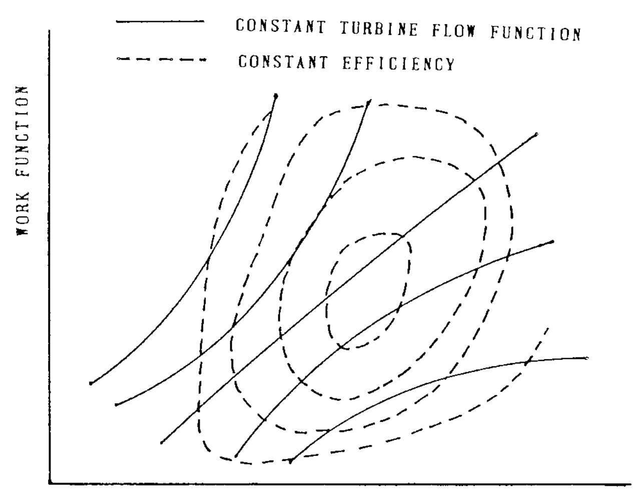

FIGURE 3 SPECIFIC TURBINE MAP

ATF TESTS

Altitude tests were conducted four times in the altitude test facilities (ATF) of Arnold Engineering Development Center (AEDC), Tullahoma, Tennessee, and General Electric (GE), Evendale, Ohio, as shown in Table 2. Overall altitude test results are discussed in [9].

Data from the 1st and 2nd test segments were analyzed to investigate the Reynolds number effects at the test points shown in Figure 5. Measured parameters on the aero-

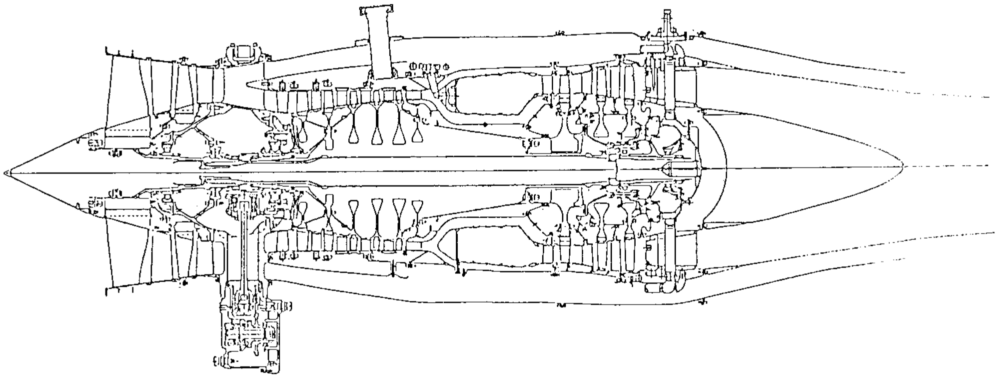

FIGURE 4 F3-30 TURBOFAN ENGINE

Thrust	16.38 kN (3680 lb)
SFC	19.22 mg/Ns (0.68 lb/h/lb)
Weight	340 kg (750 lb)
Thrust/Weight Ratio	4.9
Engine Inlet Dia.	522 mm (20.6 in)
Total Air Flow	34 kg/s (75 lb/s)
Bypass Ratio	0.9
Fan Pressure Ratio	2.65 (2 stages)
Compressor Pressure Ratio	4.2 (5 stages)
Turbine Inlet Temperature	1050℃ (1922°F)
HP Rotor Speed	21,100 rpm
LP Rotor Speed	15,300 rpm
Stage Numbers of Turbines	1-HP, 2-LP

TABLE 1 LEADING CHARACTERISTICS OF F3-30

PHASE	YEAR	PLACE	RUN TIME
SEGMENT 1	1982	AEDC	73 Hrs
SEGMENT 2	1983	AEDC	59 Hrs
SEGMENT 3	1984	GE	68 Hrs
SEGMENT 4	1985	AEDC	140 Hrs

TABLE 2 ATF TESTS OF F3-30

dynamic performance are as follows;

- Engine inlet total temperature and pressure
- Fan (engine) inlet airflow
- Fan exit total temperature and pressure
- Compressor exit total temperature and pressure
- Low pressure (LP) turbine exit total temperature
- Engine speeds (HP and LP)
- Thrust
- Fuel flow

Because the F3-30 is such a small engine, the blockage of the probes changes the engine matching performance. The total temperature at the LP turbine exit was only the parameter to be directly measured in hot section. Sixteen probes were built in eight struts at the exhaust frame (each containing two probes in order to minimize the blockage due to probes.)

