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ABSTRACT

An integrated flight and propulsion control system designed to reduce the rate of engine deterioration has been developed and evaluated in flight on the NASA Dryden F-15 research aircraft. The extended engine life mode increases engine pressure ratio while reducing engine airflow to lower the turbine temperature at constant thrust. The engine pressure ratio uptrim is modulated in real time based on airplane maneuver requirements, flight conditions, and engine information. The extended engine life mode logic performed well, significantly reducing turbine operating temperature. Reductions in fan turbine inlet temperature of up to 80 °F were obtained at intermediate power and up to 170 °F at maximum augmented power with no appreciable loss in thrust. A secondary benefit was the considerable reduction in thrust-specific fuel consumption. The success of the extended engine life mode is one example of the advantages gained from integrating aircraft flight and propulsion control systems.

NOMENCLATURE

$A8$	nozzle throat cross-sectional area, ft^2
ADECS	advanced engine control system
ALT	pressure altitude, ft
CAS	control augmentation system
$CIVV$	fan inlet variable vane angle, deg
DEEC	digital electronic engine control
DEFCS	digital electronic flight-control system
$DEPR$	digital electronic engine control engine pressure ratio uptrim command
$DEPRAB$	engine pressure ratio adjustment for augmentor operation
$DEPRSTBN$	delta engine pressure ratio between the stability and nominal scheduled values
DFCC	digital flight-control computer
$DWAC$	digital electronic engine control airflow downtrim command, lbm/s
EEL	extended engine life
EMD	engine model derivative
EPR	engine pressure ratio, $PT6$ divided by $PT2$
$EPRAJ$	maximum engine pressure ratio allowable from available nozzle trim
$EPRBNEW$	nominal engine pressure ratio at the trimmed airflow
$EPRMAX$	maximum engine pressure ratio along the constant thrust line
$EPRNEW$	the minimum of $EPRAJ$, $EPRMAX$, and $EPRSTB$
$EPRSCH$	nominal scheduled engine pressure ratio
$EPRSTB$	stability engine pressure ratio along the constant thrust line
$EPRSTBN$	stability engine pressure ratio from the advanced engine control system logic at the nominal airflow

FN	net thrust, lbf
$FTIT$	fan turbine inlet temperature, °F
HIDEC	highly integrated digital electronic control
M	freestream Mach number
$MEPRSTB$	slope of stability engine pressure ratio operating line
$MFCONST$	slope of constant thrust line
$N1$	fan speed, rpm
$N1C2$	fan speed corrected to station 2, rpm
$N2$	compressor speed, rpm
PLA	power lever angle, deg
$PS0$	freestream static pressure, lbf/in^2
$PS2$	engine inlet static pressure, lbf/in^2
$PS4$	combustor static pressure, lbf/in^2
PSC	performance seeking control
$PT0$	freestream total pressure, lbf/in^2
$PT2$	engine inlet total pressure, lbf/in^2
$PT6$	turbine exit total pressure, lbf/in^2
$RCVV$	compressor inlet variable vane angle, deg
$TSFC$	net thrust specific fuel consumption, lbm/hr/lbf
$TT2$	engine inlet total temperature, °F
WAC	corrected engine airflow, lbm/s
$WACNEW$	corrected engine airflow at the trimmed operating point, lbm/s
$WACSCH$	nominal scheduled corrected engine airflow, lbm/s
WFP	combustor fuel flow, lbm/s
$WFTOTV$	total (combustor and augmentor) fuel flow, lbm/s

INTRODUCTION

Substantial performance gains can be obtained by integrating the flight and propulsion control systems of an aircraft.[1] In current aircraft control systems, independent optimization of each system is usually compromised by worst-case assumptions of the other systems. By using the increasing throughput and memory of onboard computers, along with high-speed communication data buses, it will be possible to implement a wide range of integrated flight and propulsion control modes onboard future aircraft. Such modes will increase total vehicle effectiveness without adding significant weight and cost. The NASA Dryden Flight Research Facility conducted the Highly Integrated Digital Electronic Control (HIDEC) program to investigate the problems and assess the performance benefits of flight and propulsion control integration.

In a conventional engine control system, the engine stall margin is large enough to accommodate the worst-case combination of engine and airplane induced disturbances. In the advanced engine control system (ADECS) used on the NASA F-15 HIDEC airplane, the stall margin is modulated in real time based on the current engine and aircraft requirements and flight conditions. This modulation permits the unneeded stall margin to be traded for increased engine performance by increasing thrust, reducing fuel flow, or lowering engine operating temperatures. The exchange between unneeded engine stall margin and increased engine performance is made through the uptrim of engine pressure ratio (EPR). In the previously flight tested ADECS EPR mode, significant thrust performance benefits were obtained using EPR uptrim.[2,3,4]

A second HIDEC control mode was flight-tested in addition to the ADECS EPR mode. The extended engine life (EEL) mode uses an EPR uptrim combined with an airflow downtrim to maintain constant thrust (within 2 percent of the nominal value) while reducing engine operating temperature. Since fuel flow decreases during the airflow downtrim, turbine temperatures are reduced and the result is extended engine core life.

The HIDEC EEL mode demonstrates that an engine temperature reducing control algorithm can be used successfully on a production aircraft without significant cost or weight penalties and with no impact on aircraft operability, pilot workload, or safety. Since the main objective was to evaluate the EEL concept, a minimum of developmental testing was done on the EEL algorithm. The EEL algorithm and other HIDEC control modes were developed jointly by NASA Dryden, McDonnell Aircraft Co. (St. Louis, MO), and Pratt and Whitney Aircraft (West Palm Beach, FL).

The EEL mode was tested at altitudes from 10,000 to 40,000 ft and from Mach numbers of 0.55 to 0.95 at intermediate and maximum augmented power. The performance during steady and nonsteady flight conditions was also studied. This paper describes the EEL mode architecture and algorithm as well as flight-test results.

SYSTEM DESCRIPTION

Aircraft

The HIDEC flight-test program used a NASA F-15 airplane (fig.1). The F-15, built by McDonnell Aircraft Company, is a high-performance air superiority fighter with excellent transonic maneuverability and a maximum speed in excess of Mach 2.0. Two F100 engine model derivative (EMD) augmented turbofan engines were used for this program. The test aircraft has been modified with a digital electronic flight-control system (DEFCS) which includes a digital flight-control computer (DFCC). The DEFCS is a digital version of the F-15 production analog control augmentation system (CAS) and has the same flight-control authority. The excess capability of the DEFCS was used to execute the HIDEC control algorithms. Figure 2 shows the equipment and features used for the HIDEC EEL mode.

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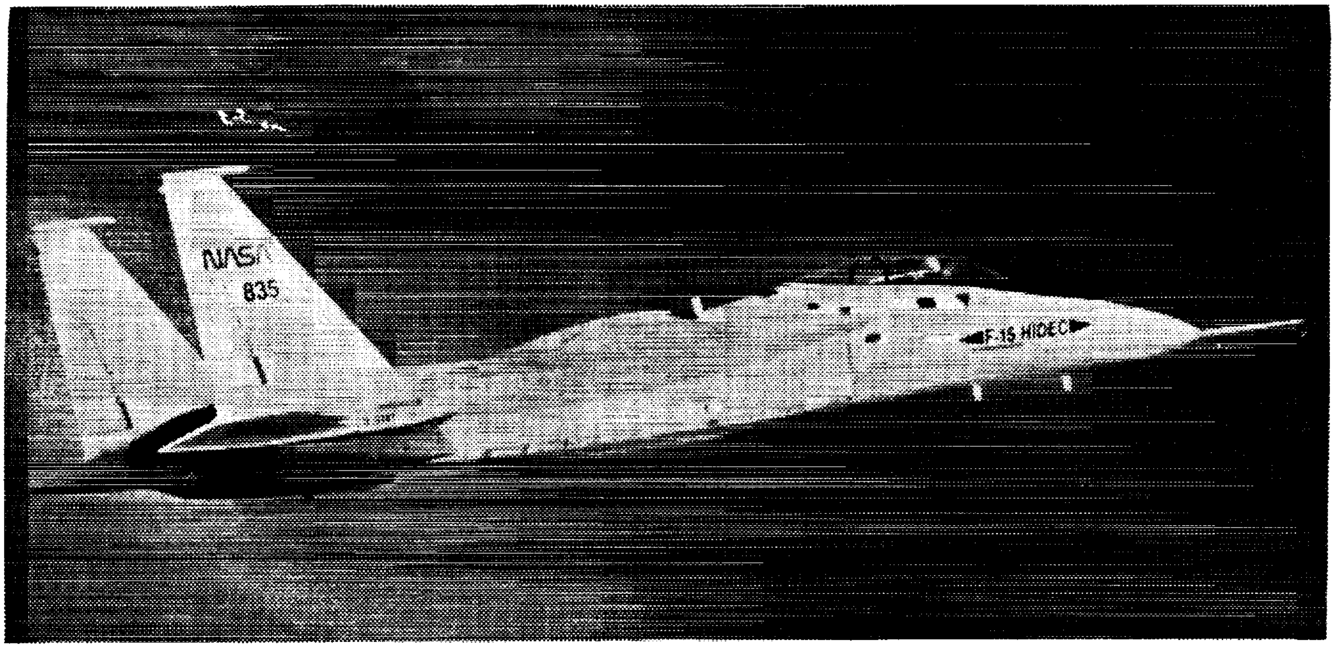

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Figure 1. The NASA Dryden F-15 aircraft.

