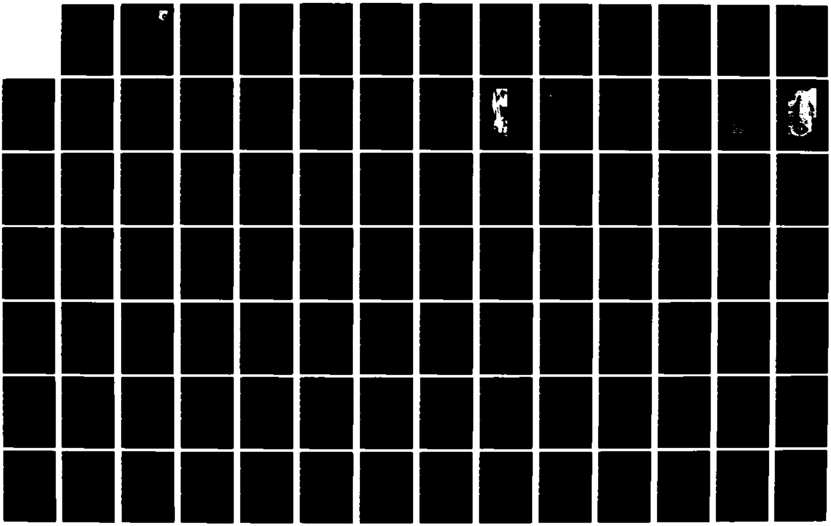
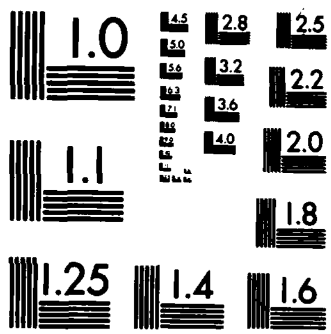
AD-A127 740 PERFORMANCE LIFE AND OPERABILITY TRADE-OFFS IN VCE CONTROL LOGIC DESIGN..(U) GENERAL ELECTRIC CO CINCINNATI OH AIRCRAFT ENGINE BUSINESS GR.. 1/2

UNCLASSIFIED R G STABRYLLA AUG 81 R81AEG266 F/G 21/5 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

AFWAL-TR-81-2059

PERFORMANCE, LIFE, AND OPERABILITY TRADE-OFFS IN VCE CONTROL LOGIC DESIGN

General Electric Company
Aircraft Engine Business Group
Cincinnati, Ohio 45215

AUGUST 1981

Final Report for Period August 1978 to February 1981

Approved for Public Release; Distribution Unlimited

Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force System Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

PAUL T. ADAMS, JR.
Project Engineer

LESTER L. SMALL
Technical Area Manager
Controls And Diagnostics

FOR THE COMMANDER

H.I. BUSH
Director
Turbine Engine Division
Aero Propulsion Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization, please notify AFWAL/POTC, W-PAFB, OH 45433 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFWAL-TR-81-2059	2. GOVT ACCESSION NO. AD-A127740	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Performance, Life, and Operability Trade-Offs in VCE Control Logic Design		5. TYPE OF REPORT & PERIOD COVERED Final Report for Period Aug 78 to Feb 81 6. PERFORMING ORG. REPORT NUMBER R81AEG266
7. AUTHOR(s) R.G. Stabrylla		8. CONTRACT OR GRANT NUMBER(s) F33615-78-C-2061
9. PERFORMING ORGANIZATION NAME AND ADDRESS General Electric Company 1 Neumann Way Cincinnati, OH 45215		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 30660385
11. CONTROLLING OFFICE NAME AND ADDRESS Aero Propulsion Laboratory (AFWAL/POTC) Air Force Wright Aeronautical Laboratories/AFSC Wright-Patterson Air Force Base, OH 45433		12. REPORT DATE August 1981 13. NUMBER OF PAGES 94
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Variable Cycle Engine
Control Trade-Off Analysis
Aircraft Performance
Operability
Engine Life Consumption

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An F-16/F101 DFE aircraft weapons system was chosen as a next generation engine and a weapon system performance operability, and engine component life capability was established for it. Using computer models, studies were carried out to quantitatively evaluate the change in these as a function of engine control logic, aircraft mission usage, and aircraft dry weight. The results obtained showed that qualitative trades can be obtained relating aircraft performance, operability, and engine life consumption through choices made in the control logic design.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

This report describes results of studies on performance, life, and operability trade-offs in VCE Control Logic Design conducted by the General Electric Company. This project was sponsored by the Aero Propulsion Laboratory of Air Force Wright Aeronautical Laboratories/AFSC, WPAFB, Ohio under Contract F33615-78-C-2061, with Messrs. J.J. Batka and, later, P. Adams (POTC) as Project Engineers. Mr. Batka's critical comments, timely suggestions, and keen interest in the Program in general were instrumental in the successful completion of the project. Mr. Adams has been helpful during the final phases of the study and in preparation of this final report. Their participation in the program is greatly appreciated.

The work reported herein was performed by Mr. R.G. Stabrylla. Mr. D.E. Uehling and Dr. A.R. Mulukutla were the General Electric Program Managers.

CONTENTS

CONTENTS (Concluded)

LIST OF FIGURES

LIST OF FIGURES (Concluded)

LIST OF TABLES

GLOSSARY

A/B	Afterburner
ACM	Air Combat Mission
ADA	Advanced Derivative Aircraft
AFT	Augmentor Fan Temperature
ALT	Flight Altitude, Ft.
AMST	Advanced Mission Subsonic Transport
AMT III	F-14 Mission Mix Accelerated Mission Test Cycle
AMT IV	F-16 Mission Mix Accelerated Mission Test Cycle
ATS	Air to Surface Mission
C_D	Aircraft Aerodynamic Drag Coefficient
C_L	Aircraft Aerodynamic Lift Coefficient
D, Drag	Aircraft Drag, Lbs.
DACCEL	Distance Travelled During Acceleration, N Mi.
DCLIMB	Distance Travelled During Climb, N Mi.
DCR	Cruise Distance, N Mi.
DFE	Derivative Fighter Engine
EMT	Equivalent Mission Hours
ERG	Engine Removal Generator
FCF	Functional Check Flight
F.I.	Flight Idle
FNIN	Engine Thrust, Lbs.
FOD	Foreign Object Damage
FTC	Fuel Thermal Cycles (LCF + Idle-Intermediate-Idle Cycles)
GD-FWD	General Dynamics - Ft. Worth Division
G.I	Ground Idle, Lbs.
HP	High Pressure
IDC	Inlet Distortion Circumferential
ISM	Increased Stability Margin Mode
LCC	Life Cycle Cost
LCCPP	Life Cycle Cost Post Processor
LCF	Low Cycle Fatigue Cycle (Start-Intermediate Power-Stop Cycle)
LoLoLo	Low Altitude Mission

LP	Low Pressure
LRU	Line Replacement Units Rate, per 1000 Engine Flight Hours
M_{cl}	Climb Thrust, Lbs.
M_{cr}	Cruise Thrust, Lbs.
MEP	Maintenance Event Processor
MMH	Maintenance Manhours, per Engine Flight Hours
M_0	Flight Mach Number
MTBMA	Mean Time Between Maintenance Actions, Hours
N/N_{ref}	Ratio of New to Reference Rotor Speeds
N_c	Core Speed, RPM
O&S	Operation and Support Cost
OPSEV	Operational Severity Computer Program
OSCAP	Operation and Support Cost Analysis Program
P/P_{ref}	Ratio of New to Reference Pressures
PCC	Parts Consumption Cost, per Engine Flight Hours
PLA	Power Lever Angle, Degrees
P_S	Excess Specific Power, fps
RAD	Turn Radius, N Mi.
RDT&E	Cost of Research, Development Test and Evaluation
REMAC	Resultant Maintenance Action Calculator
R_F	Range, N Mi.
$S_{n/r}$	Severity Ratio of New to Reference Mission
SFCIN	Specific Fuel Consumption, Lb/Hr/Lbf
SLS	Sea Level Static
SM2	Fan Stall Margin, Percent
SM25	Compressor Stall Margin, Percent
SVR	Shop Visit Rate, per 1000 Engine Flight Hours
T_2	Engine Inlet Temperature, ^oR
T_{41}	Turbine Rotor Inlet Temperature, ^oR
TAC	Tactical Air Command Cycles (LCF + .25 (FTC-LCF))
TAMP	Time at Max Power, Hours
TACCEL	Time at Acceleration, Min
TCLIMB	Time to Climb, Min
TCR	Time at Cruise, Min

T/O	Take Off Thrust, Lbs.
TR	Turn Rate, Degrees per Second
TST	Test Stand Test
UER	Unplanned Engine Removal Rate, per 1000 Engine Flight Hours
USN	U.S. Navy
VT	Flight Velocity, fps
W2R	Fan Corrected Inlet Airflow, pps
WFACCEL	Fuel Burned During Acceleration, Lbs.
WFCLIMB	Fuel Burned During Climb, Lbs.
WFCR	Fuel Burned at Cruise, Lbs.
WT	Fuel Weight, Lbs.
α, ALPHA	Aircraft Angle of Attack
β	Aircraft Side Slip Angle
$\Delta N/\Delta N_{ref}$	Ratio of New to Reference Change in Rotor Speeds
$\Delta T/\Delta T_{ref}$	Ratio of New to Reference Change in Temperatures
λ	Failure Rate
λ_{cyc}	LCF Failure Rate
λ_n	Failure Rate of New Mission
λ_r	Failure Rate of Reference Mission
λ_{ss}	All Other Failure Rates
μ	Mean Life

1.0 INTRODUCTION

The goal of this program was to derive analytical tools and methods that would allow the identification of the range of aircraft weapon system and engine life, performance and operability (LPO) trade options available through control action. The potential benefit visualized from this effort is the identification of the tools and procedures required by control designers to allow the design of controls that manage engine life as well as performance and operability.

