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SUMMARY

The exhaust jet conditions, in terms of temperature and Mach number, have been determined for a nozzle–aft end acoustic study flown on an F-15 airplane. Jet properties for the F100 EMD engines were calculated using the engine manufacturer's specification deck. The effects of atmospheric temperature on jet Mach number, M10, were calculated. Values of turbine discharge pressure, PT6M, jet Mach number, and jet temperature were calculated as a function of airplane Mach number, altitude, and power lever angle for the test day conditions. At a typical test point with a Mach number of 0.9, intermediate power setting, and an altitude of 20,000 ft, M10 was equal to 1.63. Flight measured and calculated values of PT6M were compared for intermediate power at altitudes of 15,500, 20,500, and 31,000 ft. It was found that, at 31,000 ft, there was excellent agreement between both, but for lower altitudes the specification deck overpredicted the flight data. The calculated jet Mach numbers were believed to be accurate to within 2 percent.

INTRODUCTION

The acoustic properties of exhaust jets are strong functions of the jet conditions—Mach number, temperature, and velocity. The acoustics of these jets have an impact not only on the far-field noise level, but may also result in high acoustic loads on the aircraft structure. In some cases, the engine exhaust nozzle external flaps have been subject to structural damage (Seiner and Manning, 1987). Analytical studies and model scale tests of twin jet acoustics have been conducted at the NASA Langley Research Center, but flight measurements of acoustic loads caused by afterburning twin-jet installations did not exist at the time of this writing.

To investigate acoustic loads on engine nozzle external flaps, the NASA Ames Research Center's Dryden Flight Research Facility (Ames-Dryden), in conjunction with the NASA Langley Research Center, conducted a flight investigation on an F-15 airplane. The external nozzle flaps of the engines were instrumented with microphones, dynamic pressure transducers, accelerometers, and strain gages. Correlation of these flight measurements to analytical and ground test results of Seiner and Manning (1987) requires an accurate estimation of the jet conditions, and in particular, the fully expanded jet Mach number M10. M10 cannot be directly measured in-flight, but may be inferred from the measured turbine discharge pressure and ambient static pressure, coupled with the engine manufacturer's engine performance specification computer deck. The airplane and engines were therefore instrumented to obtain data to permit these correlations to be made.

The authors present the measured and calculated jet conditions in terms of Mach number, pressure, and temperature for the acoustic tests. The typical and well-known relationships between engine pressures, temperatures, and jet Mach numbers are quantified for the F100 EMD engines in the F-15 airplane. Also presented are descriptions of the methods used to calculate flow properties, engine cycle deck, instrumentation, and a comparison of flight data to the predicted engine cycle deck data.

NOMENCLATURE

AJ	primary nozzle throat area
CIVV	compressor inlet variable vanes
DEEC	digital electronic engine control
DTSTD	difference between actual and standard day ambient temperature, °F
EMD	engine model derivative
EPR	engine pressure ratio
FTIT	fan turbine inlet temperature
h	altitude, ft

HIDEC	highly integrated digital electronic control
LOD	light-off-detector
M	airplane Mach number
M10	fully expanded jet Mach number
N1	engine fan rotor speed
N2	high compressor rotor speed
PAB	afterburner static pressure
PB	burner pressure
PLA	power lever angle
PS	ambient static pressure
PS2	static pressure at fan inlet
PT2	fan inlet total pressure
PT6M	mixed turbine discharge total pressure, $lb/in.^2$
PT7	nozzle exit total pressure
RCVV	rear compressor variable vanes
TT2	engine inlet total temperature
TT10	jet total temperature, °F
WF	main burner fuel flow
WFA	augmentor fuel flow
γ	ratio of specific heats

DESCRIPTION OF EQUIPMENT

F-15 Airplane

The NASA F-15 airplane is a single seat, high performance, air-superiority fighter aircraft with excellent transonic maneuverability and a maximum Mach capability of 2.5. It is a twin engine airplane with a high-mounted swept-back wing, twin vertical stabilizers, and large horizontal stabilizers (fig. 1). The engine inlets are the two-dimensional external compression type with three ramps and feature variable capture area. It is powered by two F100 turbofan engines closely spaced in the aft fuselage, with engine centerlines separated by 4.25 ft.

Engine Description

The F100 EMD engine (Pratt & Whitney, West Palm Beach, Florida; company designation PW1128) is a low-bypass ratio, twin spool, afterburning turbofan engine. Engine station designations are shown in figure 2. The three-stage fan is driven by a two-stage low-pressure turbine. The 10-stage high-pressure compressor is driven by a two-stage turbine. The engine incorporates compressor inlet variable vanes (CIVV) and rear compressor variable vanes (RCVV) to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a 16-segment mixed flow afterburner and a variable area convergent-divergent nozzle. More information on the engine may be found in Myers and Walsh (1987).

The engine power setting is controlled by the pilot's power lever angle (PLA), with idle being 20°, intermediate (maximum nonafterburning) 85°, minimum afterburning at 91°, and maximum afterburning at 130°.