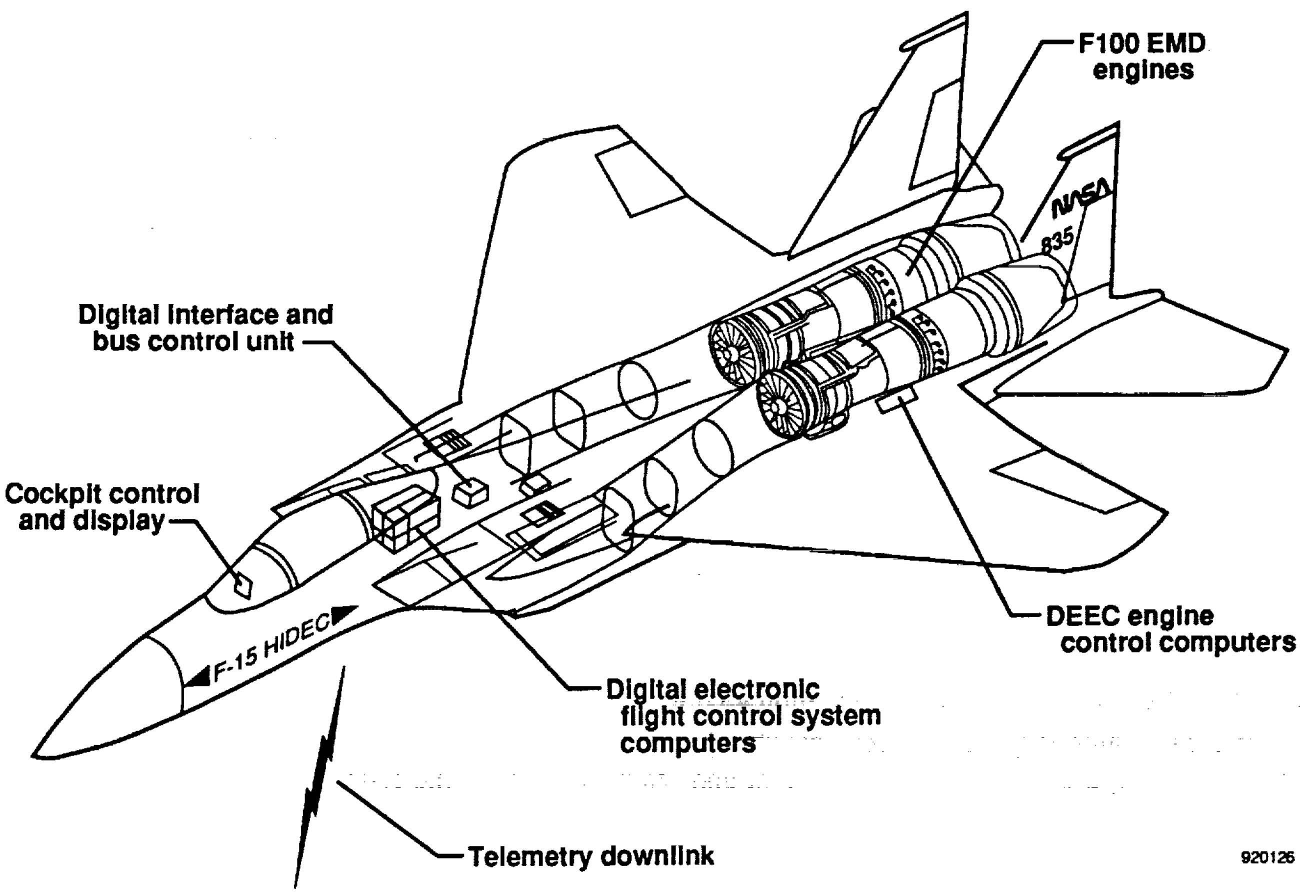

Figure 2. HIDEC extended engine life mode system features.

Engine

The F100 EMD engine,[5,6] built by Pratt and Whitney and having the company designation PW1128, is an upgraded version of the F100-PW-100 turbofan engine that currently powers most production F-15 airplanes. The engine consists of a redesigned fan (allowing higher airflow), a revised compressor and combustor, single crystal turbine blades and vanes, a 16-segment augmentor with light-off detector, and a digital electronic engine control (DEEC). Unrestricted throttle movement is permitted throughout the F-15 flight envelope.

The DEEC[6,7] is a full-authority digital engine control with an integral hydromechanical backup. The DEEC controls the gas generator and augmentor fuel flows, compressor bleeds, variable fan inlet guide vanes, variable compressor vanes, and the variable exhaust nozzle. The DEEC logic provides closed-loop control of EPR and corrected engine airflow (*WAC*) and also limits fan turbine inlet temperature (*FTIT*). It was modified for the HIDEC program to accept commands from the DFCC. The DEEC sets an upper limit on maximum EPR uptrim to help avoid inadvertent engine stalls.

Highly Integrated Digital Electronic Control Architecture

Two major components of the HIDEC system architecture are the DFCC and the DEEC. The ADECS EPR and EEL software is located in the DFCC. The algorithms compute appropriate commands within the DFCC and EEL. The commands are sent to the DEEC by way of a digital interface and bus control unit. The pilot uses a cockpit control and display panel interface to make inputs to the HIDEC system. The pilot also selects different control modes and sets algorithm operating parameters from the cockpit control. More detailed information about the HIDEC system architecture can be found in references 8 and 9.

Advanced Engine Control System Engine Pressure Ratio Logic

The maximum potential performance is not realized throughout much of the operating envelope of a typical gas turbine engine. The system is conservative because the engine or "controller" has been set to accommodate worst-case operating disturbances. When more benign conditions prevail, such as during cruise, climbs, or accelerations, a significant amount of stall margin usually remains.

The integrated control system framework of the F-15 HIDEC airplane was specifically developed to use and benefit from this extra stall margin. The ADECS EPR logic calculates the available stall margin as a function of engine and aircraft operating conditions. The HIDEC system modulates this engine operation near the stall limit in real time. This is only possible with an integrated control architecture.

The EEL logic computes the trim commands needed to produce the lower engine operating temperatures at constant thrust. However, EEL uses the ADECS EPR logic to provide the maximum EPR at which the engine can safely operate without the risk of a stall. This EPR value, which accounts for inlet airflow distortion based on aircraft maneuvering, is called the stability EPR.

A more complete description of the ADECS EPR mode algorithm and stall margin calculation procedure, along with engine and aircraft performance improvements using this mode, can be found in references 2, 3, 4, and 10.

INSTRUMENTATION AND DATA ANALYSIS

The engine schematic in figure 3 shows the location of the primary measurements used in the EEL algorithm control and subsequent data analysis. Data was telemetered from the aircraft to a ground based recording facility and then processed for post-flight use.

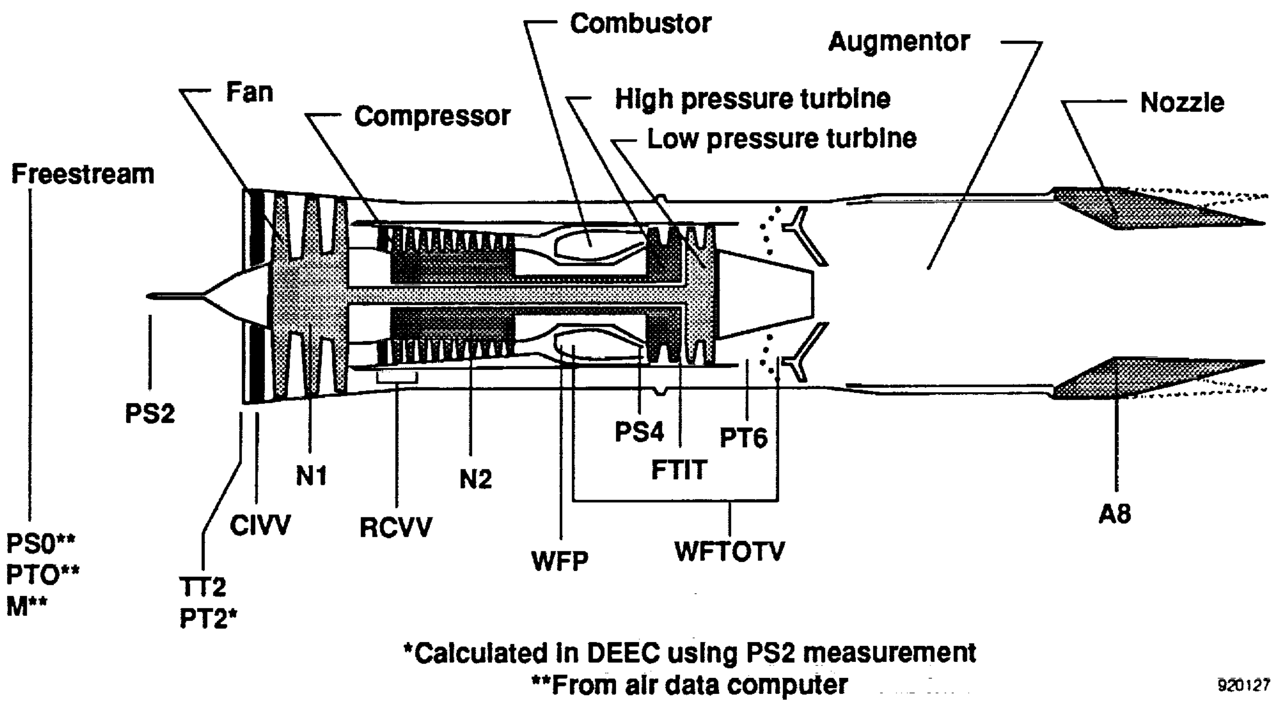

Figure 3. F100 engine model derivative engine and sensor locations.

Fan turbine inlet temperature (*FTIT*) was measured aft of the high-pressure turbine to determine the engine operating temperature reduction advantages of the EEL mode. Seven production temperature probes, equally spaced circumferentially, were used and their values averaged.

Temperature corrected volumetric flow meters measured the combustor fuel flow (*WFP*) and total fuel flow (*WFTOTV*). Combustor fuel flow was measured on the core fuel line while *WFTOTV* was measured on the main fuel line which supplies the combustor and augmentor. These fuel flow measurements were used in the calculation of net thrust specific fuel consumption (*TSFC*), which is the ratio of fuel flow over net thrust (*FN*). When the engine was at throttle settings of intermediate power (and below), *WFP* was used because it has a higher accuracy at lower fuel flow rates. During augmented power, *WFTOTV* was used. Net thrust specific fuel consumption helped establish the fuel saving benefits of the EEL mode.

A computer model calculated in-flight net thrust.[11] This model requires several parameter measurements as input in addition to WFP and $WFTOTV$. These measurements are nozzle throat area ($A8$), fan inlet variable vane angle ($CIVV$), compressor inlet variable vane angle ($RCVV$), fan speed ($N1$), compressor speed ($N2$), combustor static pressure ($PS4$), turbine exit total pressure ($PT6$), engine inlet total temperature ($TT2$), and engine inlet total pressure ($PT2$). All of these parameters, except $WFTOTV$, are available from the DEEC data stream. Static pressure ($PS0$), total pressure ($PT0$), and Mach number (M) are the freestream airdata parameters also required as input. These three parameters were calculated from the aircraft airdata computer output values of pressure altitude and calibrated airspeed. The airdata computer uses measurements from the flight-test noseboom as input. The use of actual flight data allows the program to better match the actual operating condition of the engine and to adjust for engine-to-engine performance variations.

The in-flight thrust program uses a newly developed technique based on a dynamic, linear state-variable model of the F100 EMD engine. The state-variable model is used for all but the augmentor and nozzle sections, which are modeled using traditional aero-thermodynamic relationships. Thrust is calculated using the mass flow–temperature method.[12] The main benefit of this model over a more classical full gas-path approach is that it is better able to recognize off-nominal engine operation, as would exist during EEL mode optimization. This allows a more accurate calculation of off-nominal engine thrust, and therefore of any thrust loss or gain that may occur with the EEL logic on. The engine manufacturer estimates that the thrust model accuracy during quasi-steady-state engine operation is within three percent.