Current advanced engine controls have the capacity to manage weapon system performance and inlet/engine stability as a result of the recent development of: engines with several controlled variables, ruggedized electronics and sophisticated transient control techniques. The question at hand is whether the rate of consumption of turbine engine component life can also be managed by the control design and if so, what are the quantitative trades between life, performance and operability.

The ability to predict turbine engine component life consumption as a function of weapon system mission usage and engine operating conditions for fighter systems was recently developed by General Electric on two Air Force contracts. The "Life Development and Definition Program (F33657-76-C-0213)" developed and validated techniques for correlating aircraft usage to engine removal rates using the CF6 commercial aircraft data base and applied the techniques to the AMST program. This program also identified a general life management plan. The "Design Analysis and Critical Component Development Program (F33615-78-C-2007)" applied the techniques identified to assess: (1) The B-1/F101 flight usage severity relative to the SAC training design missions, (2) the F-14/F101X fighter individual flight mission severities relative to the flight mission mix, and (3) the F-16/F101 flight mission severities relative to the design missions. The results of these efforts identified correlations between aircraft mission usage and component life consumption rates. The validation of this tool for commercial and military applications is described in reference 1, AIAA Report. Reference 2, FTD-24-291-73, shows that similar results have been obtained in Russian studies.

The engine component life consumption calculation tools developed have been used in conjunction with other existing calculation tools to identify quantitative trades between aircraft performance, operability and engine component life and Operating and Support costs. Studies have been made to assess the effect of changing control set points, mission usage and aircraft weight. In the performance of these calculations, it was found that the methodology used, i.e., problem definition, assumptions made, and the calculation sequence have a significant impact on the qualitative values obtained. As a result, two methodologies were defined and evaluated.

The approach used in this program was as follows. First, a baseline (base) F-16 ADA/F101 DFE weapon system was defined and its LPO characteristics determined. Second, specific trade studies were defined and a methodology for their solution formulated. Third, the numerical calculations were performed. Fourth, the results were normalized relative to the base system capabilities and evaluated. Fifth, the methodology was assessed. The results of this effort are presented in this report.

2.0 SUMMARY

An F-16/F101DFE aircraft weapon baseline system was established which identified baseline weapon system performance operability and engine component life capabilities. Studies were carried out to quantitatively evaluate the change in these parameters as a function of engine control mode, aircraft mission usage and aircraft dry weight. The quantitative analyses were carried out using existing computer models.

Results were obtained which showed that qualitative trade results can be obtained that relate aircraft performance, operability and engine life consumption.

THE STUDIES CARRIED OUT USED THE F-16 ADA AND F101 DFE STATUS INFORMATION THAT WAS CURRENT IN 1979.

3.0 PROBLEM DEFINITION

In order to address the goals of this program, first the broader problem of comparing weapon system capabilities with requirements must be quantified. The work breakout structure of this problem is shown on the weapon system evolution process schematic in Figure 3-1, which depicts: (1) The basis for a weapon system development, and (2) the fundamental work flow of the development. The basis is the identification of a potential threat, such as the development of a fighter with vastly superior combat capabilities, by an unfriendly power. This potential threat triggers the definition of a need to develop our own weapon system capable of countering the potential threat. This need is translated into the definition of system requirements and a commitment of resources (dollars and manpower) for the development of a new weapon system.

The weapon system development work flow structure is shown in the box. Since this effort is primarily interested in the propulsion system influences on system capability, the aircraft and its many subsystems have been lumped under one heading, and only a few of its mission oriented parameters shown, i.e., aerodynamic characteristics (lift/drag, center of gravity location), structural characteristics (maneuver off limits), engine installation, weight, payload and fuel capacity. These aircraft factors combined with the propulsion system characteristics, i.e., performance, operability and life functions describe the weapon system capabilities. Note that Operating and Support costs are included in the system capability. This inclusion is significant in that it allows assessing a balance between performance and cost.

The development of a weapon system takes a significant amount of time (7 to 14 years). At any point in time during the development, the weapon system capabilities and requirements status can change as a result of new data on subsystem capabilities or better definition of requirements resulting from a better definition of the threat. The ability to analytically quantify system capabilities as a function of subsystem status at any time during the development process would result in a powerful management decision-making tool which could be used to apply resources more effectively.

The analytical tools needed to quantify system capability are available. The difficulty lies in the quantity and quality of the input data. Vast amounts

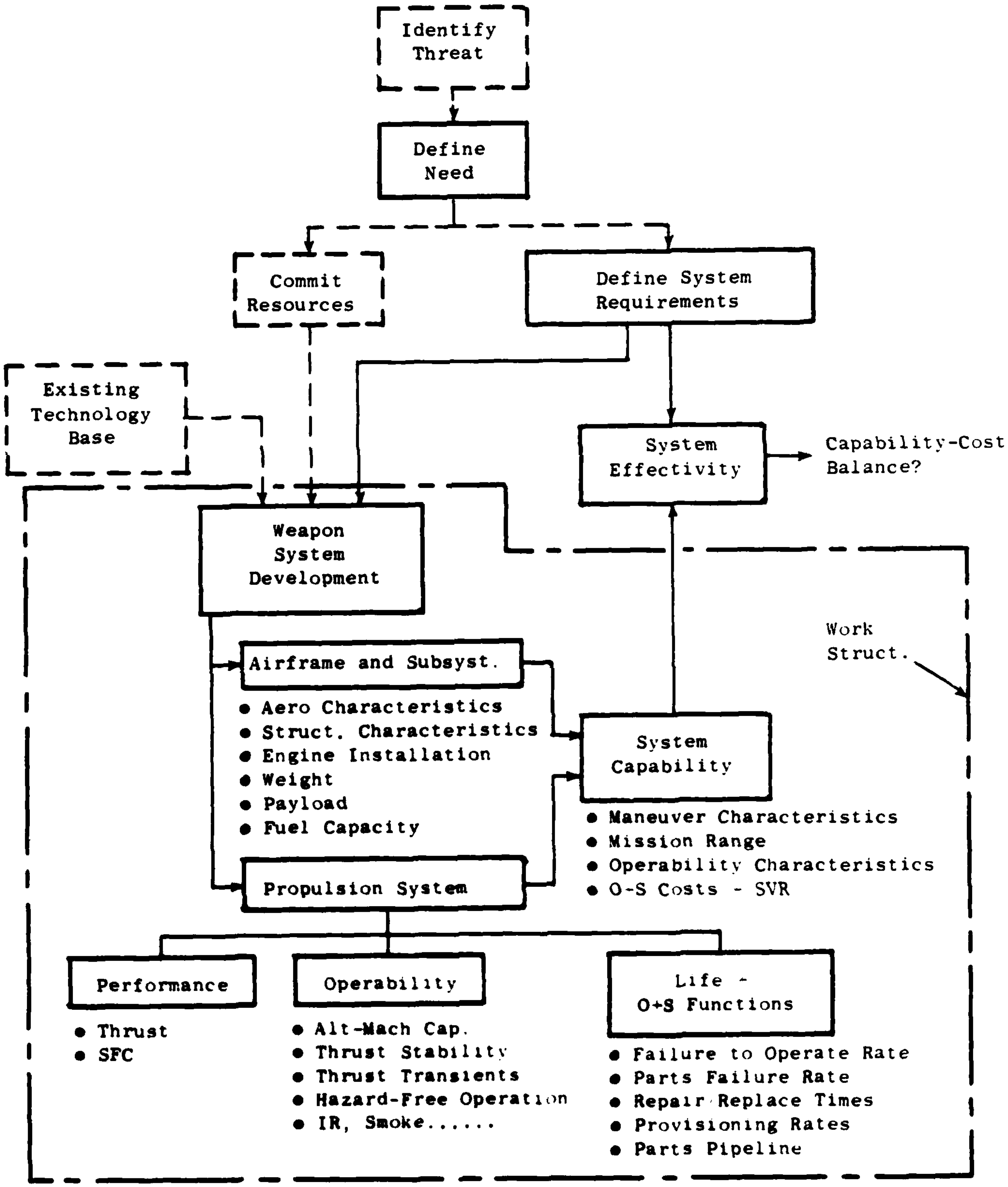


Figure 3-1. Weapon System Evolution Process.

of inputs are needed to characterize the aerodynamics of the aircraft, the engine performance, operational envelope, life and Operating and Support costs. The status of these inputs is continually changing. Initially the status is predicted on the basis of projected technology capabilities.

In time, predictions are replaced with test data as it becomes available. However, in the area of engine life and Operating and Support costs, the test data become available very late in the development (i.e., during flight test and early production and deployment) where system design flexibility is very low. In past developments, the late availability of engine life data has resulted in much higher Operating and Support costs than anticipated, leading to a conclusion that advanced fighter engines lacked durability. Subsequent studies (reference 1) showed that flight usage of these aircraft was significantly different than the design intent. This knowledge has been used to design current engines such as the F101 DFE, so their life capabilities reflect the real world. Understanding the relationships between aircraft usage and engine functions and being able to predict the effect of changing one characteristic on the system capabilities has opened a new range of trade study potentials.

Application of these tools to expand the engine control designers' capabilities can be visualized with an example. Consider a case where the system requirements and all the data needed to identify system capabilities are defined for a given control set point. Analysis of this situation shows that the system performance capabilities in terms of mission range, climb rates, acceleration rates and operational envelope exceed requirements for both the peacetime and wartime usages. The propulsion system life capabilities are less than requirements for both the peacetime and wartime usages. Further, the peacetime usage is less severe than the wartime usage in terms of performance and operational envelope. The control problem is defined as follows: Can an engine control set point be identified which reduces the system performance capability so it is equal to the wartime requirements and how much improvement in propulsion system life capability and associated Operating and Support cost results from this change? Similarly, can a control set point be defined to just satisfy the peacetime usage requirements, and if so, how does Operating and Support cost change? Finally, could a control be implemented with a control set point switch that would allow using the peacetime control set point for training and the wartime control set point for actual combat so the rate of engine life consumption could be minimized. In essence, the control designer's task is one of balancing the system performance and life capabilities without changing the physical hardware of the aircraft or engine.