The primary nozzle throat area, station 7, is controlled by the digital electronic engine control (DEEC) and varies from 2.75 ft^2 in the fully closed position to 6.5 ft^2 in the full open position. The nozzle secondary flaps are not controlled separately, but are positioned by the primary nozzle and aerodynamic loads. The ratio of secondary to primary nozzle area (nozzle expansion ratio) varies with PLA, but for subsonic conditions, it does not vary significantly with flight conditions, with typical ratios of 1.13 at intermediate power and 1.33 at maximum power.

The specific engines flown for the aft end acoustics flights were F100 EMD engines S/N P680085 and 680063. Both of these engines had been assembled from prototype engine parts, and their overall engine performance was lower than an average PW1128 engine.

F100 Engine Specification Deck

Pratt & Whitney Aircraft Customer Computer Deck, CCD 1194-1.0 (Pratt & Whitney Aircraft, 1982) is a steady-state aerothermodynamic mathematical model of the F100 EMDP turbofan engine. This engine simulation program predicts engine performance through the use of component characteristics. The engine simulation has eight basic components: fan, compressor, primary combustor, high-pressure turbine, fan turbine, augmentor, exit nozzle, and fan duct (fig. 3). The eight components are defined by appropriate aerodynamic and thermodynamic equations relating pressures, temperatures, and mass flow at various stations in the engine and in terms of individual component characteristics. The calculation flowpath of the program is similar to the actual particle flowpath in the engine. Each component accepts the required inputs from upstream components and supplies necessary output to the downstream component. The engine and control system representation is designed to give a prediction of engine performance on the test stand and in the aircraft.

Of particular interest for this report, the engine deck calculates nozzle throat total pressure, PT7, based on PT6M and an afterburner pressure loss due to friction and heat addition. The deck also calculates an exhaust nozzle secondary-to-primary area ratio based on primary nozzle area, AJ, PLA, and flight conditions.

INSTRUMENTATION

The F-15 airplane was equipped with a data system that measured over 500 parameters (Myers and Burcham, 1984). Included were airplane parameters, engine parameters, and parameters measured on the nozzle flaps and engine interfairing.

The airplane Mach number and altitude were obtained from the nose boom pressures, corrected for position errors. Angles of attack and sideslip were obtained from nose boom mounted vanes.

The instrumentation shown in figure 4 was installed on the F100 EMD engines in the F-15 airplane. From this instrumentation, the inlet total temperature, TT2, and the power lever angle, PLA, were determined and used, along with airplane Mach number and altitude, as inputs to the engine cycle deck. Several measurements were available to compare the actual engine operating conditions to the predicted values from the cycle deck. The parameters of particular interest for this report were jet nozzle area, AJ, and mixed turbine discharge pressure, PT6M. These engine parameters were all obtained in digital form from the digital electronic engine controls on each engine.

The aft end of the F-15 aircraft was instrumented for the acoustic flights with 35 additional sensors, including microphones, pressure transducers, accelerometers, and strain gages on the nozzle flaps of both engines and on the interfairing between the engines.

Most of the parameters were recorded digitally on pulse code modulation systems, which were telemetered to the ground for real-time analysis and also recorded on an on-board tape recorder. Some of the high-frequency response microphones and pressure transducers were also recorded on the on-board tape recorder in frequency modulated format.

TEST CONDITIONS

The F-15 aircraft was flown over the flight envelope shown in figure 5. Four flights were flown, with a maximum Mach number and altitude of 1.2 and 45,000 ft, respectively. Power settings varied from idle to maximum afterburning on each engine. A majority of the data was flown with the two engines at the same power setting. Real-time data was used to match the PT6M measurements on the two engines. In some cases, one engine was set at high power with the opposite engine at idle to provide essentially a single engine acoustic source.

The flights were flown in the summer at Edwards AFB, with the result that atmospheric temperatures were well above standard at low altitudes. The temperature distributions in the form of deviations from standard day temperature, DTSTD, are shown in figure 6, and are approximately 30°F above standard at low altitudes.

CALCULATIONS

A calculation of the fully expanded (station 10) jet Mach number was not available on the F100 EMD Deck PW-1194 so that it had to be added to the program. The isentropic equation relating Mach number and pressure ratio was used for this purpose:

$$\mathrm{M10} = \sqrt{\frac{2}{\gamma - 1}\left(\left(\frac{\mathrm{PT7}}{\mathrm{PS}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}$$

The values PT7, PS, and γ were obtained from the engine simulation deck, and the jet Mach number was determined.

Jet total temperature, TT10, was not available from the deck, but was assumed to be equal to TT7, as calculated by the cycle deck. Variations in TT10 versus TT7 that might result from a nonequilibrium expansion process were not considered.

One of the basic inputs to the deck was DTSTD. Values of DTSTD for each altitude were picked from figure 6 and used as inputs in all the engine calculations.

Since M10 is inferred from measurements of PT6M, it is important to know the relationship between PT6M and M10. This nonlinear relationship results in small changes in M10 for larger changes in PT6M. For a typical flight condition, a 9 percent change in PT6M results in only a 2 percent change in M10.

RESULTS AND DISCUSSION

Results of the study are presented, first in terms of the temperature effects on M10, then showing the effects of flight conditions and PLA on PT6M. Jet total temperature and Mach number are then presented, followed by a comparison of predicted to measured PT6M.