EXTENDED ENGINE LIFE MODE DESCRIPTION

The purpose of the EEL mode is to increase engine life by reducing turbine temperature, and hence deterioration, while maintaining the nominal level of engine thrust at the given operating condition. The F100 EMD engine map (fig. 4) shows that lines of constant thrust have less absolute slope than lines of constant $FTIT$. By increasing EPR and reducing airflow, thrust can be held constant at reduced temperature. The EEL mode operates throughout the subsonic portion of the F-15 flight envelope and at intermediate power and above. The computational speed of the algorithm (approximately 80 Hz) allows the mode to accommodate rapidly changing engine and flight conditions.

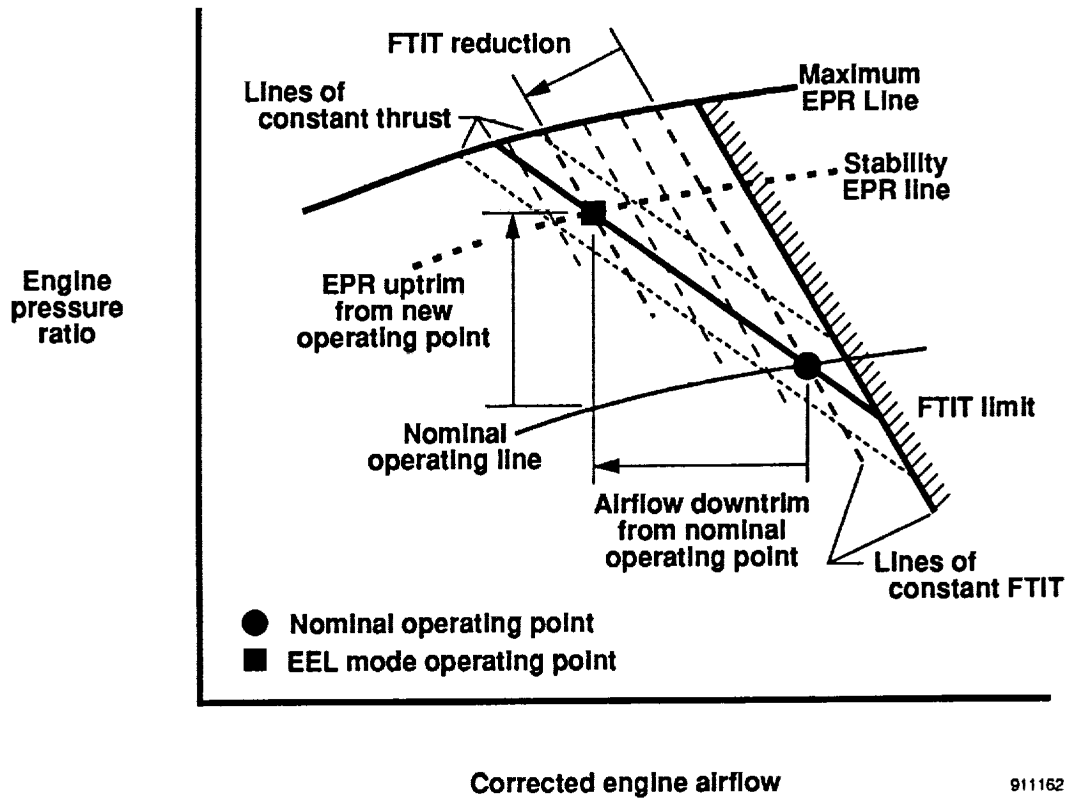

Figure 4. Extended engine life operation on the F100 engine map.

The EEL algorithm computes a set of EPR and airflow trim commands based on current engine and aircraft operating conditions. The trim commands are then sent from the DFCC to the DEEC to produce the desired results. Increased EPR is obtained by raising the engine back pressure. The DEEC raises this pressure by closing down the nozzle throat area appropriately. The decreased airflow is realized through a reduction in fan speed, which the DEEC implements through a decrease in combustor fuel flow. As a result, a secondary benefit of the EEL mode is the reduction in $TSFC$.

Figure 5 shows how the EEL mode operates. The EEL logic requires the input of $TT2$ and $PT2$. Figure 6 shows parameters from the algorithm calculation process displayed in the F100 engine map. The algorithm starts with calculations of the scheduled corrected engine airflow ($WACSCH$) and scheduled engine pressure ratio ($EPRSCH$) at the nominal (EEL mode off) operating condition. The slope of the constant thrust line ($MFCONST$) through the nominal operating point is then calculated.

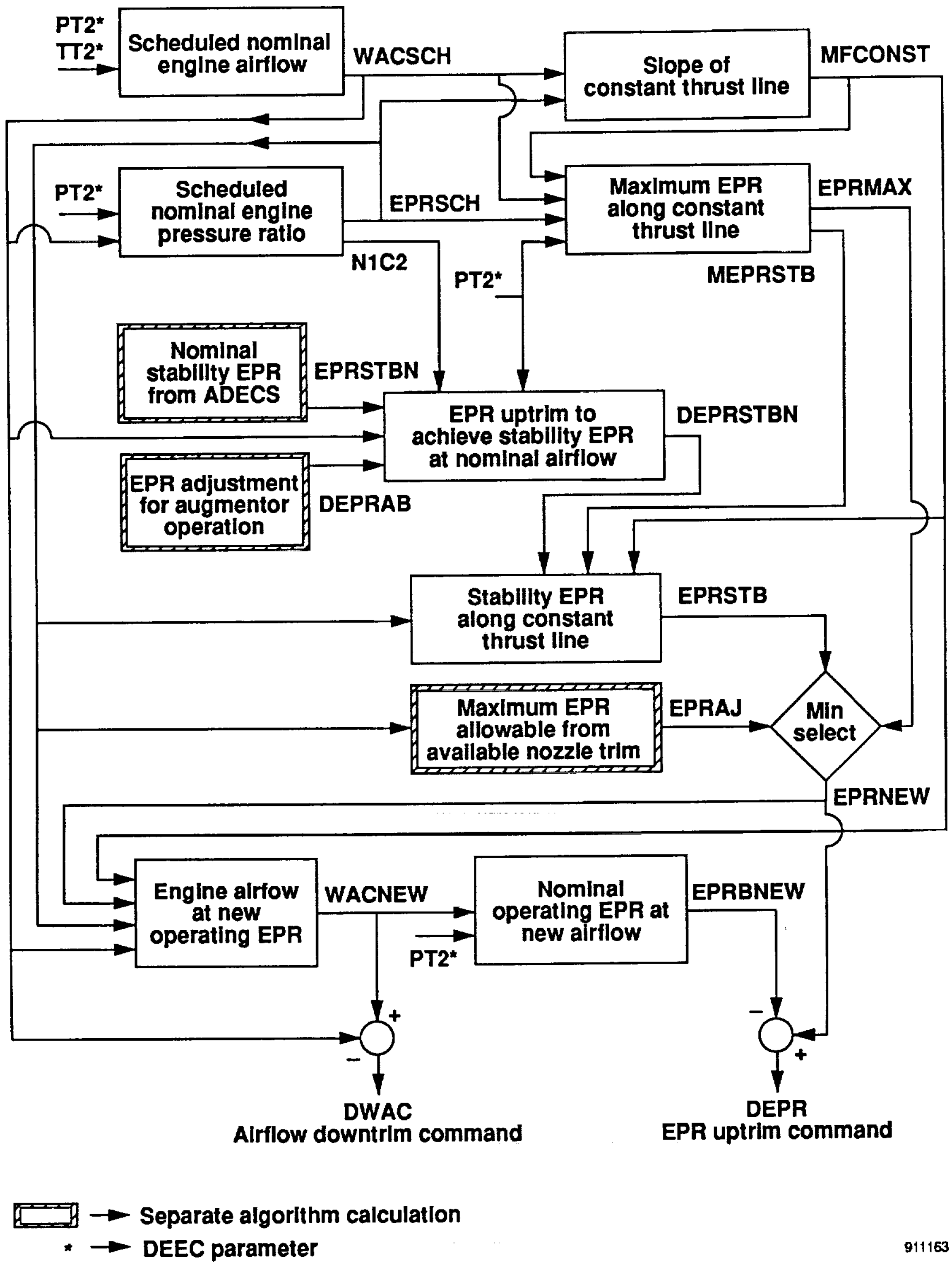

Figure 5. Extended engine life algorithm flow chart.

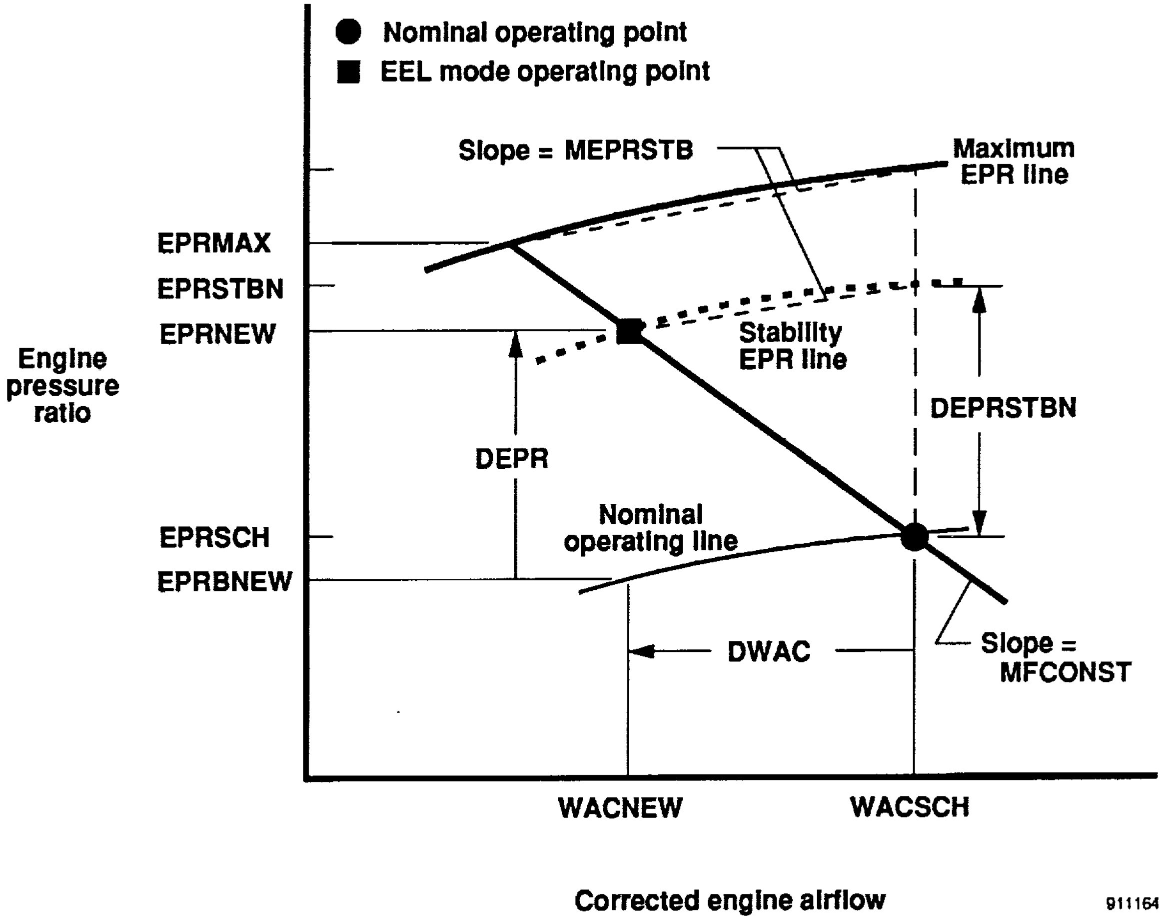

Figure 6. Extended engine life algorithm parameters on the F100 engine map.