4.0 BASELINE SYSTEM

The baseline system is composed of the F-16 Advanced Derivative Aircraft (ADA) and the F101 derivative fighter engine (DFE). The aircraft characteristics have been defined using information obtained from General Dynamics, who was a subcontractor on this program. Definition of the F-16ADA mission usage and operational envelope were obtained from the Air Force F-16 SPO. The F101 DFE performance, stability, operability, control set point, durability and O&S cost definition were obtained from the General Electric's F101 DFE Project.

4.1 F16 ADA Aircraft

Figure 4-1 shows the F-16 multirole aircraft weapon system and its specifications. The aerodynamic characteristics (drag polars, etc) of the F-16 were obtained from General Dynamics, Ft. Worth Division (GD-FWD) and incorporated into a existing General Electric aircraft performance calculation program for use in this program.

The F-16 mission and power schedules are shown in Figure 4-2. Figure 4-3 defines the mission and the estimated flight envelope usage associated with the missions and mix described above. The missions and mix were obtained from the Air Force F-16 SPO in 1979.

4.2 F101 DFE Engine

4.2.1 Engine Description

The F101 DFE engine is a dual rotor, augmented turbofan with aerodynamically coupled low and high pressure systems. The engine configuration utilizes a three-stage 270 lb/sec fan, a two-stage LP turbine, a mixed flow augmentor, and a core common to both the F101-GE-100 for the B-1 and CFM56 engines.

Thrust class, lb	29,000
Length, inch	181.9
Diameter Inlet, inch	35.6
Diameter Maximum, inch	46.5
Airflow, lb/sec	270
Fan pressure ratio	3.2
High pressure compressor ratio	9.5
Bypass ratio	0.87
Turbine inlet temperature class, °F	2500

SPECIFICATIONS

Wing Span (ft)	32.8*
Wing Root Chord (in.)	195
Wing Area (ft^2)	300
Overall Length (ft)	47.6
Empty Weight (lb)	15,137
Max Takeoff Gross Wt (lb)	35,400
Fuel Capacity (lb)	6,972
Takeoff Roll (max) (ft)	3,030
Landing Distance (max) (ft)	2,830**
Maximum Speed (mach No.)	2.0
Maximum Cruise Speed (Mach No.)	0.93

* With wing tip missiles. Without missiles, span is 31 ft.
** Using brakes only.

Figure 4-1. F-16/F101 DFE.

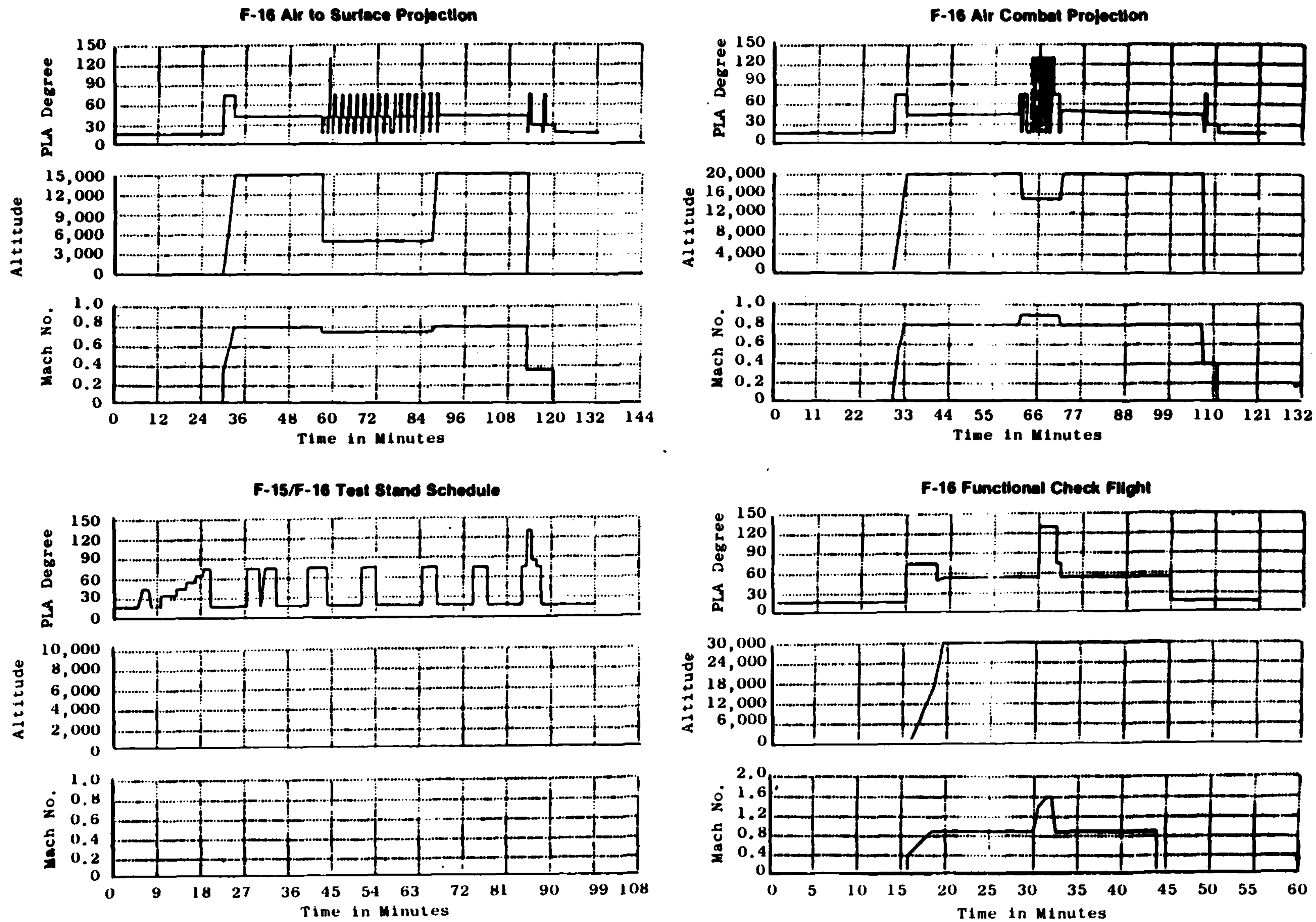
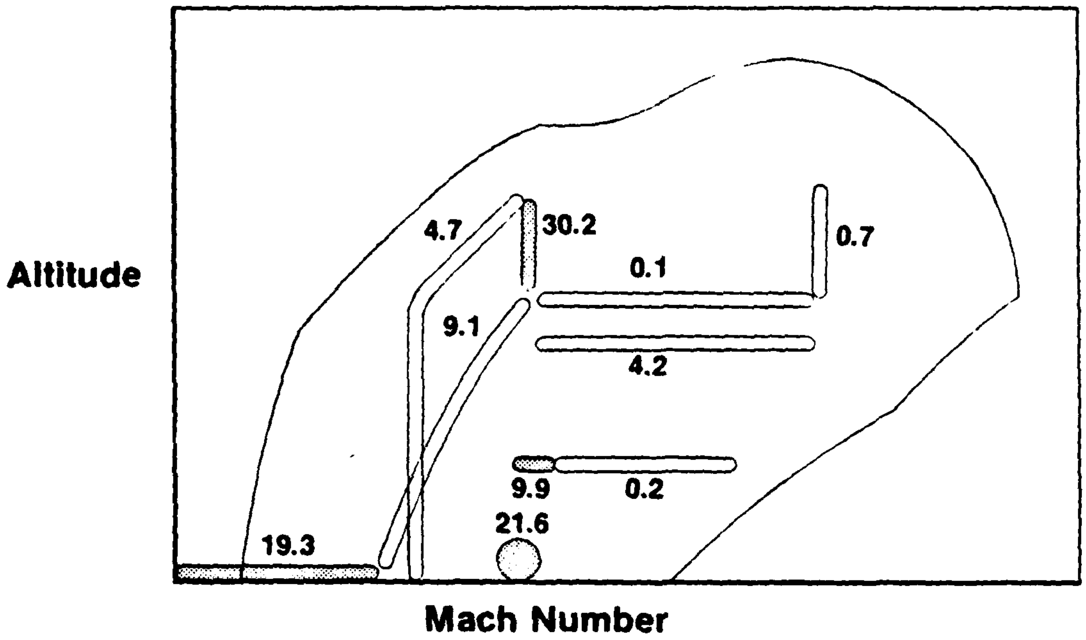


Figure 4-2. F-16 ADA Missions and Power Schedules.

Estimated Flight Envelope Usage

Typical
(Per Cent Time)



F-16 ADA Mission Mix

Mission	% Use	No. of Sorties	Mission Length (min.)
Air to Surface (ATS)	45	409	132
Air Combat (ACM)	44.2	431	123
Functional Check Flight (FCF)	2.8	60	56
Test Stand Test (TST)	8.0	95	98.9
	100.0	995	

Figure 4-3. F-16 ADA Mission Mix and Flight Envelope Usage.

A cross-section of the engine is shown in Figure 4-4. The engine is a very compact two-bearing core and three-bearing LP system supported by a three-frame structural system, similar to the F101-GE-100 and F404-GE-400 engines.

Simplicity, the prime objective governing the F101 DFE design provides the key to greater reliability and ease of maintenance, reduced manufacturing and increased capability for growth.

The F101 DFE engine is interchangeable with the existing engines in the F-16 and F-14A. For the F-16, mounts are provided on the front frame and turbine frame. For the F-14A installation a 20.9 inch inlet piece with a thrust mount is attached to the engine as shown by Figure 4-4. The rear mount consists of a mount ring on the tailpipe. Other functional and physical interfaces of the engine meet the F-16 and F-14A installation requirements. Figure 4-5 shows the engine model in the F-16 configuration.

4.2.2 Performance

This section summarizes the aero-thermodynamic performance of the F101 DFE augmented turbofan engine. These characteristics along with the effects of Reynold's number, tip clearance, operating loads and control schedules are programmed into the F101 DFE steady-state performance computer program.