Atmospheric Temperature Effects

Atmospheric temperature has a significant and well-known effect on engine operating conditions and hence jet Mach number. This effect is quantified in the following figures. Figure 7 shows plots of jet Mach number versus PLA, M, and altitude for a range of values of DTSTD: 0, +20°F, and -20°F. Figure 7(a) shows, for $M = 0.9$ and $h = 20{,}000$ ft, M10 increases with PLA until intermediate power is reached. After this point, it decreases slightly due to pressure loss from heat addition from afterburning. Also, as ambient temperature decreases, M10 increases, the difference being close to a 5 percent increase for a 20° temperature decrease.

The jet Mach number, M10, varies approximately linearly with M as shown in figure 7(b). As the temperature decreases, the jet Mach number increases. It is seen that the effect of temperature is more predominant for Mach numbers between 0.75 and 2.25.

M10, when plotted versus altitude as shown in figure 7(c), varies linearly up to a specific altitude and becomes constant thereafter, as engine operating limits are observed. This altitude is a function of the temperature difference DTSTD.

Due to the significant atmospheric temperature effects on M10, all data shown hereafter was computed at the average test day temperature taken from figure 6 for the actual altitudes flown.

PT6M

Since PT6M is a key parameter in determining the jet Mach number, and since PT6M is measured on the engine, it is of interest to see how PT6M varies with PLA and altitude (fig. 8). PT6M increases with increasing PLA until intermediate power is reached, becoming constant for afterburning power settings. The effect of increasing altitude is to reduce PT6M.

Jet Temperature

The jet velocity calculation requires that the jet temperature, TT10, be known. The variation of TT10 with PLA is shown on figure 9 for $M = 0.9$. TT10 increases slowly with PLA in the nonafterburning range, with values of approximately 1000°F at intermediate power. When afterburning is used (PLA above 85°), TT10 increases rapidly with PLA. At maximum afterburning, TT10 values are in excess of 3000°F. The effect of altitude on TT10 is seen to be small, especially for altitudes higher than 20,000 ft.

Jet Mach Number

Plots of jet Mach number versus PLA are shown in figure 10. Data were obtained for different altitudes and Mach numbers, ranging from 0.6 to 1.0, as shown in figures 10(a) through 10(e). The temperatures used at each altitude were obtained from figure 6. As the PLA is increased from 30° (near idle) to 85° (intermediate), M10 increases. Increases in PLA into the afterburning range result in slight decreases in M10, due to the additional pressure loss from heat addition.

At a typical flight point of $M = 0.9$, PLA = 85° at 20,000 ft, then M10 = 1.63.

Figure 11 is a cross plot of data from figure 10, showing the effect of altitude on M10 at PLA = 85°, and $M = 0.9$. As the altitude increases up to 30,000 ft, M10 increases linearly, but at high altitudes (greater than 30,000 ft), there is little or no effect of altitude on jet Mach number.

Comparison of Engine Deck to Flight Data

A comparison between the calculated PT6M and the flight measurement of PT6M as a function of M is shown in figure 12, at a PLA of 85°. In figure 12(a), at $h = 31,000$ ft, the flight measured data agrees very well with the calculated values from the engine deck. For values of M up to 1.0, agreement is 1 to 2 percent. At a lower altitude of 20,500 ft, as noted in figure 12(b), the difference is approximately 5 percent, and at an altitude of 15,500 ft, in figure 12(c), it is as much as 8 percent.

A comparison of other engine parameters such as airflow and temperature showed that the deteriorated condition of the flight engines becomes more significant at the lower altitudes (because of engine control system schedules), causing a larger discrepancy between the calculated and measured PT6M values. Nevertheless, the difference between flight and predicted PT6M results in a change in M10 that is small. From the isentropic relationship between

PT6M and M10, it is seen that for a 9 percent difference in PT6M, there is only a 2 percent difference in M10. Therefore, the calculated jet Mach number from the engine deck is likely within 2 percent of the actual engine jet Mach number at all flight conditions tested.

CONCLUDING REMARKS

The exhaust jet conditions for the F100 EMD engines in the F-15 airplane were calculated using the manufacturer's specification deck. The well-known effects of atmospheric temperature on jet Mach number, M10, were calculated, and it was found that a 20° temperature difference caused as much as 5 percent difference in M10.

The turbine discharge pressure, PT6M, was seen to increase with PLA until intermediate power was reached, becoming constant for afterburning power settings. The effect of altitude was to decrease PT6M.

The variation of jet total temperature, TT10, with PLA was calculated. At $M = 0.9$, TT10 increased slowly as PLA increased until afterburning is used, then increased rapidly with PLA. TT10 was approximately 1000°F at intermediate power and 3000°F at maximum power.

The effects of altitude and Mach number on M10 were analyzed for a range of power settings. As altitude increased, values of M10 increased. Also, as the Mach number increased from 0.6 to 1.0, the jet Mach number was seen to increase proportionally. At a typical test point, $M = 0.9$, $\text{PLA} = 85°$, $h = 20{,}000$ ft, and $\text{M10} = 1.63$.

Measured and calculated values of PT6M were compared for intermediate power, at altitudes of 31,000, 20,500, and 15,500 ft. It was found that at 31,000 ft, there was excellent agreement (1 to 2 percent) between both. At lower altitudes, at 20,500 ft, the difference was approximately 5 percent, and at 15,500 ft, it was close to 8 percent. This would result in differences of M10 of less than 2 percent.