With $MFCONST$ known, an incremental calculation is performed that gradually reduces the estimate of the airflow from the nominal value. At each point, a new maximum EPR is calculated. This EPR is an estimate of the value above which the engine would most likely stall. Finally, the maximum EPR along the constant thrust line ($EPRMAX$) is determined. Using the maximum EPR data, the maximum EPR operating line is approximated as being linear and its slope is calculated. It is assumed that the slope of the stability EPR operating line ($MEPRSTB$) is similar and it is set equal to the slope of the maximum EPR operating line.

In parallel with the slope calculations, the ADECS EPR logic is called and a preliminary stability EPR for the nominal operating point ($EPRSTBN$) is passed back. If the logic is operating under engine augmentation, an adjustment to this EPR value is made ($DEPRAB$). This allows the logic to accommodate the instability that results during augmentor segment light-off. The result is a delta value in EPR ($DEPRSTBN$) that, when added to $EPRSCH$, gives the true stability EPR at the nominal operating point. With this value, along with the approximated slopes of the stability EPR operating line and constant thrust line, the stability EPR along the constant thrust line ($EPRSTB$) is established.

The EEL logic then determines the maximum EPR value ($EPRAJ$) that can be achieved with the amount of remaining nozzle trim. This is necessary because of the minimum size restriction on the nozzle throat area. Because EPR cannot exceed $EPRMAX$ for stall avoidance and must be less than $EPRAJ$ because of physical constraints, the minimum value ($EPRNEW$) of $EPRMAX$, $EPRAJ$, and $EPRSTB$ is selected as the new operating EPR point.

The logic then uses $EPRNEW$ to estimate the new corrected engine airflow ($WACNEW$) at this EPR. The difference between $WACNEW$ and $WACSCH$ gives the required airflow downtrim ($DWAC$) to the new operating condition. The $WACNEW$ determines the EPR that would be required at that airflow if the engine were operating nominally ($EPRBNEW$). Subtracting this value from $EPRNEW$ gives the required EPR uptrim ($DEPR$) from the new nominal operating point. The trim commands $DWAC$ and $DEPR$ are then sent to the DEEC and the new EEL operating condition is obtained.

The F100 EMD nominal WAC schedule, the nominal EPR schedule, the maximum EPR schedule, and the constant thrust line data were integrated into the DFCC as tabular data as a function of appropriate parameters. These sets of data were calculated during the algorithm development using a high-fidelity, steady-state F100 EMD engine simulation model.[13] Unlike the in-flight thrust program, this model is a complete, self-contained simulation requiring, as a minimum, only flight condition and engine throttle setting as input. The model estimates operating parameter values throughout the entire engine. The input file of this simulation model also allowed EPR and WAC to be trimmed from the nominal scheduled values so that the effects on $FTIT$ and thrust could be determined. This allowed pre-flight predictions of the $FTIT$ reductions available to the EEL mode to be documented.

The cruise phase of a typical air superiority mission normally accounts for up to 85 percent of mission flight time.[14] Because of this, an EEL-type mode would be used for the longest duration during the cruise phase. The F-15 cruises subsonically at throttle settings below intermediate. The steady-state results presented do not particularly pertain to the engine state that is common during cruise conditions because the throttle of the test engine was held at intermediate power. The flight test was conducted in this manner because the HIDEC system was designed to take full advantage of excess engine stall margin only at intermediate power and above. The EEL algorithm was developed and tested primarily to verify the extended engine life concept. The performance seeking control (PSC) flight-test program,[15] using the NASA F-15 airplane and F100 EMD engines, will explore the reductions in $FTIT$ available at lower throttle settings.

EXTENDED ENGINE LIFE FLIGHT RESULTS

The HIDEC EEL mode achieved significant reductions in $FTIT$ throughout the F100 EMD subsonic flight envelope. Steady-state and quasi-steady-state engine operation were analyzed at intermediate power and above.

Some variation in $FTIT$ reduction was seen between the left and right engines at the same flight and engine conditions while the EEL mode was operating. In general, the differences were not significant, and for consistency, only left engine results are presented.

Intermediate Power

Table 1 lists steady-state *FTIT* reductions seen during flight test throughout the subsonic flight envelope at intermediate power. Steady-state engine operation was achieved by attaining the desired flight condition, holding the test engine at intermediate power, and using the non-test engine as required to maintain condition.

Table 1. Average steady-state reductions in *FTIT* during extended engine life mode operation at intermediate power.

	FTIT reduction, °F			
	Mach number			
Altitude, Kft	0.6	0.7	0.8	0.9
40	40	60	65	70
35	70	–*	–*	–*
30	80	70	30	65
10	15	–*	–*	15

*no data collected at these steady-state flight conditions

The largest steady-state reduction in *FTIT*, 80 °F, occurred at 30,000 ft, $M = 0.6$. The smallest reduction seen, 15 °F, occurred at 10,000 ft, $M = 0.6$ and 0.9. Reduction in *FTIT* of approximately 60 °F was typical throughout the rest of the flight envelope at intermediate power.

Steady-state reductions in *FTIT* at 30,000 ft and above were significantly greater than those at 10,000 ft. The *FTIT* reductions become less at lower altitude as the effectiveness of trading stall margin for lower *FTIT* decreases.

Fan turbine inlet temperature is plotted in figure 7 for the 30,000 ft, $M = 0.6$ flight condition at intermediate power. Data for EEL mode on and off are shown. Mach number varied between 0.615 and 0.630 for the test points. The average 80 °F-reduction in *FTIT* can be seen. Figure 8 displays *FN* against Mach number for the same condition. The plot shows that the EEL algorithm holds thrust to within about 2 percent (100 lbf) of the EEL mode off case.

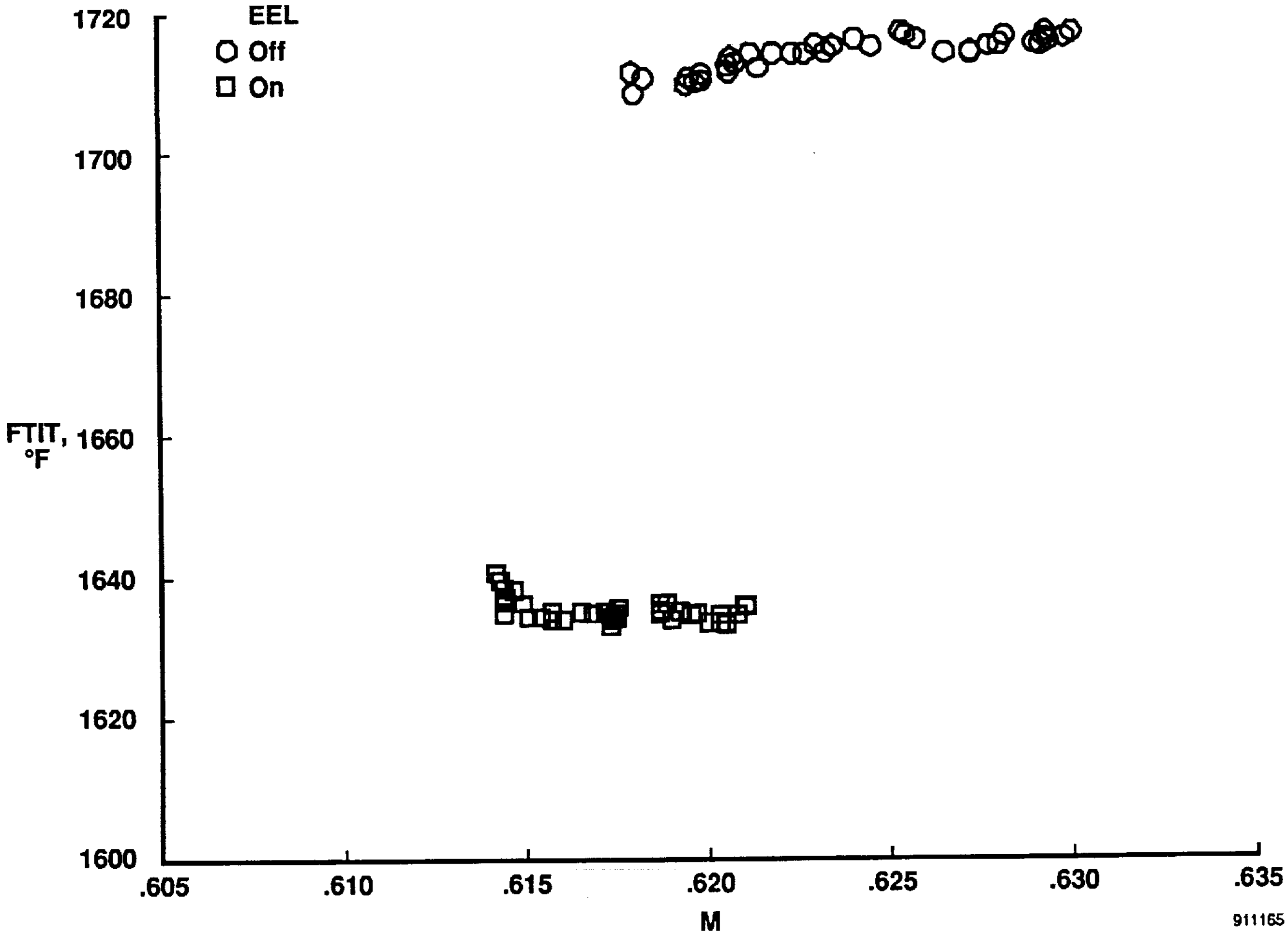

Figure 7. Fan turbine inlet temperature as a function of Mach number. Intermediate power, $M = 0.6$, $ALT = 30{,}000$ ft.