HP turbine inlet temperature and core air-flow were calculated with the measured fuel flow, compressor exit total temperature and pressure, using the HP turbine flow function (corrected gas flow) and combustor efficiency which were measured prior to the ATF engine test.

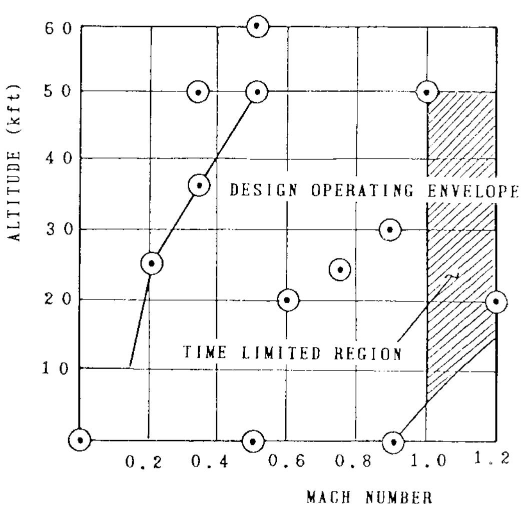

FIGURE 5 TEST POINTS

REYNOLDS NUMBER EFFECTS ON FAN AND COMPRESSOR

Fan and compressor characteristics represented by pressure ratio, corrected airflow and adiabatic efficiency were determined from the test data at each altitude and flight Mach number test point. Then the differences of pressure ratio, flow and efficiency parameters ($\Delta\pi$, ΔQ and $\Delta\eta$) from SLS condition at 100% of the corrected speed were obtained.

For example, changes in fan characteristics at 50,000ft altitude and 0.5 Mach number (50kft/0.5M_0) are shown in Figure 6. The operating point is shifted up by 2 % in pressure ratio and down by 4.2 % in flow at 100 % corrected fan speed. The constant speed line at 100% corrected fan speed which was obtained from the SLS component rig test is also shown in Figure 6, for reference.

Reynolds number is defined in terms of the relative velocity and chord length at mid span of the rotor blade together with consistant values of kinetic viscosity.

$$Re = \frac{V \cdot c}{\nu} \qquad \text{Eqn (1)}$$

The Reynolds numbers for the fan and compressor at each altitude and Mach number condition are shown in Table 3. The variations of fan and compressor parameters from SLS data are plotted in Figure 7 and 8 as a function of Reynolds number. The changes in airflow resulting from changes in Reynolds numbers are notable in both the fan and compressor. Changes in pressure ratio are negligibly small for both the fan and compressor. The Reynolds number effect on fan efficiency is only about half its effect on compressor efficiency.

SYMBOL	ALT. (kft)	M_0	FAN Re	COMP. Re
◫	0	0	2.3×10^6	1.6×10^6
■	0	0.5	2.6×10^6	1.8×10^6
⊡	0	0.9	3.2×10^6	2.2×10^6
△	20	0.6	1.5×10^6	1.0×10^6
▲	20	1.2	2.2×10^6	1.4×10^6
⊙	25	0.2	1.1×10^6	7.5×10^5
◕	25	0.75	1.4×10^6	9.3×10^5
◇ (dotted)	30	0.9	1.3×10^6	8.6×10^5
◆	36	0.34	8.0×10^5	5.5×10^5
☆	50	0.35	4.0×10^5	3.3×10^5
★	50	0.5	4.2×10^5	3.2×10^5
✡	50	1.0	5.6×10^5	4.0×10^5
◇ (ticked)	60	0.5	2.6×10^5	2.0×10^5

TABLE 3 REYNOLDS NUMBER AT EACH TEST POINT (AT 100% CORRECTED SPEED)