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Edwards, California, December 21, 1987

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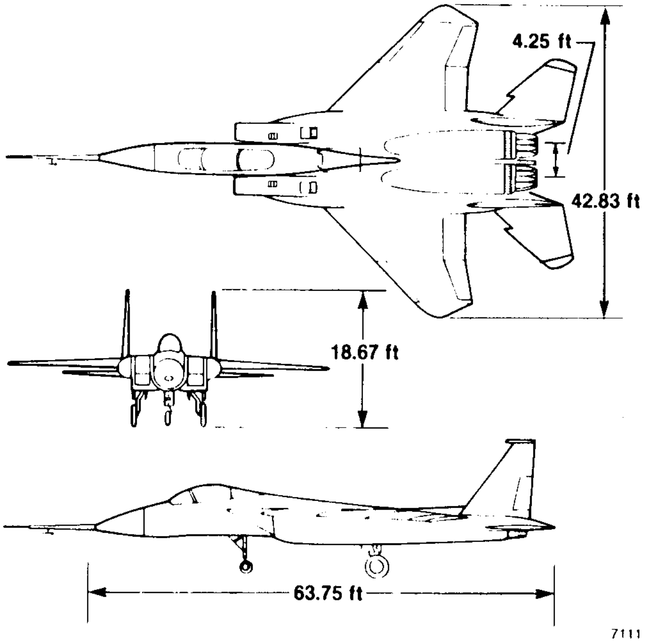


Figure 1. Three views of test airplane.

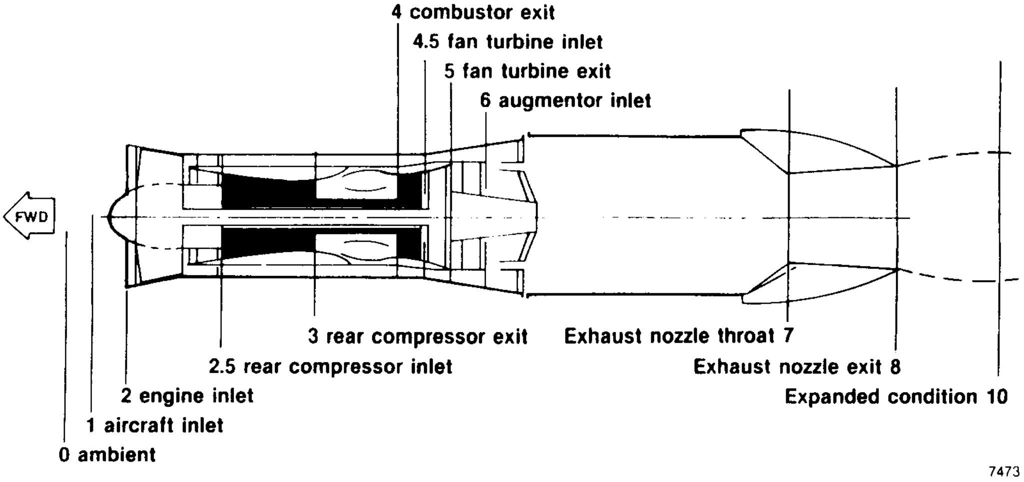


Figure 2. F100 engine stations.

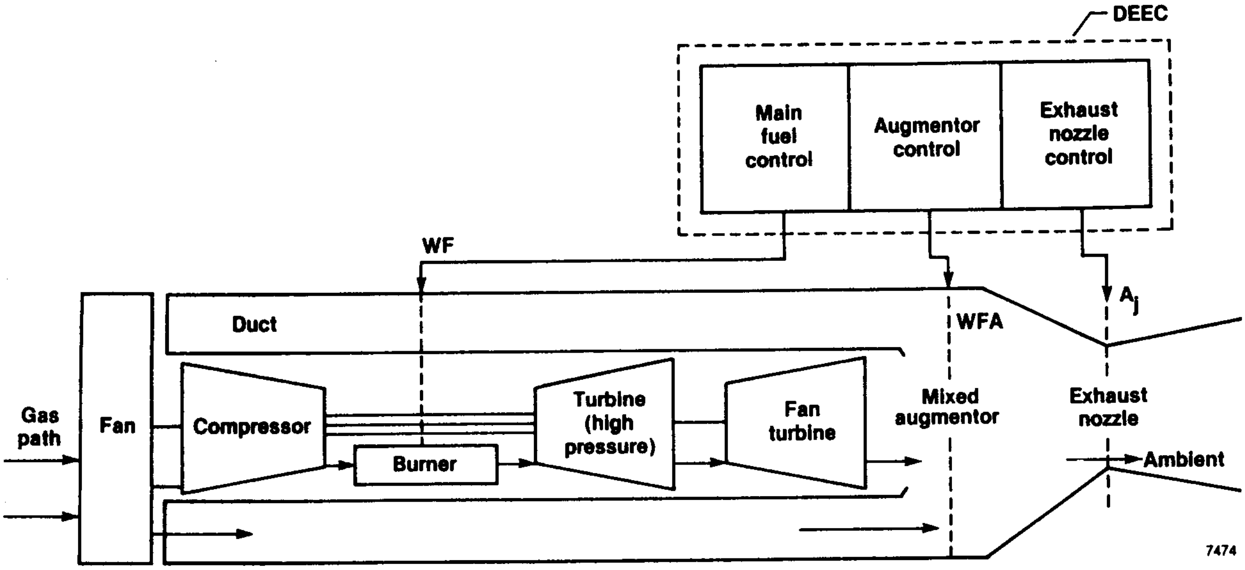


Figure 3. Engine component schematic and gas flowpath.