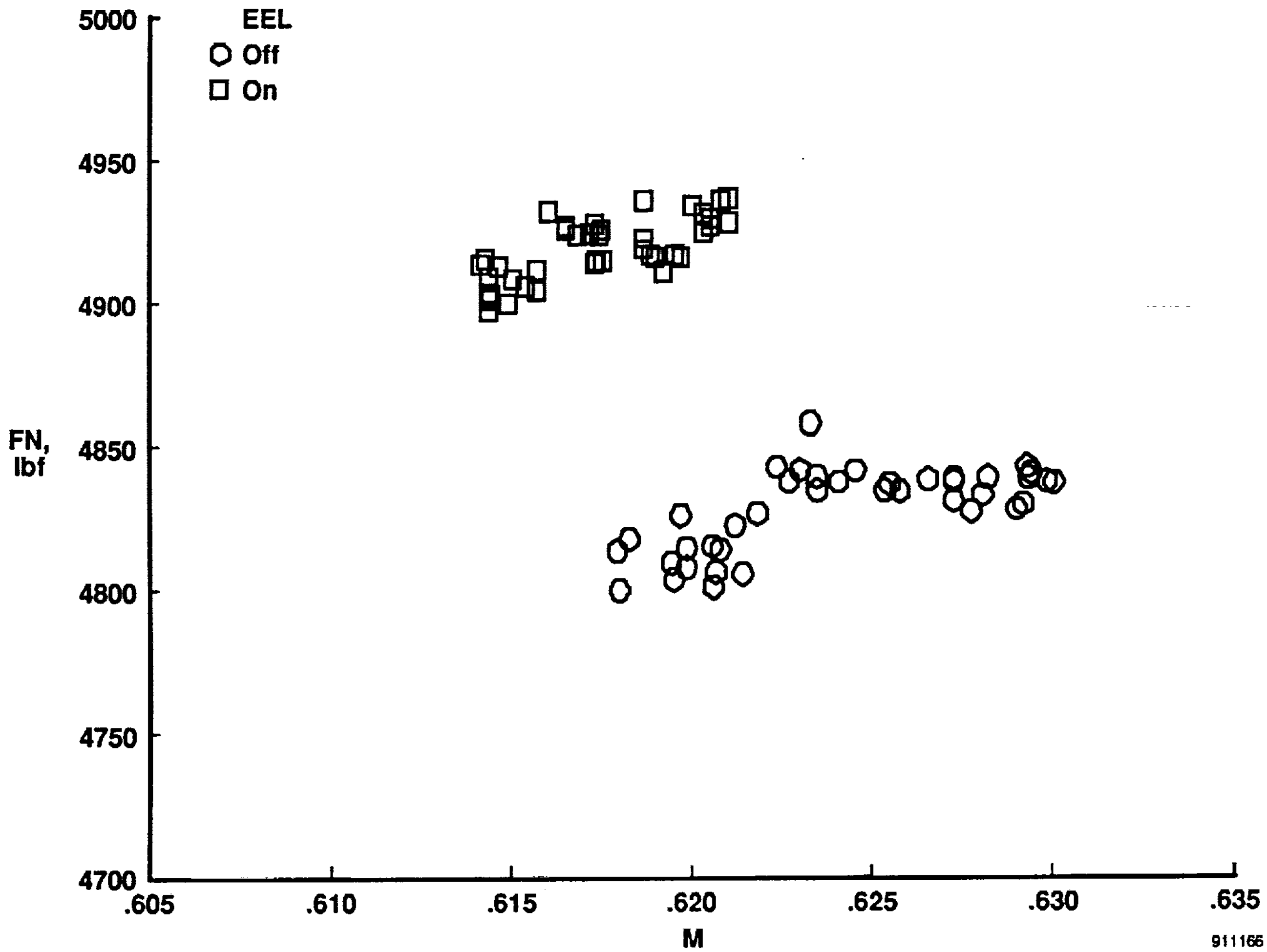

Figure 8. Net thrust as a function of Mach number. Intermediate power, $M = 0.6$, $ALT = 30{,}000$ ft.

The EEL mode benefits are not limited to a decrease in the engine temperature. The reduction in $FTIT$ results from the decrease in WFP. A reduction in specific fuel consumption and a corresponding increase in aircraft range factor results. Figure 9 shows the reduction in $TSFC$ as a function of Mach number for the 30,000 ft, $M = 0.6$ case. A reduction in $TSFC$ of about 0.045 lbm/hr/lbf (4.5 percent of the value for EEL mode off) is evident.

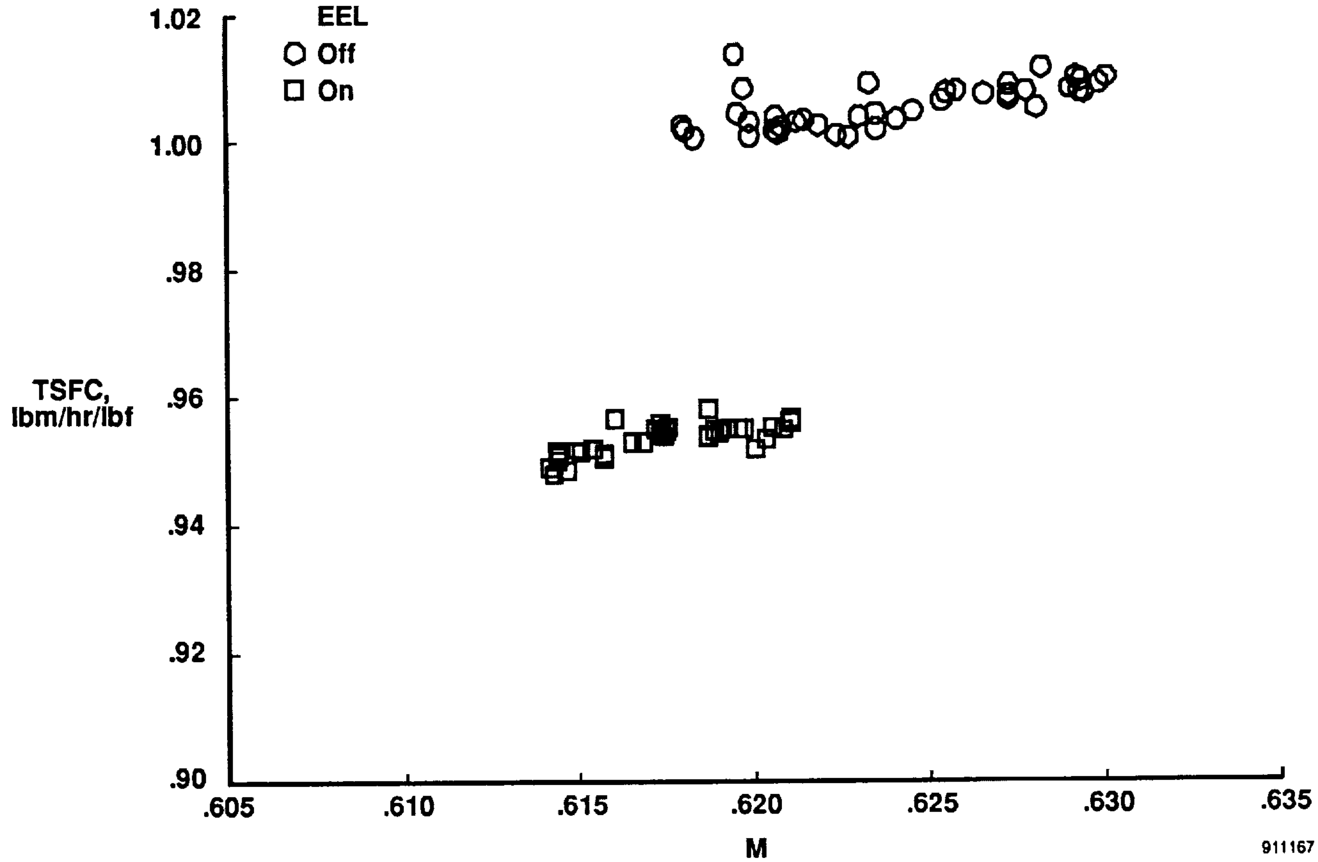

Figure 9. Net thrust specific fuel consumption as a function of Mach number. Intermediate power, $M = 0.6$, $ALT = 30{,}000$ ft.

Results using the algorithm during quasi-steady-state engine operation were also studied. This type of operation occurs during aircraft accelerations and climbs, for example, where the engine operates at a fixed power setting but with moderately varying inlet and exit conditions. Significant $FTIT$ reductions during aircraft accelerations were obtained. Table 2 lists $FTIT$ reductions seen at intermediate power during aircraft accelerations in the subsonic flight envelope. As in the steady-state results, the magnitude of the $FTIT$ reduction decreases with decreasing altitude. The maximum $FTIT$ reduction seen during the accelerations, 90 °F, occurred at 30,000 ft, $M = 0.8$. The smallest, 10 °F, occurred at 20,000 ft, $M = 0.9$. Reductions in $FTIT$ from 40 to 80 °F were typical in the 30,000- to 40,000-ft range, and from 20 to 40 °F in the 10,000- to 20,000-ft range.

Figure 10 displays $FTIT$ as a function of Mach number at 30,000 ft, intermediate power during an aircraft acceleration from $M = 0.55$ to 0.95. Data are displayed for EEL on and off. The $FTIT$ reductions are similar in magnitude to those seen at 30,000 ft in the steady-state cases except at $M = 0.8$ (table 1). The benefit of the EEL mode decreases at Mach numbers greater than 0.90.

Figure 11 plots time against Mach number for the EEL mode on and off cases and from $M = 0.55$ to 0.95. The times taken to complete the two back-to-back accelerations are similar. This indicates that actual excess thrust, and therefore FN, was similar during the EEL on and off accelerations. Figure 12 plots FN, from the in-flight program, against Mach number for the same point previously mentioned.

The figure shows that, at the same Mach number, the algorithm holds thrust well (within approximately 1 percent of the EEL off case), despite the lower turbine temperature.

Figure 13 shows the decrease in *TSFC* between the accelerations for EEL mode on and off. An average drop in *TSFC* of about 4 percent throughout the acceleration resulted except at $M = 0.95$, where the benefit was not as great.

Table 2. Reductions in *FTIT* during extended engine life mode operation at intermediate power during aircraft accelerations.