The basis for the computer performance program/deck is data obtained from over 1600 hours of F101 performance testing at sea level and altitude conditions of the F101 DFE demonstrator engine in both the GE and AEDC altitude facilities.

The aero-thermodynamic performance of the engines for the F-14 and F-16 is identical except for different maximum fan speed and fan operating line control schedules. The engine for the F-14 utilizes the full 270 lb/sec corrected airflow capability of the engine; whereas, the engine for the F-16 is based on a maximum corrected airflow of 245 lb/sec at static conditions and 254 lb/sec above Mach 0.5 for inlet matching purposes. This provides both a flat rated thrust and reduced turbine temperatures for enhanced engine life at inlet temperatures below 90° F.

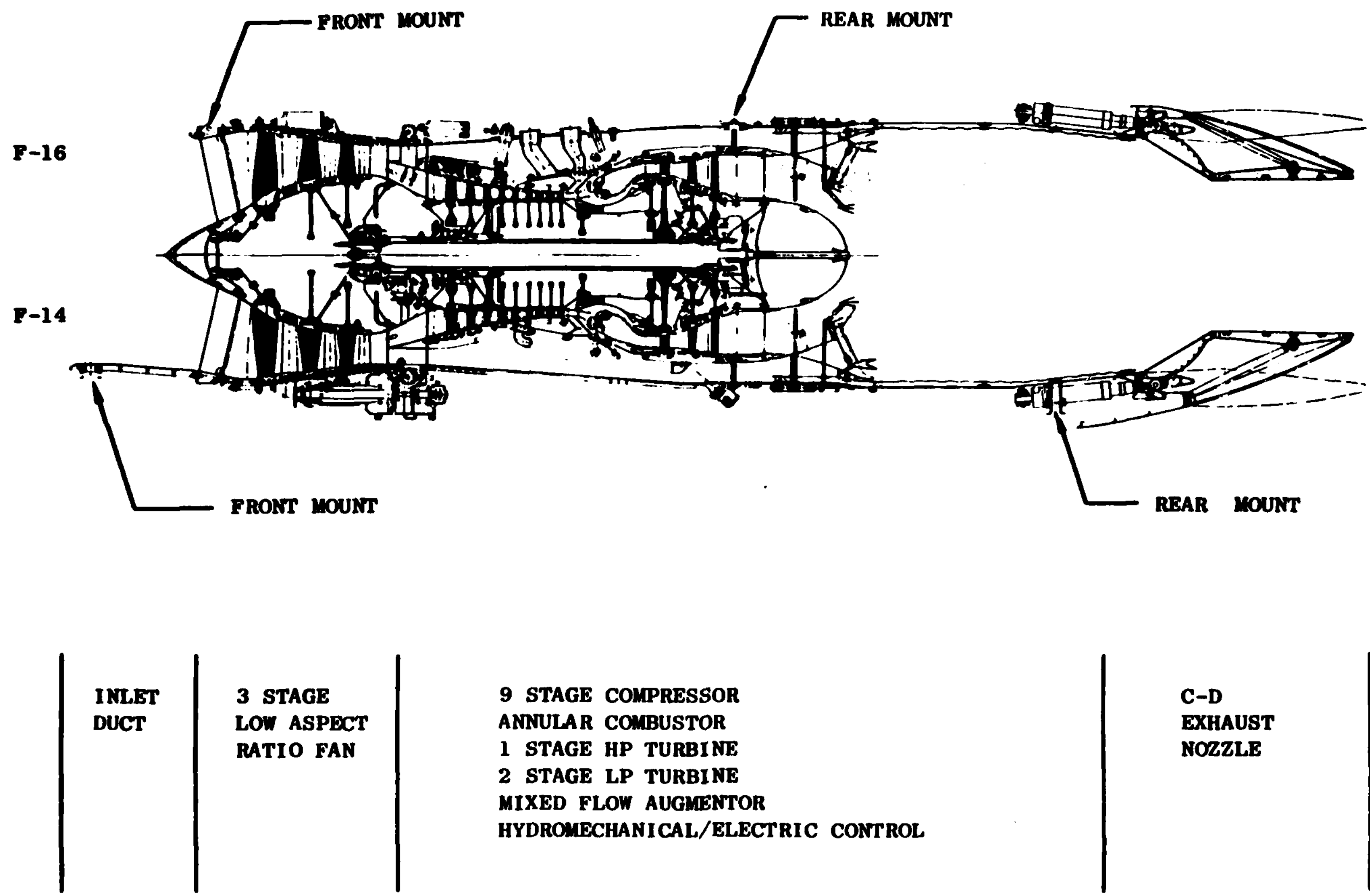


Figure 4-4. F101 DFE Engine Configuration.

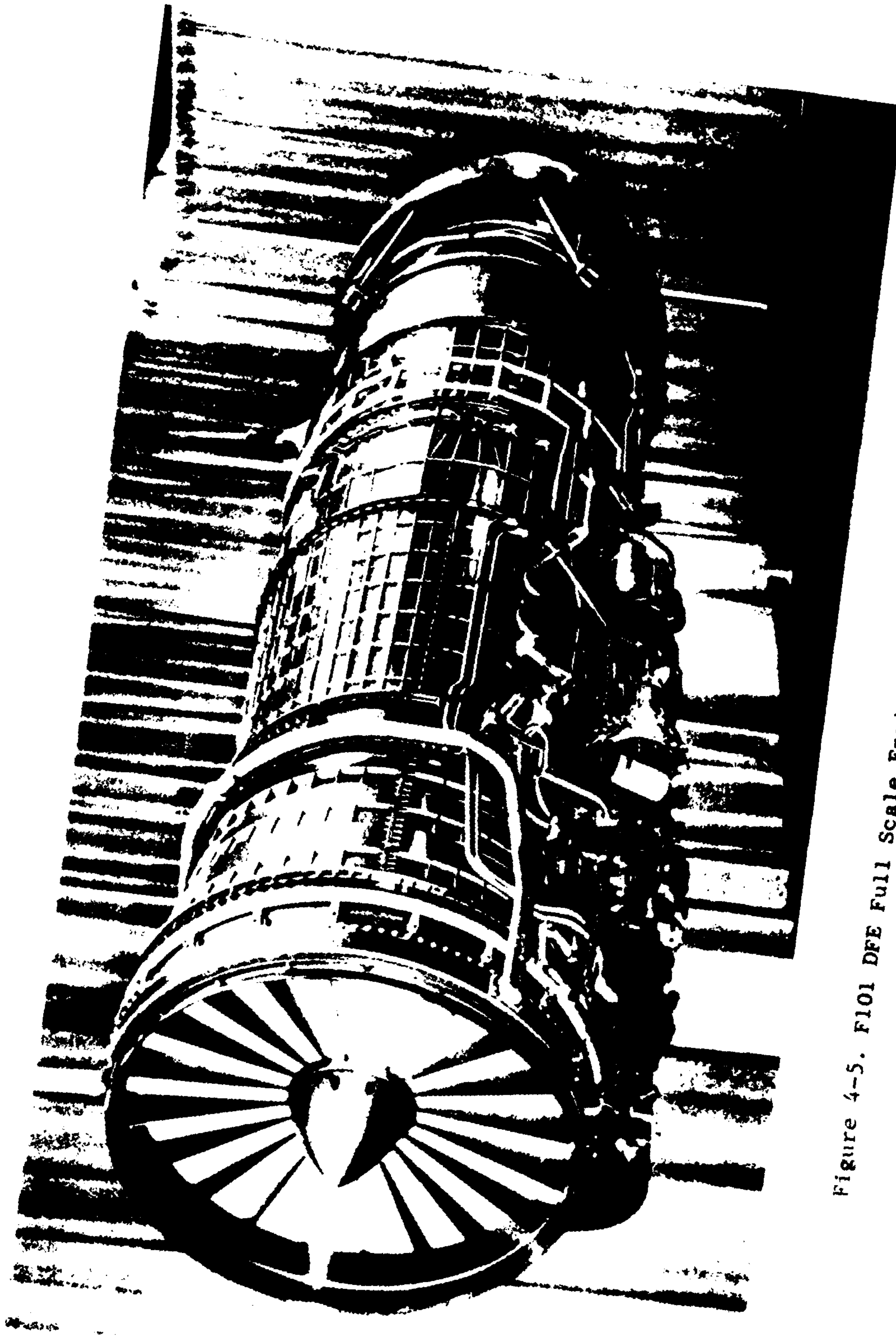


Figure 4-5. F101 DFE Full Scale Engine Model - Left Side

Cycle

The thermodyuamic cycle of the F101 DFE engine has been designed to provide low fuel consumption and a high level of augmented and non-augmented thrust. The nominal cycle design parameters at the sea level static, standard day are as follows:

Fan Corrected Airflow - lb/sec	254
Fan Pressure Ratio	3.10
Compressor Corrected Airflow - lb/sec	51
Compressor Pressure Ratio	9.1
Bypass Ratio	0.87
Turbine Inlet Temperature - °F	2500
Augmentor Final Burning Temperature - °F	3200

The F101 DFE engine configuration is based on F101 core turbomachinery and F101 technology for the LP turbine and augmentor. The fan and exhaust nozzle are based on F404 technology and the control system is F101. Within these requirements a fan airflow and thrust size were selected which meet the needs of current modern combat fighter aircraft.

Specific design choices made and some of the reasons were:

- Sizing of Fan - Optimum cycle performance is provided at an inlet temperature of about 100° F (hot day takeoff, sea level dash, M0.9/10Kft and M1.6/30Kft) at a corrected airflow of 245 to 250 lb/sec. Maximum corrected airflow of the fan is 270 lb/sec. This relative large fan size is capable of providing a thrust increase of up to 20 percent for a growth engine without a change in the external dimensions of the engine.

- Bypass Ratio and Fan Pressure Ratio - The gas horsepower capability of the present F101 core engine established the mixed-flow cycle at a bypass ratio of 0.87 and fan pressure ratio of 3.1 at Sea Level Static conditions. The F101 DFE core gas horsepower requirements do not exceed those of the F101-GE-100. Also the turbine temperature limit is the same as the F101-GE-100.