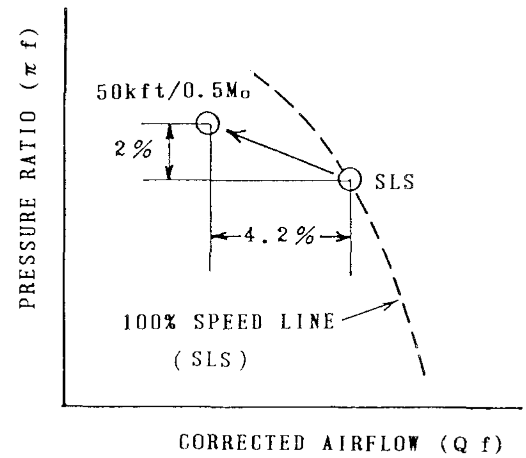

FIGURE 6 FAN OPERATING POINTS AT 100% SPEED

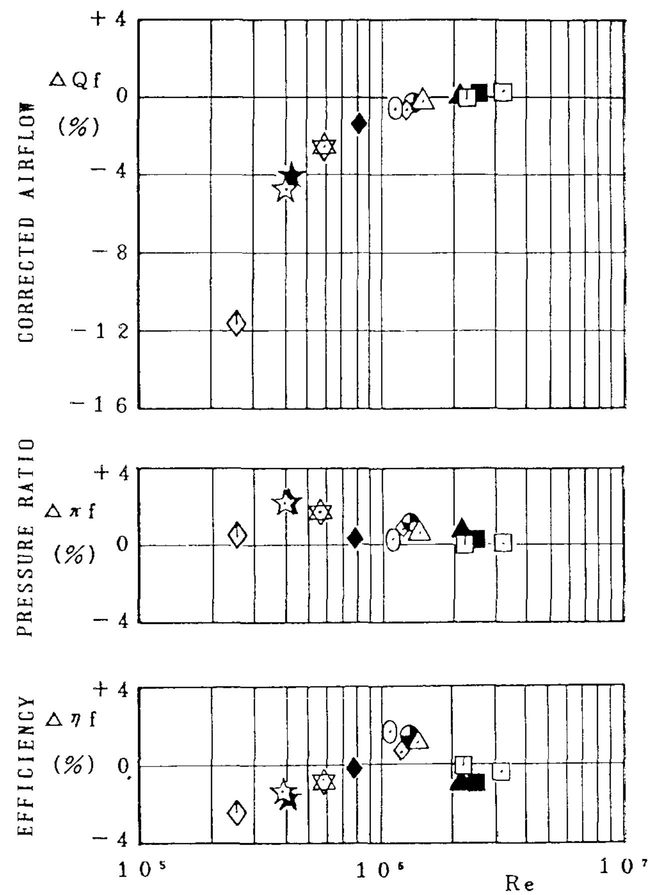

FIGURE 7 EFFECTS OF REYNOLDS NUMBER ON FAN PERFORMANCE (SYMBOLS ARE DEFINED IN TABLE 3)

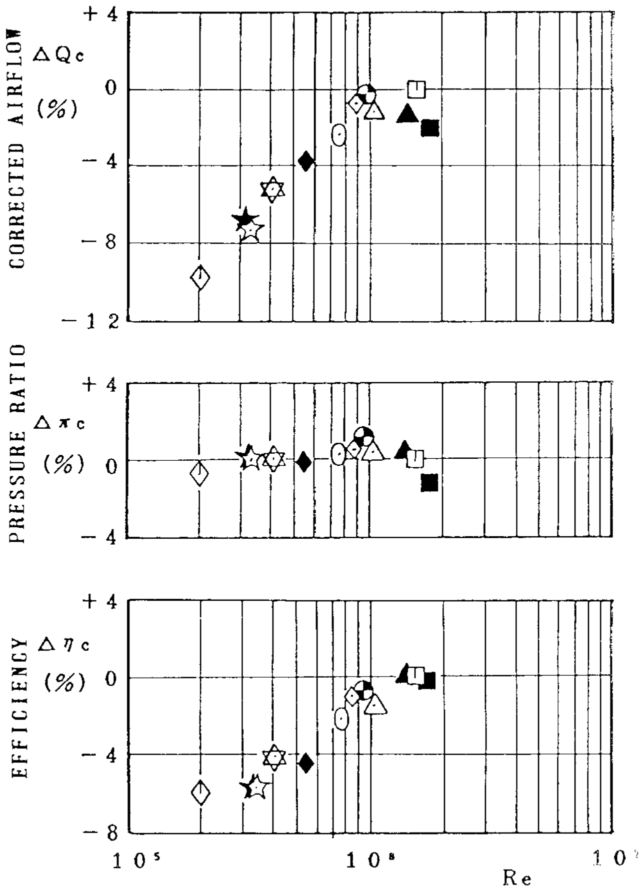

FIGURE 8 EFFECTS OF REYNOLDS NUMBER ON COMPRESSOR PERFRFORMANCE (SYMBOLS ARE DEFINED IN TABLE 3)

REYNOLDS NUMBER EFFECTS ON LP TURBINE

Engine off-design calculations were made at 50kft/0.5M_0 without any consideration of Reynolds number effects (Case 1 in Figure 9), and for the fan and the compressor maps which were corrected with the correlation factors given in Figure 7 and 8 (Case 2 in Figure 9). It can be seen that the Reynolds number effects correlation factors of fan and compressor give a better estimation of the engine matching performance than the original calculation, but the difference from the measured data (ATF engine test data in Figure 9) is still significant. This suggested the necessity of considering the Reynolds number effects on the turbine characteristics.