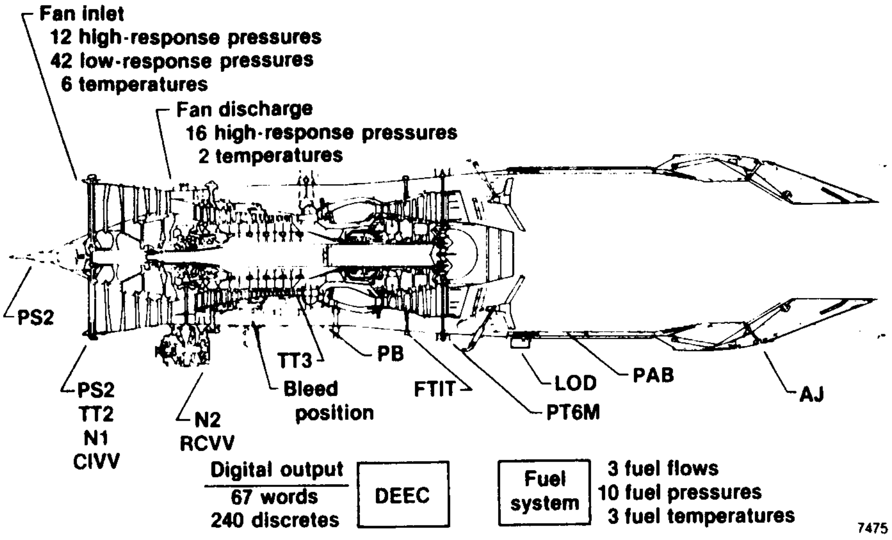


Figure 4. F100 engine instrumentation.

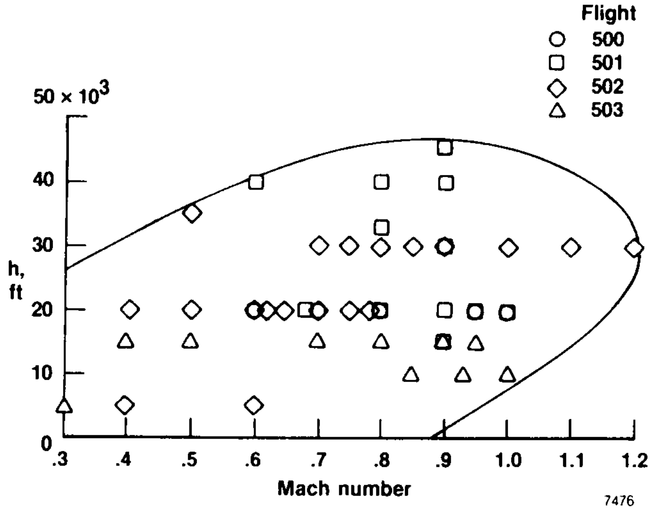


Figure 5. Flight envelope for acoustic flights.