- Augmentation Ratio - Thrust agumentation ratio is 1.67 at takeoff and increases with increasing flight Mach number. The augmentor discharge temperature of 3200° F is the same as the F101-GE-100. Ample cooling air (fan discharge) is provided for cooling of the exhaust system. In addition, the mixed-flow design provides a low temperature exhaust gas plume for a lower IR signature during non-augmented operation.

- Augmented and Cruise SFC - The F101 DFE components have high efficiencies and provide a high cycle pressure ratio. This gives an sfc which is significantly lower than other current combat fighter engines, which, in turn, can be used to extend the range capability of the aircraft, or reduce operating costs.

Engine Performance Data

Engine performance data from F101 DFE Computer Deck R79AEG570 (1979) was used in the studies performed. The data are for zero customer bleed and power extraction, MIL-5008C ram recovery, 1962 U.S. Standard Atmosphere.

Operating Limits

The F101 DFE has been designed to operate without power lever restriction in the flight envelope shown in Figure 4-6. Augmentation is available throughout the entire envelope. Idle power is established by the aircraft ECS pressure requirement for the supply of high pressure bleed air, a minimum fuel flow of 300 lb/hr or idle rpm, whichever is the greater.

Thrust Response

The F101 DFE provides rapid thrust response to throttle changes. The expected response characteristics for throttle bursts from Idle to Intermediate are shown on Figure 4-7. The response characteristics for throttle chops from Intermediate to Idle are shown on Figure 4-8; in both figures the assumed starting idle thrust level is 5 percent of intermediate.

4.2.3 Engine/Aircraft Compatibility & Operability

The approach taken to engine inlet compatibility is the development of assured thrust stability at the highest stable airflow of the inlet. This achieves two objectives:

- Maximum installed thrust capability
- Airflow is constant at inlet temperatures below 90° F for the F-16. Thus, operation at lower temperatures is at a reduced turbine temperature providing enhanced engine life.

The features of the F101 DFE engine which facilitate the tailoring of this engine to a fighter inlet and operational scenario are:

- The low internal surge margin consumption of the engine when performing transient throttle operations.
- Low distortion sensitivity of the fan and compressor units of the engine.
- Aerodynamic independence of fan and compressor operation.
- Use of the F101 DFE gas generator and control system which are the same as those employed in the F101 engine which has demonstrated exceptional stability characteristics in the B-1 aircraft.

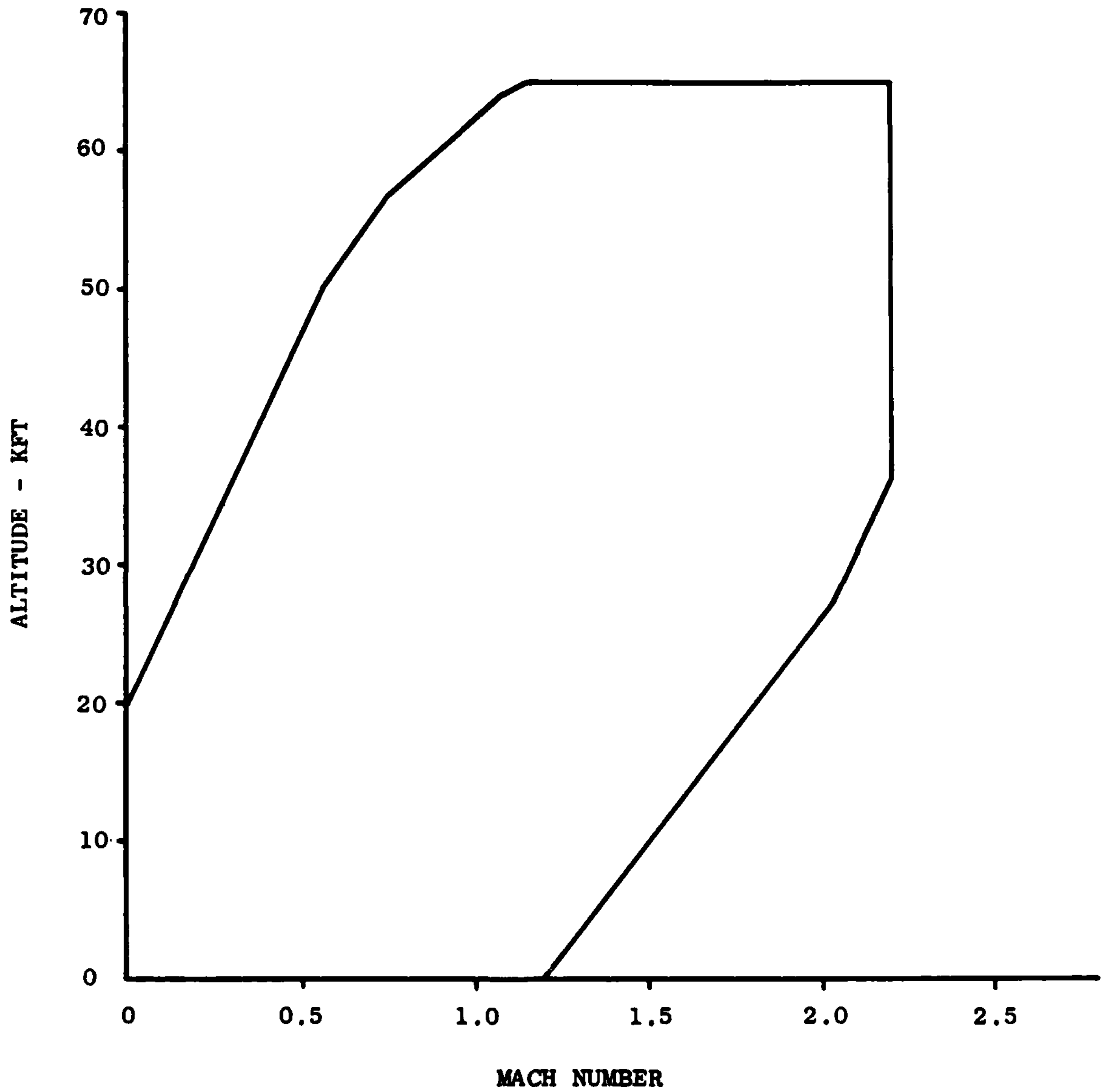


Figure 4-6. F101 DFE Standard Day Flight Envelope.

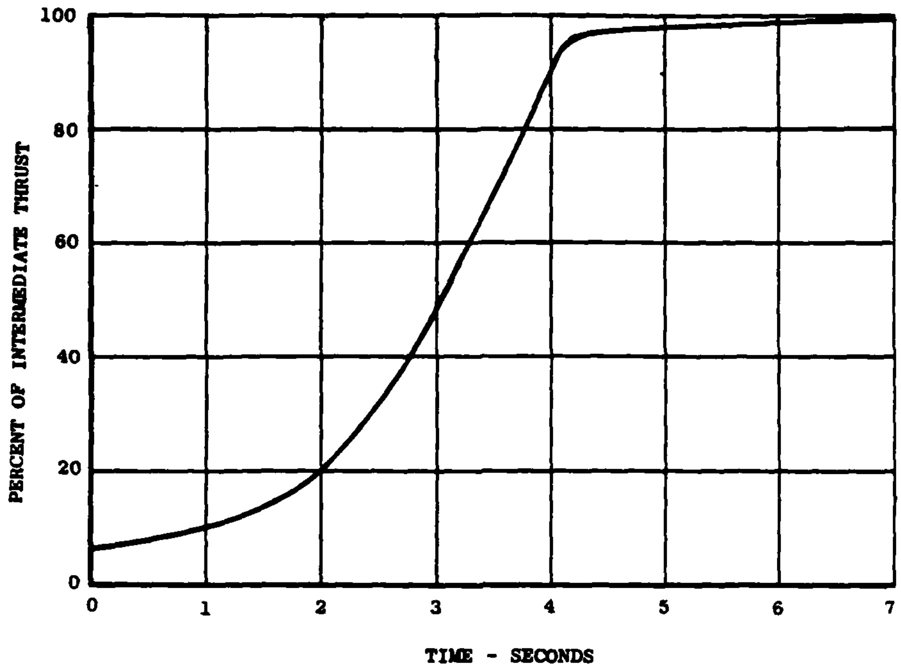


Figure 4-7. Acceleration Thrust Response, Idle to Intermediate at Sea Level

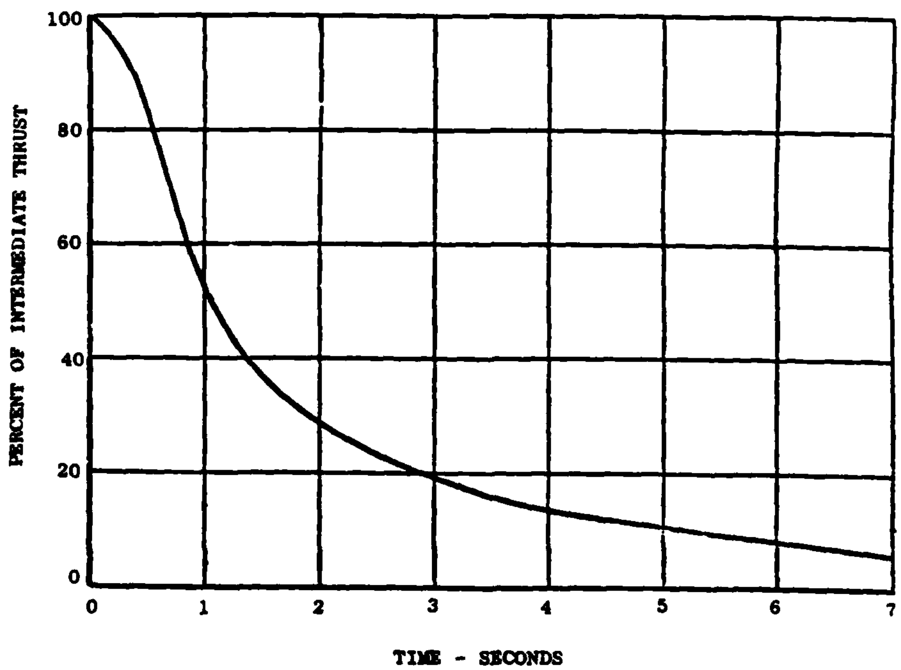


Figure 4-8. Deceleration Thrust Response, Intermediate to Idle at Sea Level

Inlet/Engine Stability Matching

The dynamic distortion data obtained during the 0.15 scale F-16 model inlet test was used to match the F101 DFE engine airflow with the inlet characteristics to provide stable propulsion system operation over the flight envelope.