	FTIT reduction, °F			
	Mach number			
Altitude, Kft	0.6	0.7	0.8	0.9
40	60	40	40	60
30	80	80	90	65
20	30	20	20	10
10	40	20	40	15

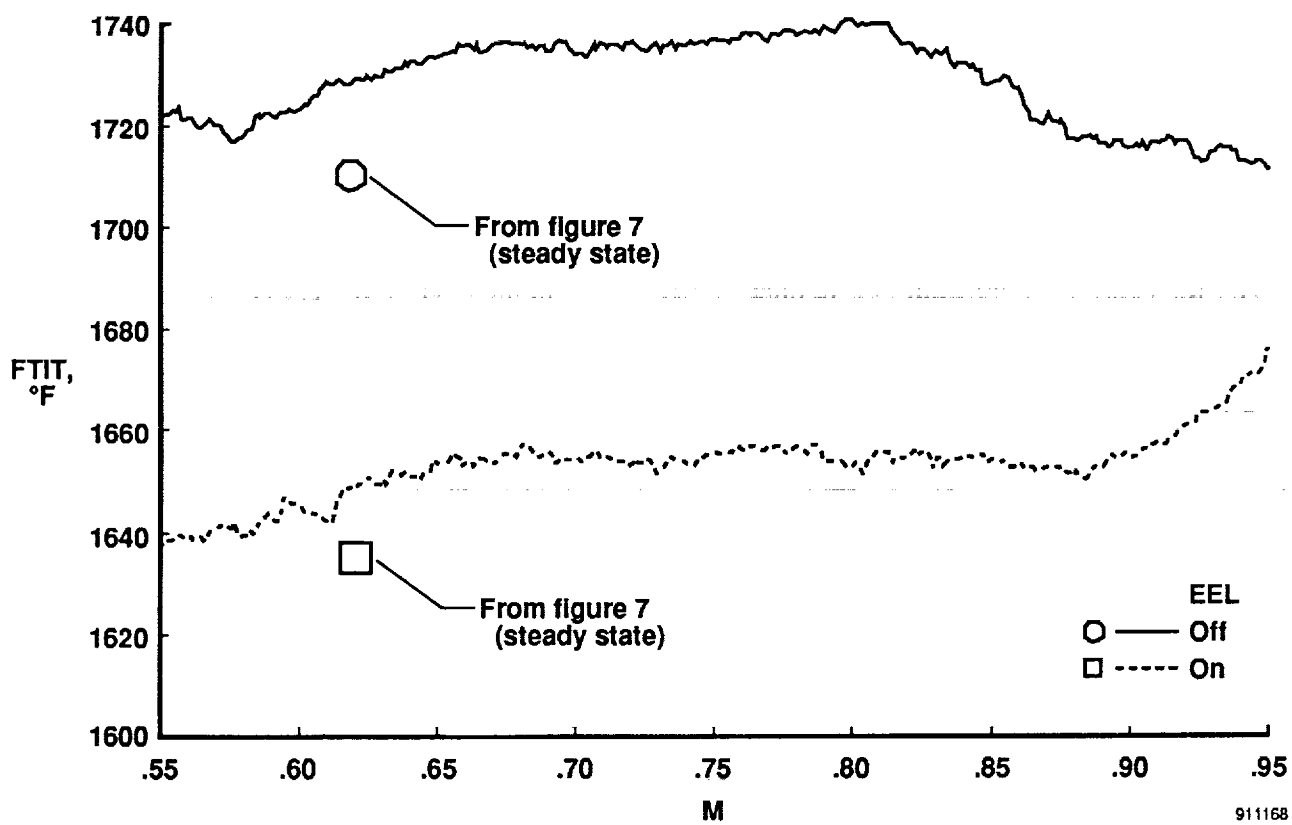

Figure 10. Fan turbine inlet temperature as a function of Mach number. Intermediate power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

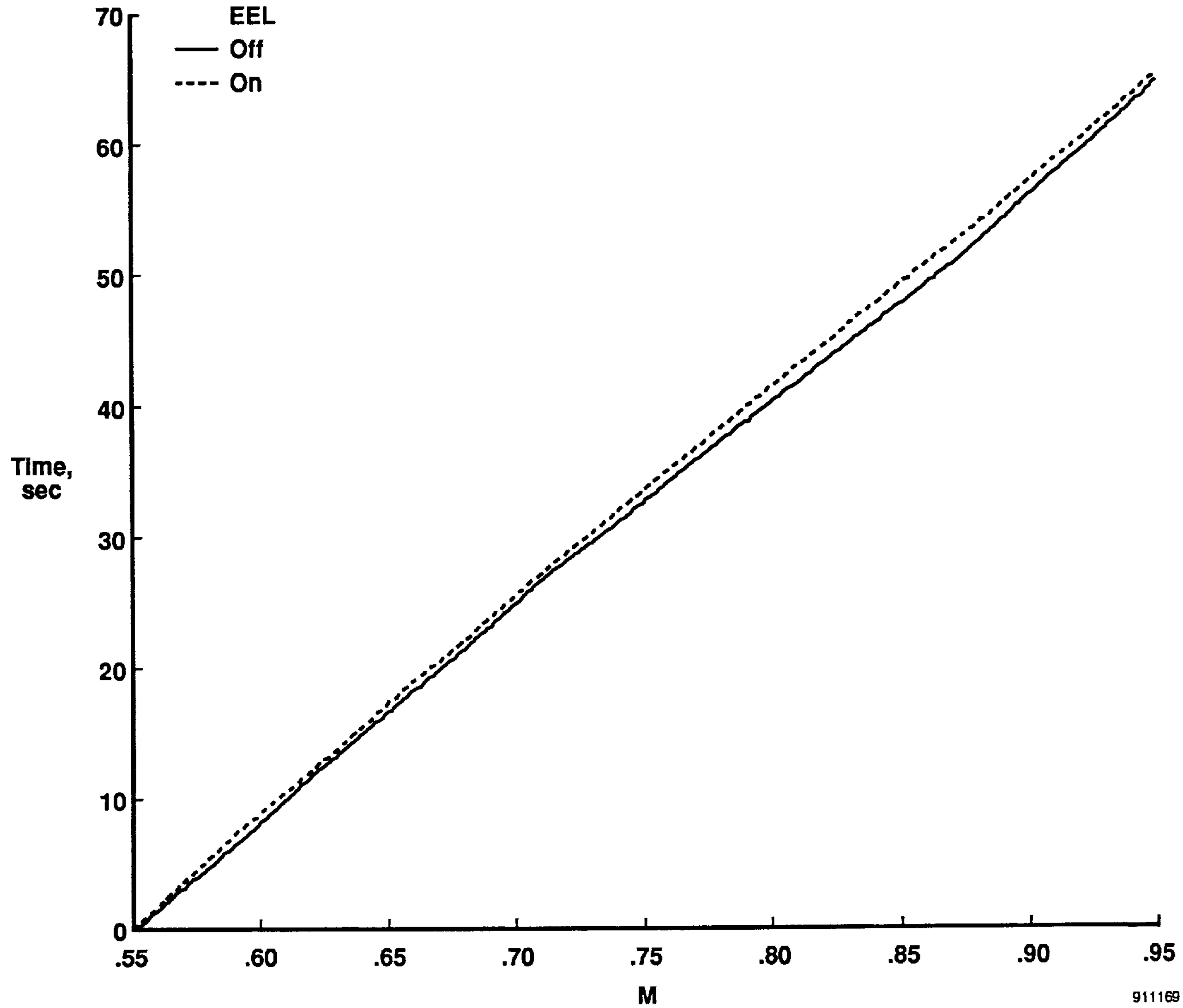

Figure 11. Acceleration time as a function of Mach number. Intermediate power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

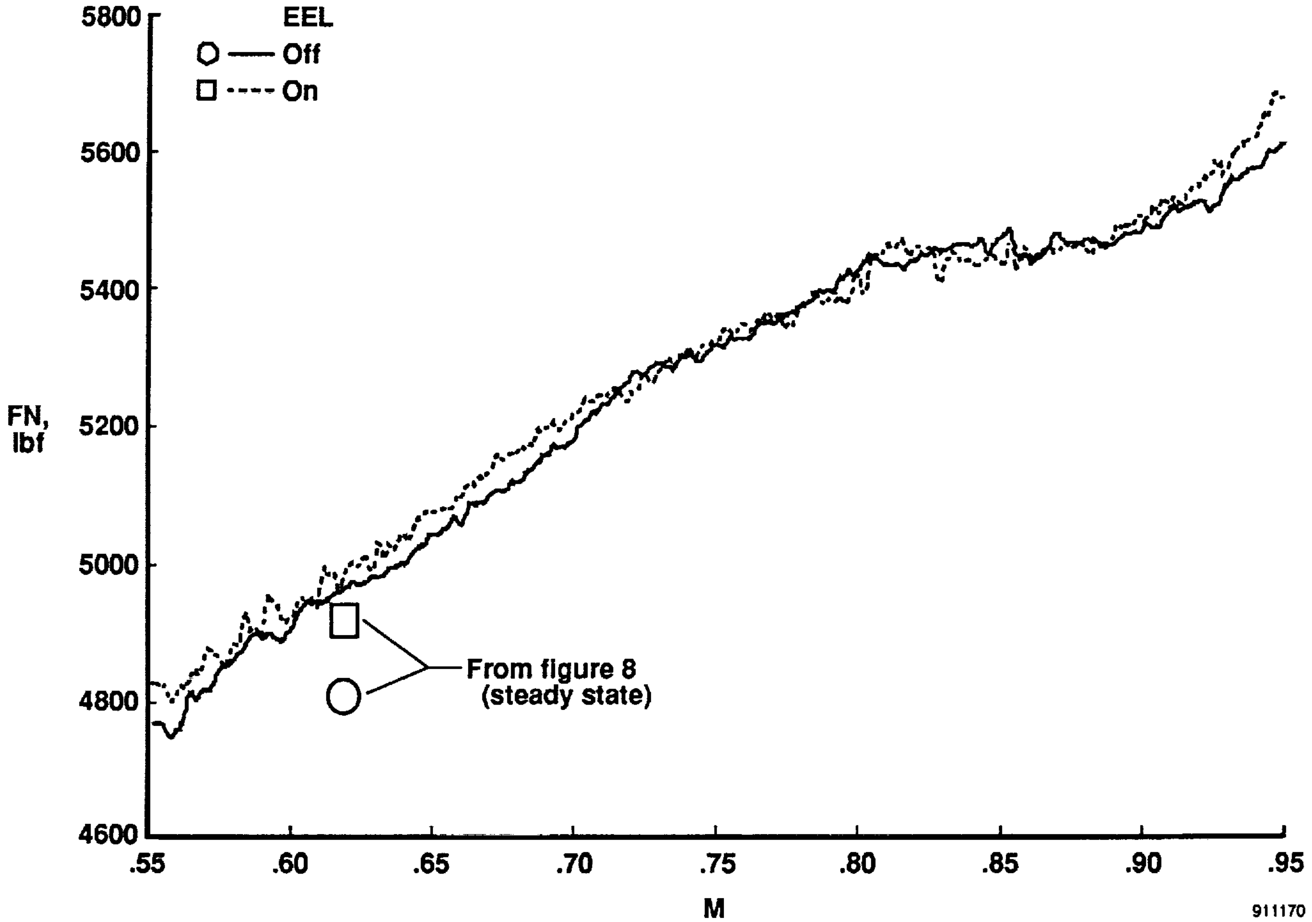

Figure 12. Net thrust as a function of Mach number. Intermediate power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