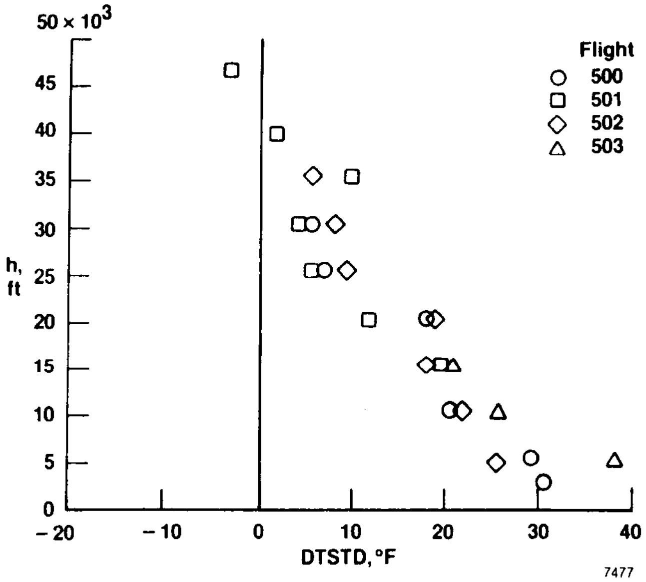
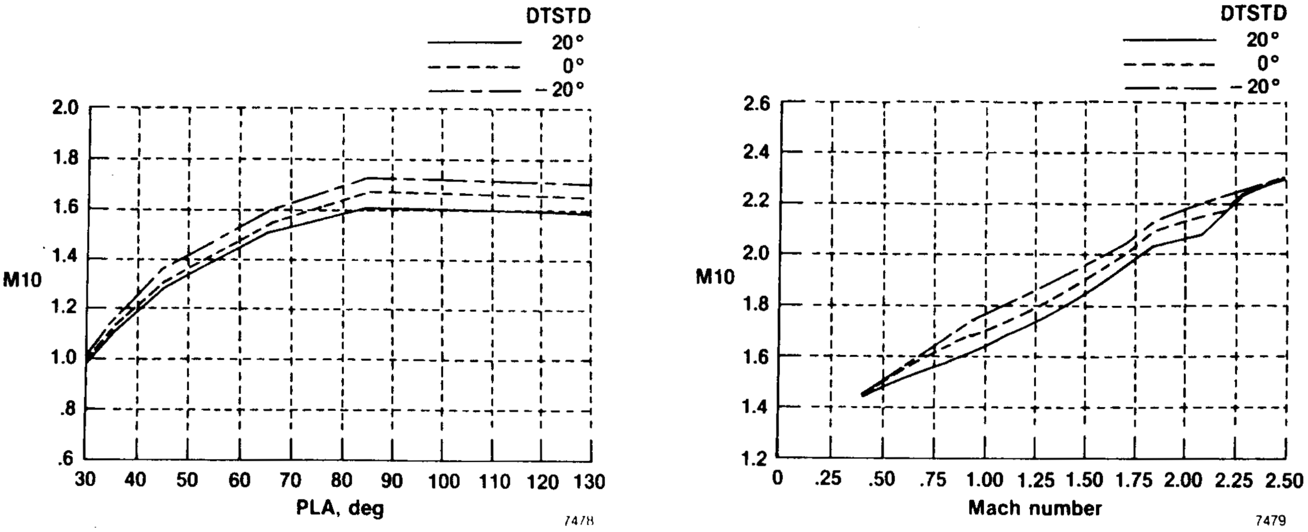
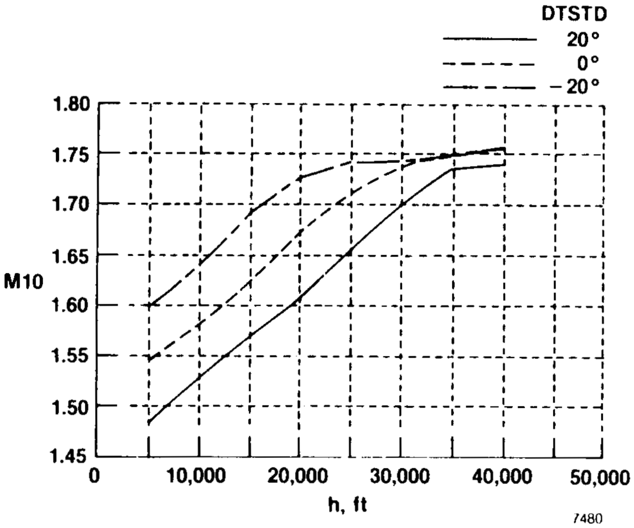


Figure 6. DTSTD versus *h* for acoustic flights.



(a) M = 0.9, h = 20,000 ft.

(b) h = 20,000 ft, PLA = 85°.



(c) M = 0.9, PLA = 85°.

Figure 7. Effect of ambient temperature on M10.

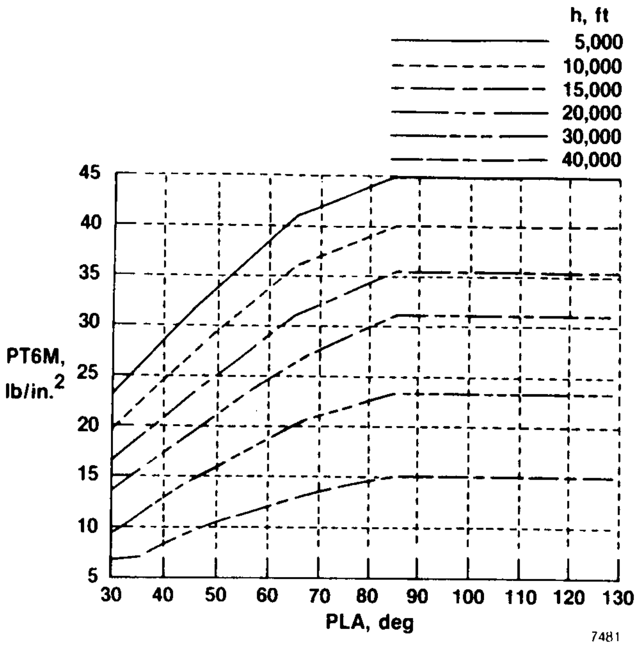


Figure 8. Variation of PT6M with *h* and PLA, M = 0.9.