The following procedure was employed for performing this stability matching. The inlet data was scanned at each Mach number condition to identify the attitude (α, β) which resulted in the most severe dynamic distortions within the aircraft control envelope. Using the adverse stack-up procedures, fan/compressor surge margins available for inlet distortion were identified and converted into allowable dynamic distortion levels via the F101 DFE distortion methodology. This yielded the maximum engine airflow for stable inlet/engine operation with unrestricted throttle transients. A 3 percent flow tolerance was applied to determine the scheduled engine flow. The results of this assessment are presented in Figure 4-9. The nominal engine airflows required for stable F101 DFE/F-16 system operation are compared to the initial airflow schedule for the F101 DFE. As indicated, flow limiting is needed in the Mach 0 to 0.5 range for the most severe maneuver attitudes, no cutback being required for cruise attitudes except at static conditions. The F101 DFE control system performs this flow limiting function using an available signal from the F-16 aircraft. For flight Mach numbers above 0.5 or T2's above 90° F the engine corrected airflow is not cutback because the engine is not limited by the F-16 inlet duct.

Performance shown in Figure 4-9 reflects the engine flow limits. The effect of flow limiting on max A/B thrust at SLS condition is presented in Figure 4-10 using measured F-16 inlet ram recoveries. The 3.5 percent lower flow reduces standard day thrust by 2.2 percent. Increased inlet ram recovery at the reduced flow levels partially offsets the performance loss caused by the flow limiting. SLS hot day thrust is not affected by the flow cutback as the hot day corrected airflow at intermediate to max A/B power is the same for initial and matched airflow schedules.

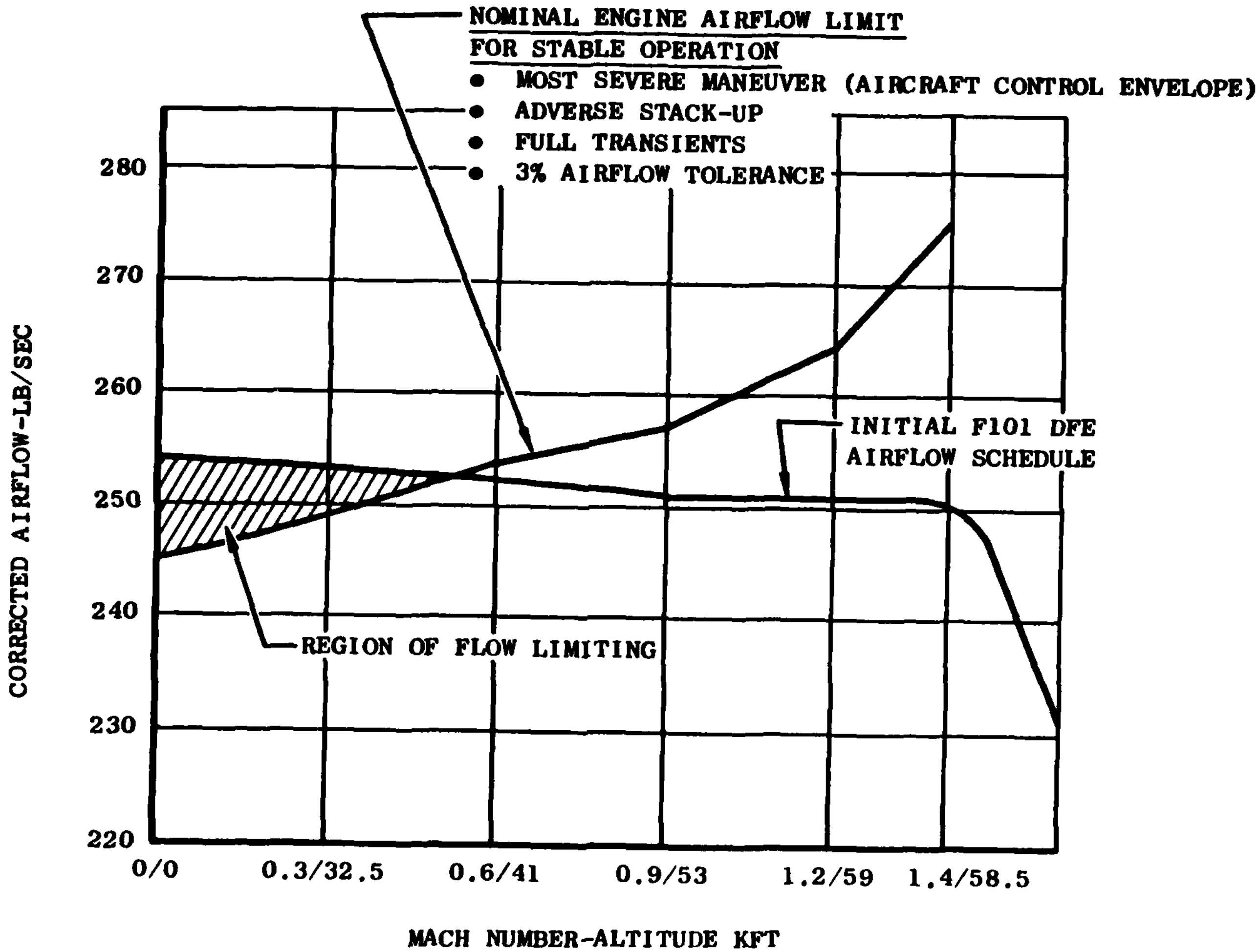


Figure 4-9. **F-16 Inlet/Engine Stability Matching.**

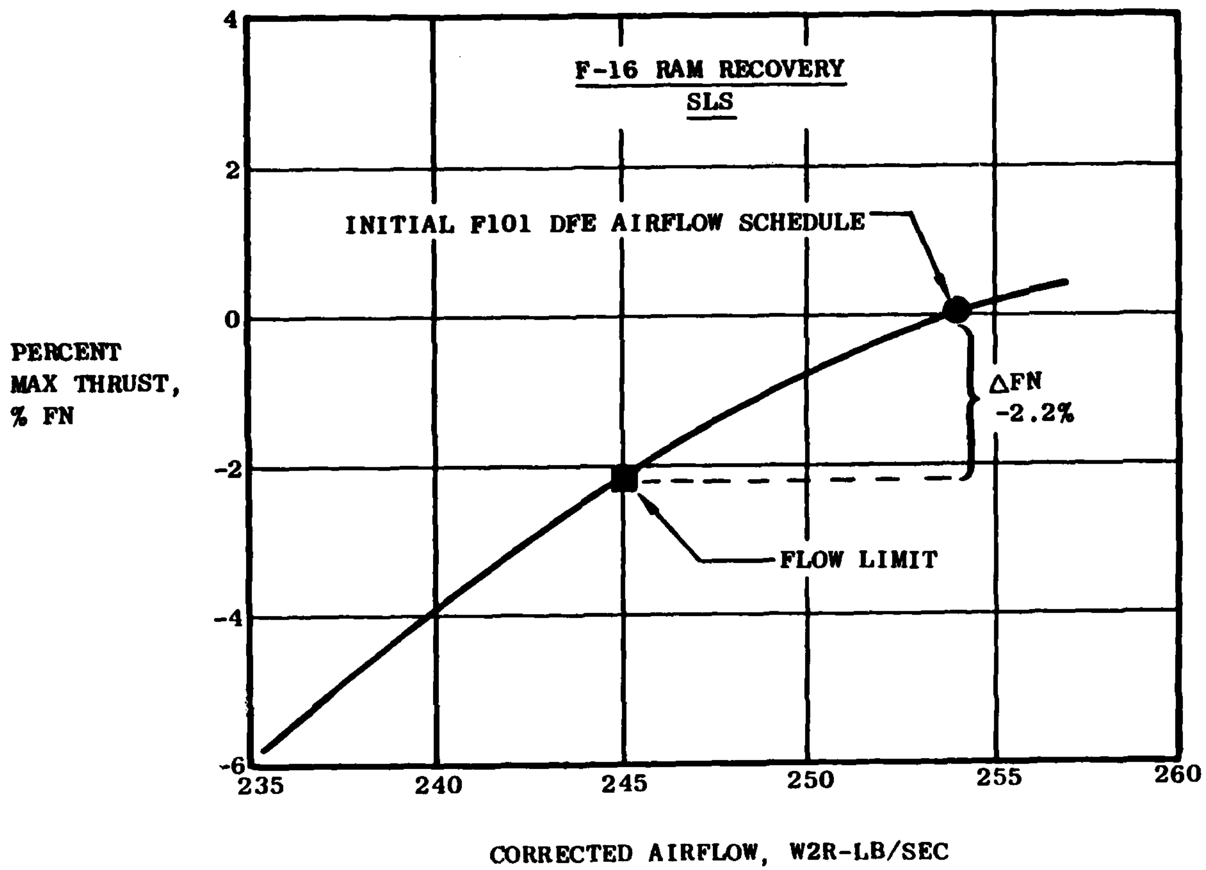


Figure 4-10. Effect of Airflow Limiting on Max A/B Thrust.

Increased Stability Margin Mode (ISM)

Examination of the 0.15 scale F-16 model inlet data indicated that at extreme conditions of angle of attack and yaw very high distortion levels could be encountered. This is shown in Figure 4-11. These conditions are outside the normal controlled maneuver envelope but could be encountered during aircraft departures. Stable system operation under these extreme conditions has been assured by incorporating an increased stability margin mode into the F101 DFE control system. This mode is actuated using an angle of attack signal from the aircraft computer. The triggering logic in the AFT control selects the increased stability margin mode when the α-signal exceeds a specified limit. Reset to the normal operating mode occurs when α drops below a specified level. The ISM mode is not activated if T2 exceeds 100°F. The normal engine operating mode will be selected in case of an α-signal loss.