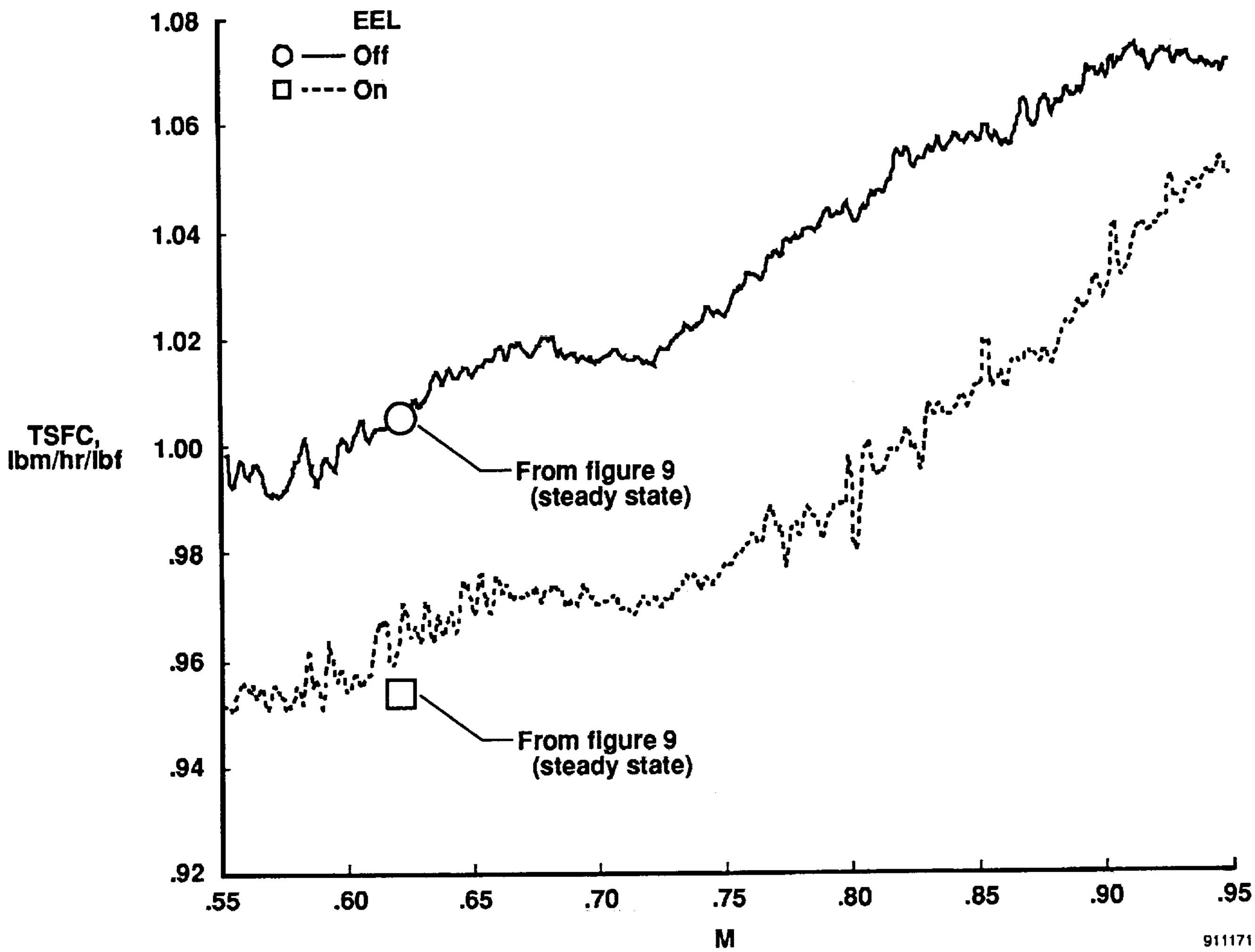

Figure 13. Net thrust specific fuel consumption as a function of Mach number. Intermediate power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

Augmented Power

The EEL algorithm performance was also investigated during maximum augmentor operation. Table 3 lists $FTIT$ reductions seen at maximum augmented power during aircraft accelerations in the subsonic flight envelope. Again, the magnitude of the $FTIT$ reduction decreased significantly with decreasing altitude. At 20,000 ft and above, the reductions in $FTIT$ during maximum augmented power usually exceeded the results seen at intermediate power at the same flight condition. An average reduction of approximately 100 °F was seen in the 30,000- to 40,000-ft range. However, much smaller reductions were seen at 10,000 ft and 20,000 ft. A maximum $FTIT$ reduction of 170 °F occurred at 30,000 ft, $M = 0.55$.

Table 3. Reductions in *FTIT* during extended engine life mode operation at maximum power during aircraft accelerations.

	FTIT reduction, °F			
	Mach number			
Altitude, Kft	0.6	0.7	0.8	0.9
40	85	–*	110	100
30	140	100	100	90
20	60	30	25	20
10	20	0	10	10

*EPR fluctuation anomaly

An EPR fluctuation anomaly occurred during an augmentor segment light-off sequence at 40,000 ft and $M = 0.7$. The algorithm had miscalculated the time at which the next augmentor segment would sequence on. This, combined with a significant amount of input signal noise at this condition, led to an oscillation in the EPR uptrim value which limited the *FTIT* reduction.

Figure 14 presents *FTIT* as a function of Mach number during aircraft accelerations from $M = 0.55$ to 0.95 at 30,000 ft at maximum power for EEL mode on and off. The figure shows the large reduction in *FTIT* that occurred during the acceleration, particularly at lower Mach numbers. The rise in *FTIT* seen from $M = 0.74$ to 0.80 for the EEL mode on case was caused by the EPR cutback that the algorithm imposed during an augmentor segment light off to maintain engine stability.

Figure 15 shows net thrust versus Mach number for the same 30,000-ft maximum power accelerations as in figure 14. Net thrust for the EEL mode on case is slightly greater than for EEL off during much of the acceleration. The differences in *FN* between the two cases range from about 2 percent early in the acceleration, to almost 5.5 percent during the augmentor light-off sequence, down to approximately 1 percent at $M = 0.95$. It may have been possible to achieve greater reductions in *FTIT* had thrust been held to a tighter tolerance. Figure 16 shows the resulting *TSFC* values for the same condition. A significant reduction in *TSFC* was achieved throughout much of the acceleration with EEL on, ranging from about 2.5 percent initially and decreasing steadily as $M = 0.95$ was approached.

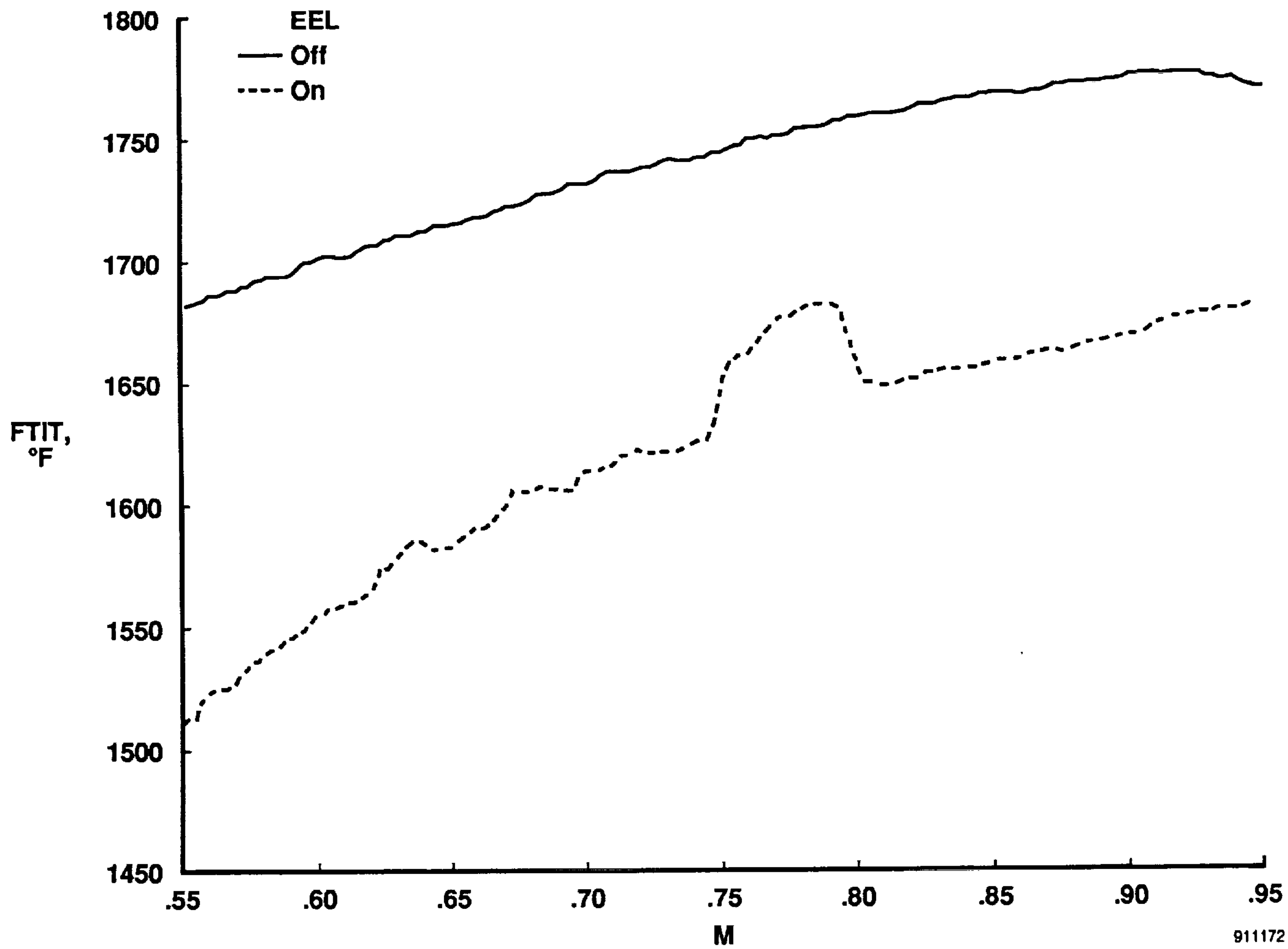

Figure 14. Fan turbine inlet temperature as a function of Mach number. Maximum power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