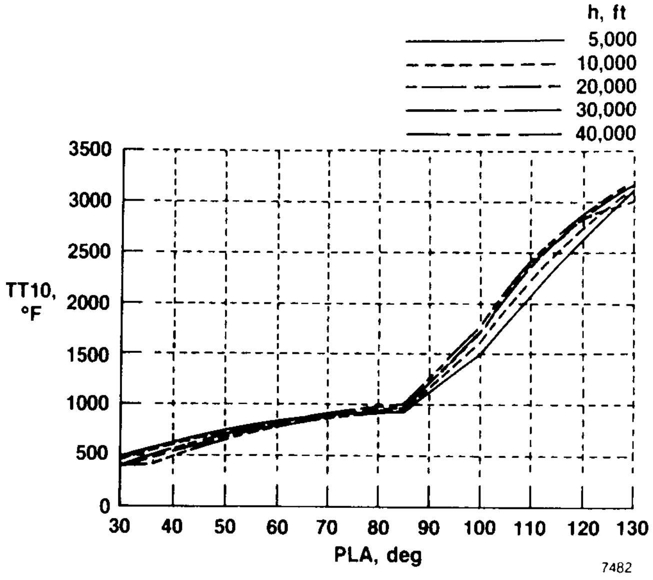
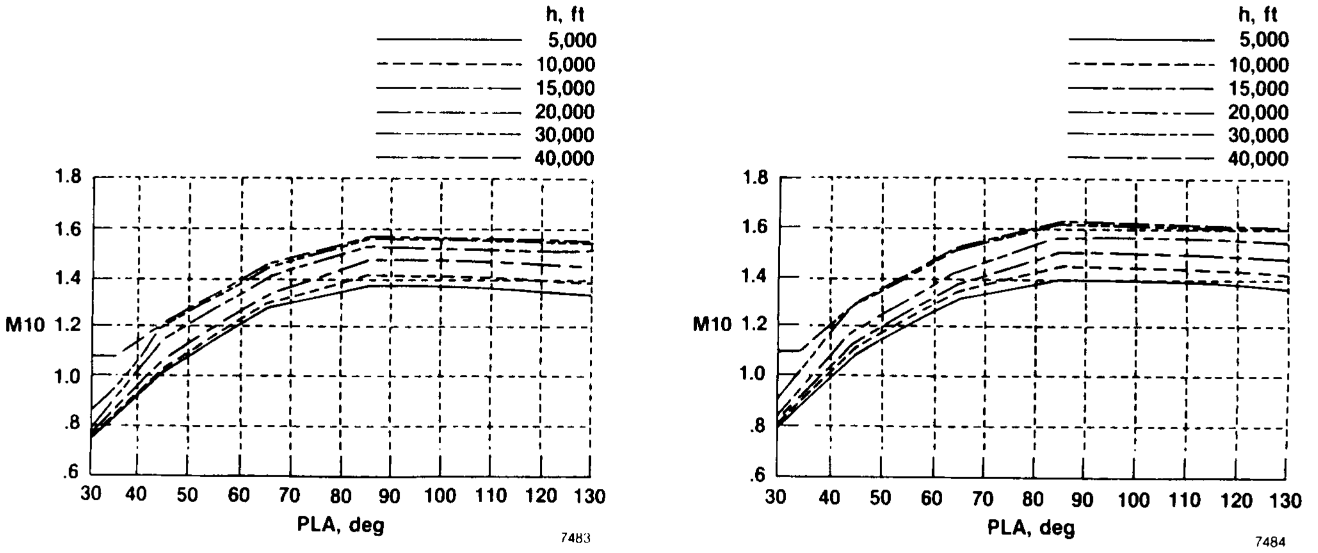


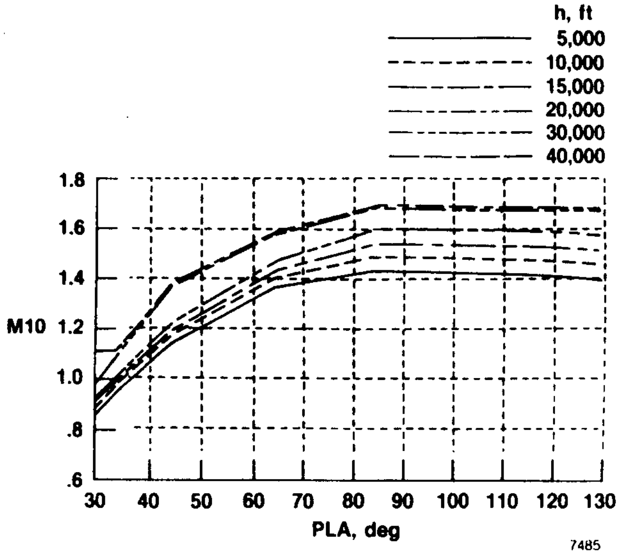
Figure 9. Variation of TT10 with PLA, M = 0.9.



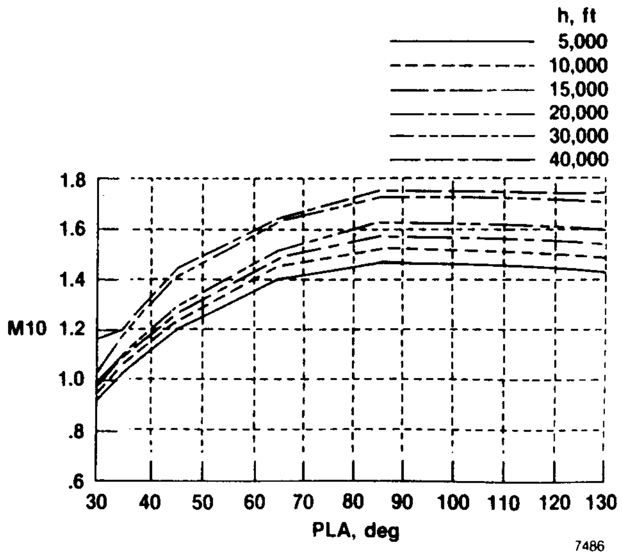
(a) M = 0.6.

(b) M = 0.7.