During operation in the ISM mode the control system is reset to:

- Reduce engine flow by a cutback in fan speed
- Increase fan stall margin by opening the nozzle
- Reduce A/B to min. if power lever is above min.

4.2.4 Controls

The electro-hydromechanical control system, with the exception of minor refinements and physical configuration is identical to the system used on the F101 DFE demonstrator, and the similar F101 system. The system has demonstrated several capabilities.

- Engine control within budgeted stall margin consumption at all flight conditions.
- Rapid thrust transients.
- Automatic Self-trim
- Reliability and safety in the B-1 application.
- Predictable performance.

For the single engine F-16 application the F101/F101 DFE demonstrator system has been modified as follows:

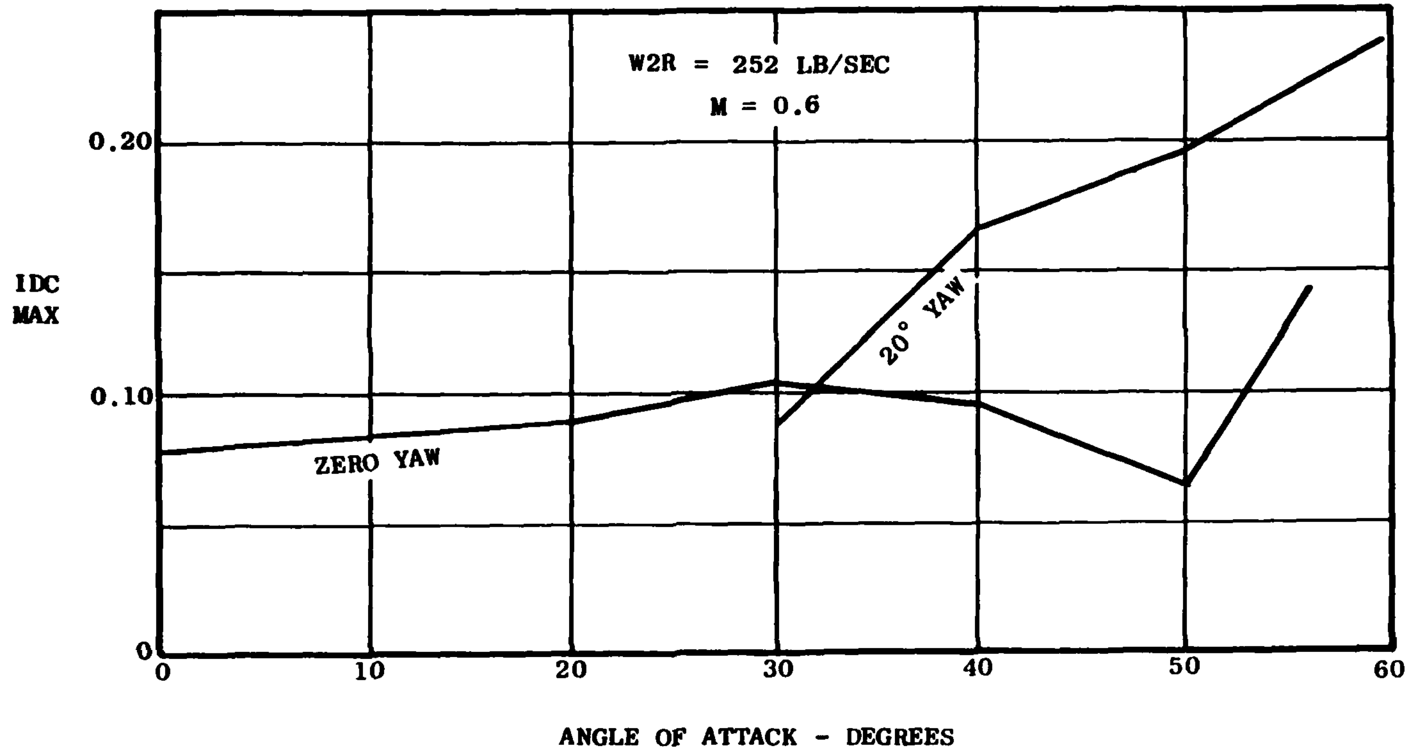


Figure 4-11. Effect of Angle of Attack on Inlet Distortion Level.

- Emergency control has been added to provide a capability to operate the engine over the complete thrust range with failures of the hydromechanical main fuel control.
- An electronic override switch is provided which turns off the electronics and allows near full dry power by operation on the hydromechanical main control.
- The fixed displacement vane type fuel pump used in both F101 and F404 engines has been replaced by a single element fixed displacement gear pump using rotating elements similar to CF6 and TF30 pumps.
- A redundant hydromechanical T25 sensor has been added to the control to provide back-up to this sensor.

The control system is a combination of electrical and hydromechanical which exploits the best features of each for simple reliable operation using demonstrated technology and drawing extensively on the F101 experience.

The control system provides for automatic engine operation at all power settings throughout the flight map. A single power lever input provides essentially linear thrust variation between idle and maximum power level. The system positions engine variable geometry and schedules main and augmentor fuel flows to provide stall free engine operation and to keep within safe limits for any rate of power lever movements. A feature of the control system is the elimination of engine trimming procedures following installation, engine component changes or a major control replacement. Any control can be replaced in the field and provide proper engine operation without the necessity of engine operation for trim purposes. This technique has been proven on the F101/B-1 and F404/F18 programs.

4.2.5 Durability/Life Predictions

The primary factor contributing to the low predicted Life Cycle Cost of the DFE engine is durability. Based on performance demonstrated in the F101 program for the core, the F101 DFE demonstrator program for the LP system and most recently (Dec. '79) for the complete flight engine 509-003, the F101 DFE engine performance has been quoted conservatively. Thus, demonstration of full mission durability is the only major task remaining in the engine development program and is its major objective.

For the engine design, durability requirements are defined by:

- Actual usage derived from flight test data and expected missions, and providing number and type of transients, power settings and inlet conditions (P1, T1).
- Life, by the number of missions required.

For the F101 DFE engine, baseline design requirements have been established as follows:

- Cold parts life - 4000 hours
- Hot parts life - 2000 hours
- Mission usage - from F-14, F-15 and F-16 mission data

This mission usage data, as well as B1 mission usage, has been used to define accelerated mission tests: AMT II and AMT IV. These tests were used in the development testing of the F101 engine (and hence the core for the F101 DFE). The AMT IV test will continue to be used in the current and planned development phases of the F101 DFE.

While the expected mission is used as a base for design of an accelerated mission test, it is of importance that the mission and the test cycle are as closely related as possible to minimize errors in the translation of life demonstrated in the test cycle into available mission life.

Since the eventual mission usage of the engine/aircraft system is not always predictable, an assessment of engine life for a variety of missions is required; this assessment is made possible by the use of the OPSEV Program (Operational Severity) which has been used to "translate" the durability data obtained from AMT testing to specified mission usage.

The overall approach, to assuring that the engine has the durability characteristics required to meet the needs of advanced fighters, is:

- Sound design basis by using demonstrated technology levels
- Early durability tests simulating planned use
- Redesign of parts to meet life requirements, as required

The F101 DFE engine design has, therefore, been based on F101 and F404 technology. Development and flight test results from these programs in addition to the F101 DFE program can analytically be related to the severity of any fighter mission to determine the F101 DFE life capability.

Most durability problems in fighter type missions, which are characterized by a high cyclic content, are associated with the hot section. Hence, the low risk approach to long life is through the use of a developed hot section that has been tested to requirements similar to those for the planned fighter application (AMT III, AMT IV). This objective was accomplished by selecting:

- Core - F101
- LPT Turbine - scaled F101
- Augmentor - scaled F101

In addition, the remaining components are based on similar designs which have been exposed to cyclic and steady state endurance tests:

- Nozzle - scaled F404 and simplified F101 and J79
- Fan - scaled F404
- Controls and Accessories - F101 - TF34 - CF6

This approach provides a head start for development and a balance between new hardware and overall risk.

Status and Projection

The design of the F101 DFE engine meets the life requirements for the F-16 aircraft. The life requirements for the component designs include operating at extremes, off-schedule engine operation and maneuvers.

Durability of the engine components is essential in meeting life objectives, low maintenance requirements and low operating costs.

The accelerated mission testing performed on the F101-GE-100 engines provides a significant data base and lends credibility to the life projections of the F101 DFE core engine. In addition, the tests conducted on the F101 DFE demonstrator engines provide considerable insight into the durability of the fan hardware. Table 4-I summarizes the status and projected durability/life of selected hot section components.

The testing conducted on engine 470-022 containing F101 DFE hot section components (combustor, HPT nozzle, HPT shrouds, HPT blades and dual core fuel nozzles) has provided durability test experience for assessment of these components. The F101 DFE low pressure turbine design is based on the F101 engine and incorporates life improvements. Analytical predictions and F101 engine test experience provide a basis for durability predictions.

Table 4-I. F101 DFE Hot Section Component B Life Predictions.

Component	STATUS			1983 PROJECTION		
	No. of AMT IV Cycles	F-16 Flight Hrs.	F-16 Mission Hrs.	No. of AMT IV Cycles	F-16 Flight Hrs.	F-16 Mission Hrs
HPT Shroud	1000	1490	2130	1415	2240	3200
HPT Blade	700	1110	1590	1400	2210	3160
HPT Nozzle	750	1120	1600	1180	1870	2670
Combustor	1000	1270	1820	1250	1650	2360
LPT Rotor Structural	----	----	----	3775	6990	7580
LPT Stage 1 Nozzle	----	----	----	2500	2770	3960
LPT Stage 1 Blade	----	----	----	1700	2970	4250
LPT Stage 2 Blade	----	----	----	2275	3973	5690
*Augmentor A/B Flameholder	----	----	----	1840	1720	2460
*Exhaust Nozzle Flaps & Seals	----	----	----	1245	1260	1800

Note: All numbers in the table are B10-values i. e. 10% not serviceable.