In general, turbine performance is not affected so much as fan and compressor performance, since the velocity of flow is increased through the turbine and so the flow in turbine is not so likely to separate as in the compressor. Klassen, et al. [6] investigated the effects of Reynolds number on turbine performance over a range of Re from 4,900 to 188,000, and the results showed that turbine performance changes significantly when Re is lower than 10^5.

Reynolds numbers of each component at SLS and 50kft/0.5M_0 are shown in Table 4, which suggests that the LP turbine performance should be changed at high altitude, because the Re of LP turbine is one-order smaller than the other components (only 4.4x10^4 at 50kft/0.5M_0).

LP turbine performance was not measured directly from the ATF engine test (LP turbine exit temperature was the only measured parameter as mentioned earlier).

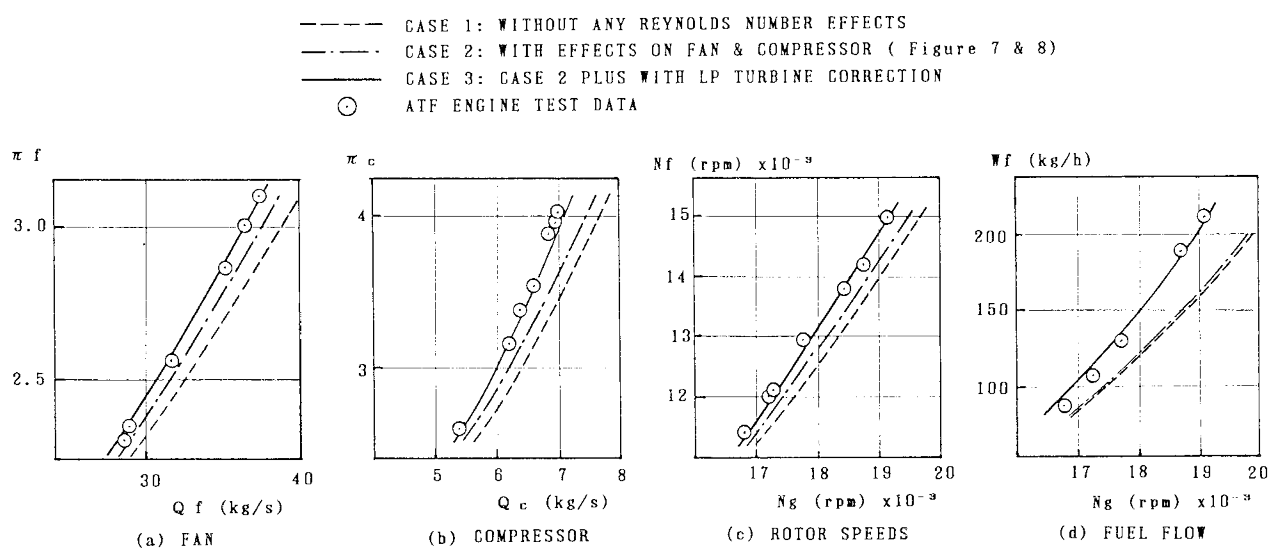

FIGURE 9 ENGINE MATCHING PERFORMANCE AT 50KFT/0.5M_0

It was assumed that the flow function (corrected gas flow) and efficiency of LP turbine were affected by the Reynolds number, and engine off-design calculations were made with assumed numbers of correlation factors (ΔQ_{LPT} and $\Delta\eta_{LPT}$) on a trial and error basis until the calculation met the measured engine matching performance. It was found that the calculation agreed well with the measurement if ΔQ_{LPT}=-4.5 % and $\Delta\eta_{LPT}$=-8 % were assumed at 50kft/0.5M_0(Case 3 in Figure 9).