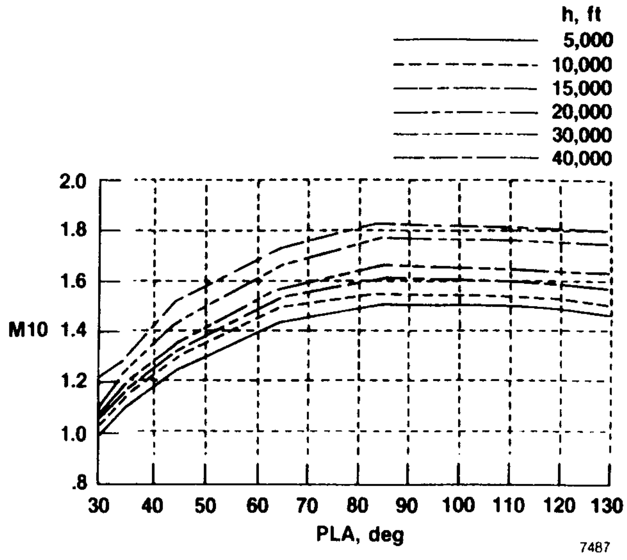
Figure 10. Effect of PLA, *h*, and M on M10.



(c) M = 0.8.



(d) M = 0.9.



(c) M = 1.0.

Figure 10. Concluded.

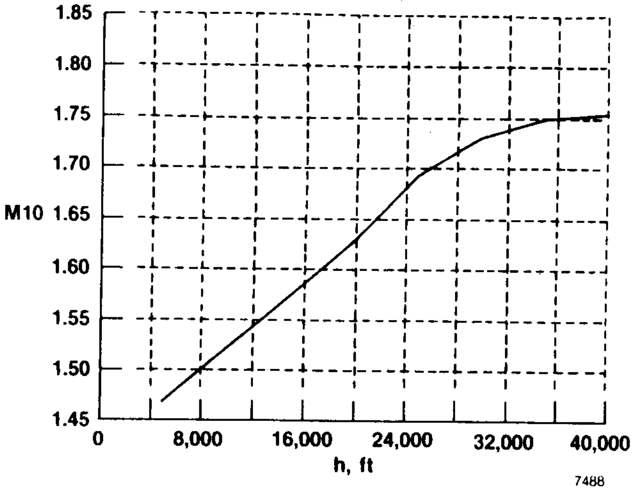
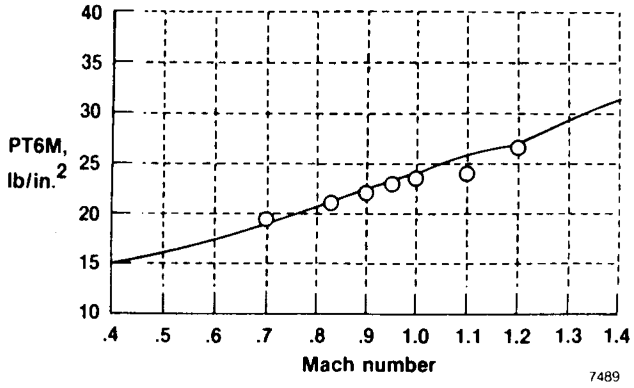
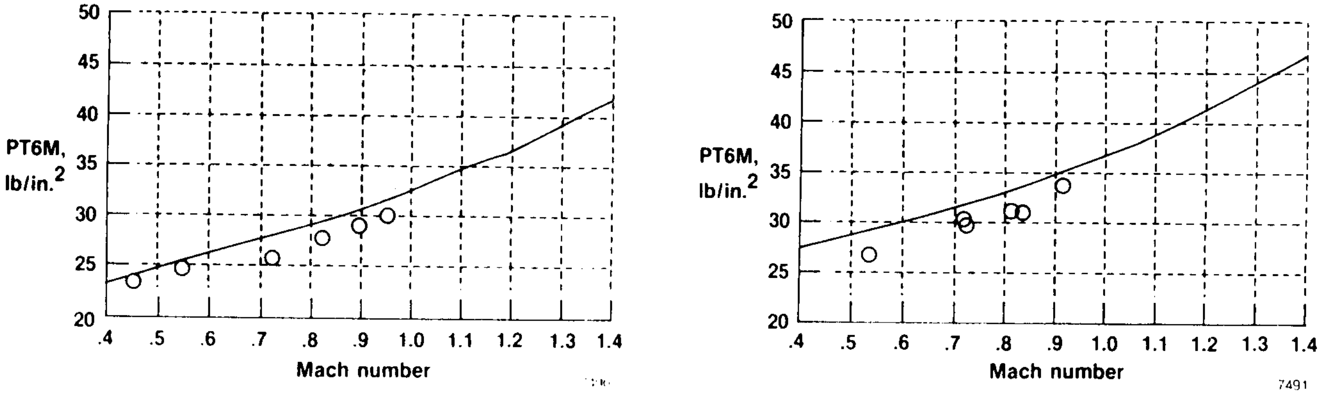


Figure 11. M10 versus h, M = 0.9, PLA = 85°.



(a) h = 31,000 ft.



(b) h = 20,500 ft.

(c) h = 15,500 ft.

Figure 12. Comparison between the calculated PT6M and the flight measured PT6M as a function of M, PLA = 85°.

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16. Abstract

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Jet Mach number

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