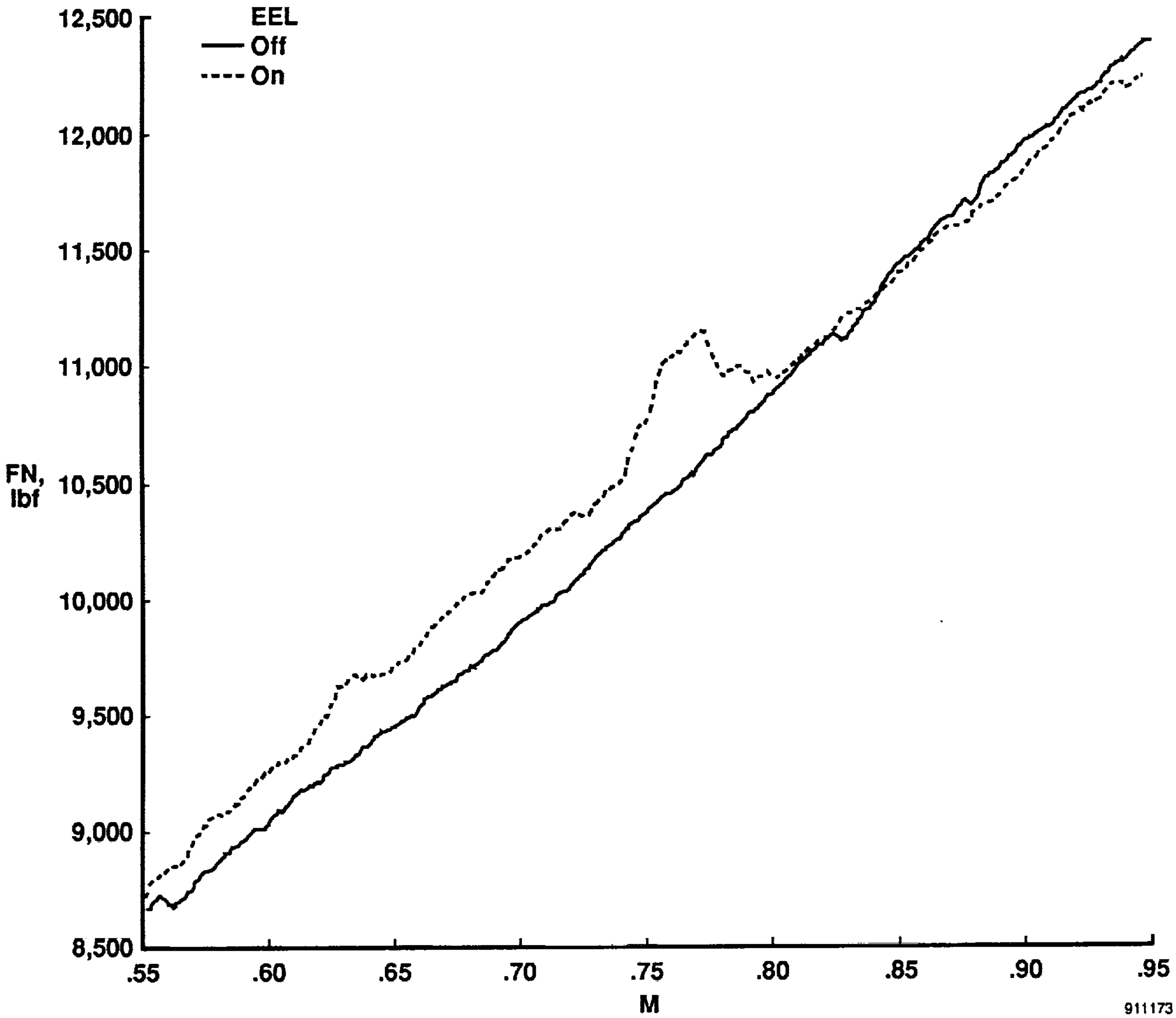

Figure 15. Net thrust as a function of Mach number. Maximum power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

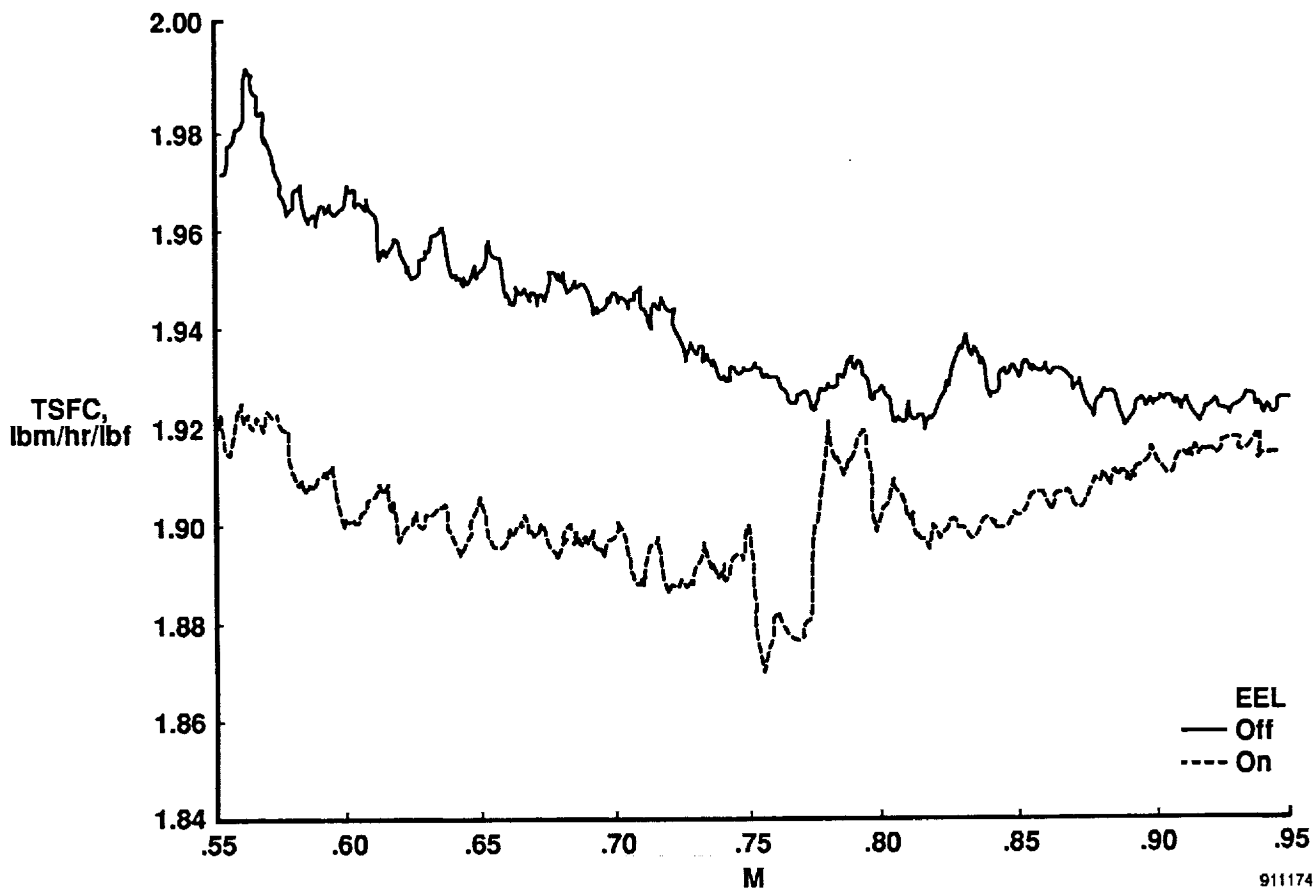

Figure 16. Net thrust specific fuel consumption as a function of Mach number. Maximum power aircraft acceleration, $M = 0.55$ to 0.95, $ALT = 30{,}000$ ft.

At the same Mach number and altitude, there were noticeable differences between the $FTIT$ reductions obtained during steady-state and quasi-steady-state engine operation. Repeatability of the data was more difficult to achieve for the acceleration cases. The data were sensitive to engine dynamics that occurred immediately before the accelerations began. It was important to verify that $FTIT$ had completely stabilized before a flight-test maneuver was initiated.

No significant problems were experienced during the EEL program. The engine did not experience any stalls, indicating that the ADECS EPR logic worked successfully in maintaining engine stability under increased EPR. There were no adverse effects on engine operability or pilot workload. Except for the previously mentioned anomaly during augmented operation, there were no instabilities in the EEL algorithm itself. With EEL on, the goal of holding thrust constant to within 2 percent of the nominal value was met in almost all cases.

The engine manufacturer estimates that an EEL-type mode used to the greatest extent possible can increase engine core life by as much as 10 to 12 percent. This estimate of life extension is based on the temperature reductions seen during the EEL program.

CONCLUSIONS

The NASA F-15 highly integrated digital electronic control research aircraft has been used successfully to test and evaluate an extended engine life mode. This mode was designed to reduce operating temperatures with no significant loss in thrust performance. The extended engine life mode was flight demonstrated from Mach 0.55 to 0.95 and from 10,000- to 40,000-ft altitude. Operation during intermediate and maximum augmented power was studied.

The extended engine life mode achieved significant reductions in fan turbine inlet temperature throughout the F100 engine model derivative subsonic flight envelope. Steady-state and quasi-steady-state engine operations were analyzed at intermediate power and above. The largest intermediate power steady-state reduction in fan turbine inlet temperature, 80 °F, occurred at 30,000 ft, Mach 0.6. Reduction in fan inlet turbine temperature of approximately 60 °F was typical at intermediate power for steady-state and quasi-steady-state operation at 30,000 ft and above.

In addition to significant reductions in fan inlet turbine temperature, substantial decreases in net thrust specific fuel consumption were also seen. For instance, at 30,000 ft, Mach 0.6, and intermediate power, a reduction in net thrust specific fuel consumption of about 0.045 lbm/hr/lbf (4.5 percent of the value for extended engine life off) was obtained.

The extended engine life algorithm performance was also investigated at maximum augmented power during aircraft accelerations. At 20,000 ft and above, the reductions in fan inlet turbine temperature during maximum power usually exceeded the results seen at intermediate power at the same flight condition. An average reduction of 100 °F was seen in the 30,000- to 40,000-ft range. A maximum fan inlet turbine temperature reduction of 170 °F occurred at 30,000 ft, Mach 0.55.

No significant problems were experienced during the extended engine life program. The engine did not experience any stalls, indicating that the advanced engine control system engine pressure ratio logic worked successfully in maintaining engine stability under increased engine pressure ratio. There were also no significant instabilities in the extended engine life algorithm itself. With extended engine life on, the goal of holding thrust constant to within 2 percent of the nominal value was met in almost all cases.

The extended engine life mode demonstrated that an engine temperature reducing control algorithm can be successfully implemented on a production aircraft with no significant cost and weight penalties and with no adverse impact on aircraft operability, pilot workload, or safety.

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13. ABSTRACT ***(Maximum 200 words)***

An integrated flight and propulsion control system designed to reduce the rate of engine deterioration has been developed and evaluated in flight on the NASA Dryden F-15 research aircraft. The extended engine life mode increases engine pressure ratio while reducing engine airflow to lower the turbine temperature at constant thrust. The engine pressure ratio uptrim is modulated in real time based on airplane maneuver requirements, flight conditions, and engine information. The extended engine life mode logic performed well, significantly reducing turbine operating temperature. Reductions in fan turbine inlet temperature of up to 80 °F were obtained at intermediate power and up to 170 °F at maximum augmented power with no appreciable loss in thrust. A secondary benefit was the considerable reduction in thrust-specific fuel consumption. The success of the extended engine life mode is one example of the advantages gained from integrating aircraft flight and propulsion control systems.

14. SUBJECT TERMS

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