COMPONENT	SLS	50kft/0.5M_0
FAN	2.3×10^6	4.2×10^5
COMPRESSOR	1.6×10^6	3.2×10^5
HP TURBINE	1.6×10^6	2.8×10^5
LP TURBINE	2.5×10^5	4.4×10^4

TABLE 4 REYNOLDS NUMBERS AT 100% CORRECTED SPEED

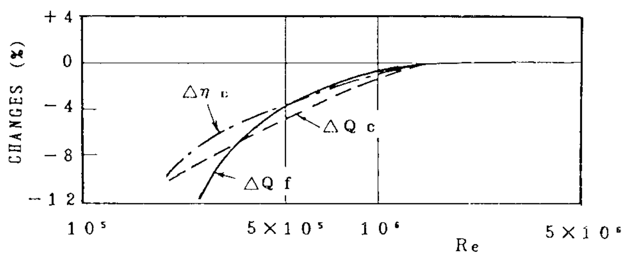

FIGURE 10 CORRELATION FACTORS FOR FAN AND COMPRESSOR

CORRELATION FACTORS APPLIED TO THE PERFORMANCE PREDICTION

It was concluded from the above study that fan and compressor airflow, compressor efficiency, LP turbine efficiency and gas flow should be corrected with the changes of Reynolds number. The correlation factors for fan and compressor were based on the ATF test data given in Figure 10. The correlation factors for the LP turbine were assumed to vary linearly from SLS to 50kft/0.5M_0; these are given in Figure 11.

Prior to the segment 4 ATF test (executed as the qualification test) of the F3-30, the performance prediction was made applying those correlation factors to the component maps. Test results showed good concurrence between the predictions and the measured values as shown in Figure 12.

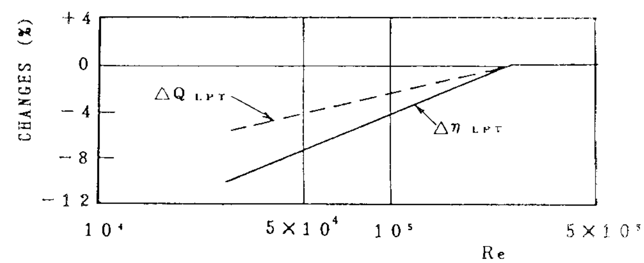

FIGURE 11 CORRELATION FACTORS FOR LP TURBINE

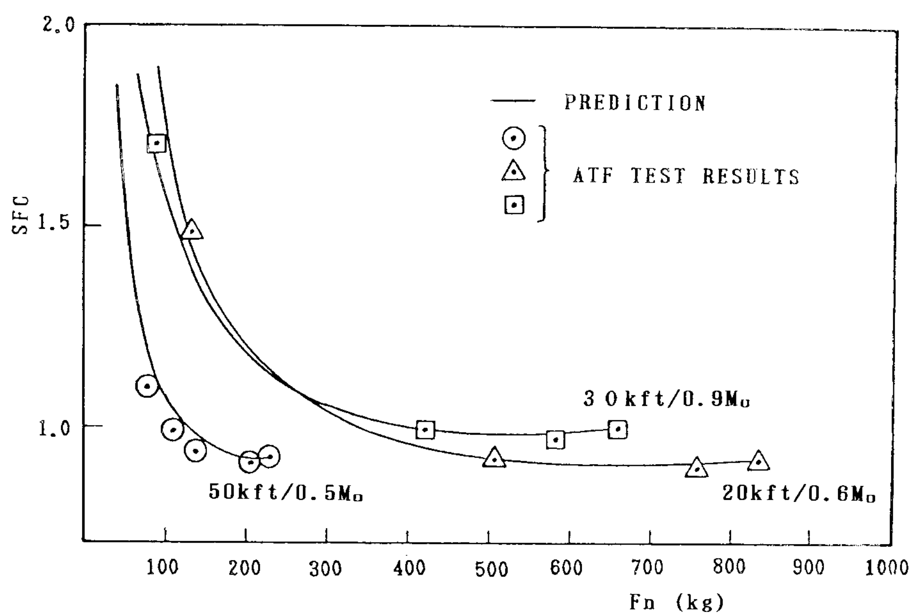

FIGURE 12 PREDICTED AND MEASURED ENGINE PERFORMANCE

CONCLUDING REMARKS

The Reynolds number effects on the engine matching performance are very significant for small turbofans such as the F3-30, which fly at high altitudes (50,000ft).
The correlation factors for fan, compressor and low pressure turbine performance maps were obtained from the analysis of the ATF engine test data; these have proved to be effective for the improvement of the performance prediction of the F3-30 and have been applied to the customer computer deck.

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