* Estimated life is based on previous experience and is judged to be conservative; it will be updated as more test data becomes available.

The exhaust nozzle and augmentor hardware have also been designed based on the F101 designs. Improvements in durability of the nozzle components have been incorporated on the F101 DFE designs by the addition of wear coatings and utilizing replaceable pivots and hinges in critical areas.

The F101 DFE core compressor is the same as the F101 engine and CFM56 engines. The extensive cumulative amount of testing that has been accomplished on the F101 and CFM56 engines coupled with analysis substantiates the ruggedness and durability of the compressor design.

F101 DFE demonstrator engine testing has accumulated 460 test hours and the fan durability demonstrated by the F404 engine has been impressive. Life calculations of the F101 DFE fan have been performed. It is anticipated that the durability and life objectives for the fan will be exceeded.

In summary, the durability assessment of the F101 DFE components is based on analytical evaluation, test experience of similar designs, and for many components actual engine test experience. The Phase I Development Program emphasizes durability and operability testing and will provide the needed test experience to demonstrate durability of the components and define areas requiring improvement.

Methodology

The Operational Severity Computer Model (OPSEV) has been used in forecasting the relative effects per operating hours on engine/component life of the differences between any two sets of engine installed thrust profiles. The OPSEV model outputs are the predicted effects of a "new" mission, calculated by scaling of the operational effects of a known "baseline" mission. This basic OPSEV output is termed the "severity ratio", which is defined as the engine/component maintenance event rate (failure rate fraction) for the "new" mission divided by the engine/component maintenance event rate of the known "baseline" mission.

The OPSEV model calculates the failure rate fractions for 25 components, including selected modules and Line Replaceable Units (LRU's), based on the controlling variables of component operating conditions such as pressure, temperature, stress, strain, and strain rate. The mix of the six original design missions of the B-1/F101 proposal was established within the OPSEV model as the "baseline" mission, and empirically derived severity ratios for each component have been established. The total failure rate fractions are comprised of both steady state and cyclic portions. Cyclic parameters are rotor speed, pressure and temperature.

The AMT III and AMT IV test cycles and the current F-14/F-16 missions have been evaluated by the OPSEV model. The results show that the AMT cycles are 2.5 to 8 times more severe than the "baseline" mission depending on the particular component being evaluated. Normally, an AMT cycle should have an increase in its severity relative to the mission as a function of the degree of acceleration achieved by the test cycle.

Planned Usage

The F101 DFE life characteristics have been evaluated using the USN seven peacetime missions mix of the F-14A aircraft as its usage base. This base was developed from the USN peacetime scenario and F-14A flight data supplied by the USN. Similar data on the F-16 aircraft will be analyzed, when available, to identify any life limiting differences between these applications of the F101 DFE.

The seven missions of the F-14A mix were analyzed in terms of their steady state and transient characteristics. The mission mix steady state characteristics were then summarized as functions of flight Mach number, altitude and time for various power settings. The F101 DFE cycle deck was subsequently run to provide temperatures, pressures and rotor speeds for evaluation of parts life and to aid in establishing design criteria.

For the F-16 and F-15 missions the principal throttle positions with superimposed transients have been used. These missions were received from the USAF in May 1979 and are composed as follows:

- F-16 - 2000 mission hour mix
  - 95 test stand cycles
  - 409 air-to-surface missions
  - 431 air combat missions
  - 60 post maintenance check flights
- F-15 - 2000 mission hour mix
  - 95 test stand cycles
  - 861 subsonic missions
  - 87 low altitude missions
  - 40 post maintenance check flights

Table 4-II summarizes the three missions. This summary indicates that the F-14 missions consume more available life compared to other less severe missions. As further mission data becomes available, from flight test and/or real usage, continued analysis is planned to evaluate the severity and also to update component life predictions based on those inputs.

Accelerated Mission Testing

The principal results of the F101 Continued Engineering Development Program (CED), that are directly transferable to the F101 DFE, comprise the extensive endurance testing in the form of Accelerated Mission Test Cycles (AMT III, See Figure 4-12 and AMT IV, See Figure 4-13).

The AMT III test cycle was designed to simulate the B-1 SAC training mission based on:

- SAC training mission as defined by the B-1 SPO, in terms of altitude, Mach number, duration and power setting for the various legs in the mission.
- Superimposed upon this mission are engine throttle transients actually experienced during the B-1 flight test program for selected legs of the training mission.

The AMT IV test cycle (Figure 4-13) is based on the F-16 mission mix and includes simulation of three flight missions and two ground test cycles; also included is a single High Cycle Fatigue (HCF) cycle to demonstrate that no HCF problem exists in the engine. The test cycles are run in a specific sequence and at ambient inlet conditions with the exception of the low altitude cycle which is run at elevated inlet temperature and pressure.

A total of 542 cycles represents 1009 F-16 mission hours or 689 F-16 flight hours. Table 4-III shows a comparison of the severity of the F-14 and F-16 missions and AMT III or AMT IV test cycles.

Correlation of Data and Usage

Using the data and methods defined above, several parts of the F101 DFE in the F-14A mission environment were identified as being life limited and therefore significant contributors to engine life and consequently shop visit rate and maintenance cost. Data was gathered to assess the expected life of

Table 4-II. Comparison of Mission Mix Durability Parameters.

2,000 MISSIONS HOURS

Aircraft	F-14	F-16	F-15
No. of Flights	1144	995	1326
Mission time, hours	2000	2000	2000
Flight duration, hours	1.40	1.45	1.21
LCF cycles	1144	995	1326
FTC cycles	15878	12470	11448
TAC cycles	4828	3863	3857
TAMP hours	275	200	-
FTC cycles/flight	13.88	12.0	8.6
TAC cycles/flight	4.2	3.75	2.90

LCF = "start - intermediate - stop" cycle

FTC = "idle - intermediate - idle" cycle (includes LCF cycles)

TAC = LCF + 0.25 (FTC - LCF)

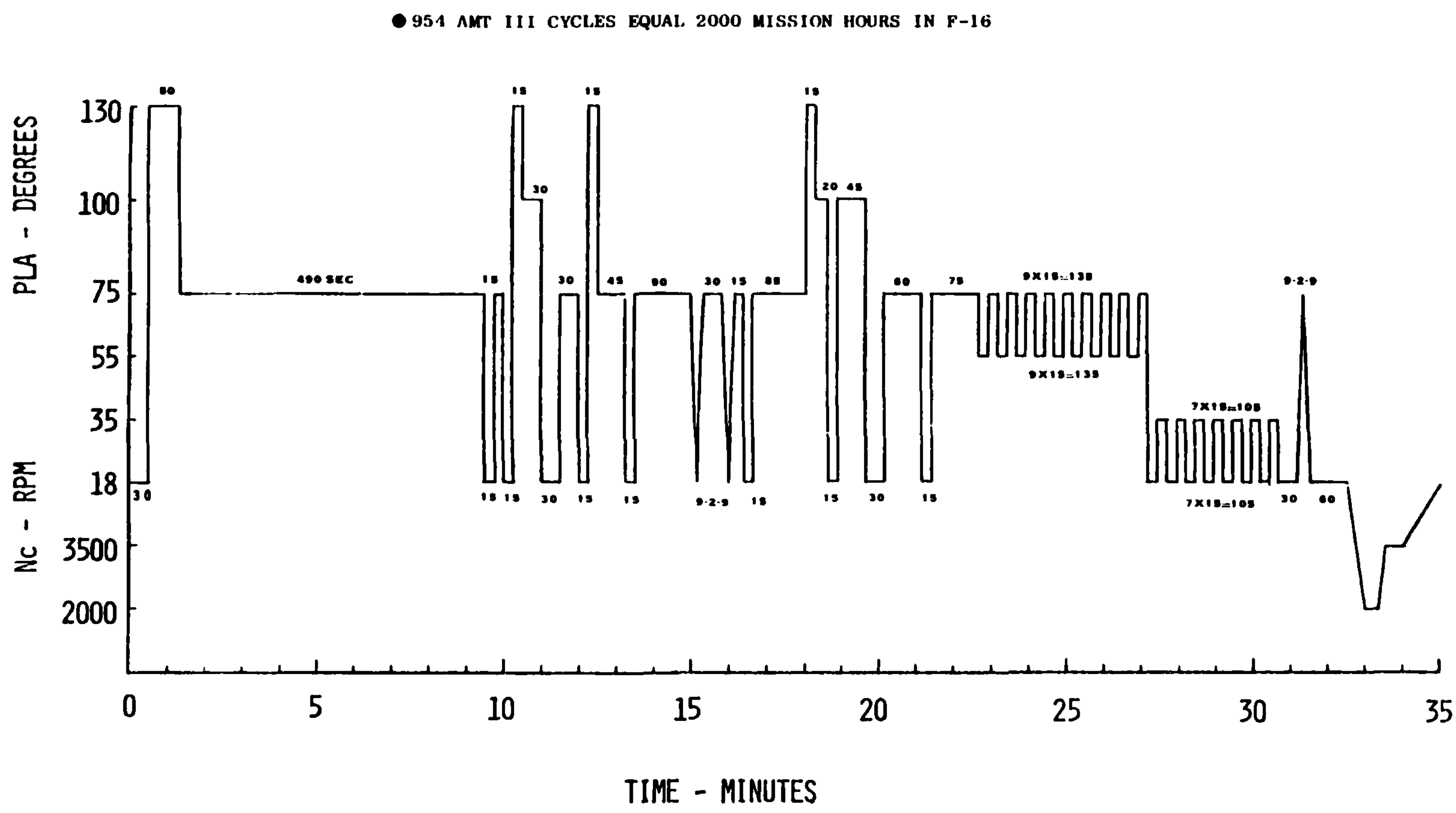


Figure 4-12. Accelerated Mission Test III.

• THE AMT IV CYCLE MIX SHOWN EQUALS 1009 MISSION HOURS ON F-16

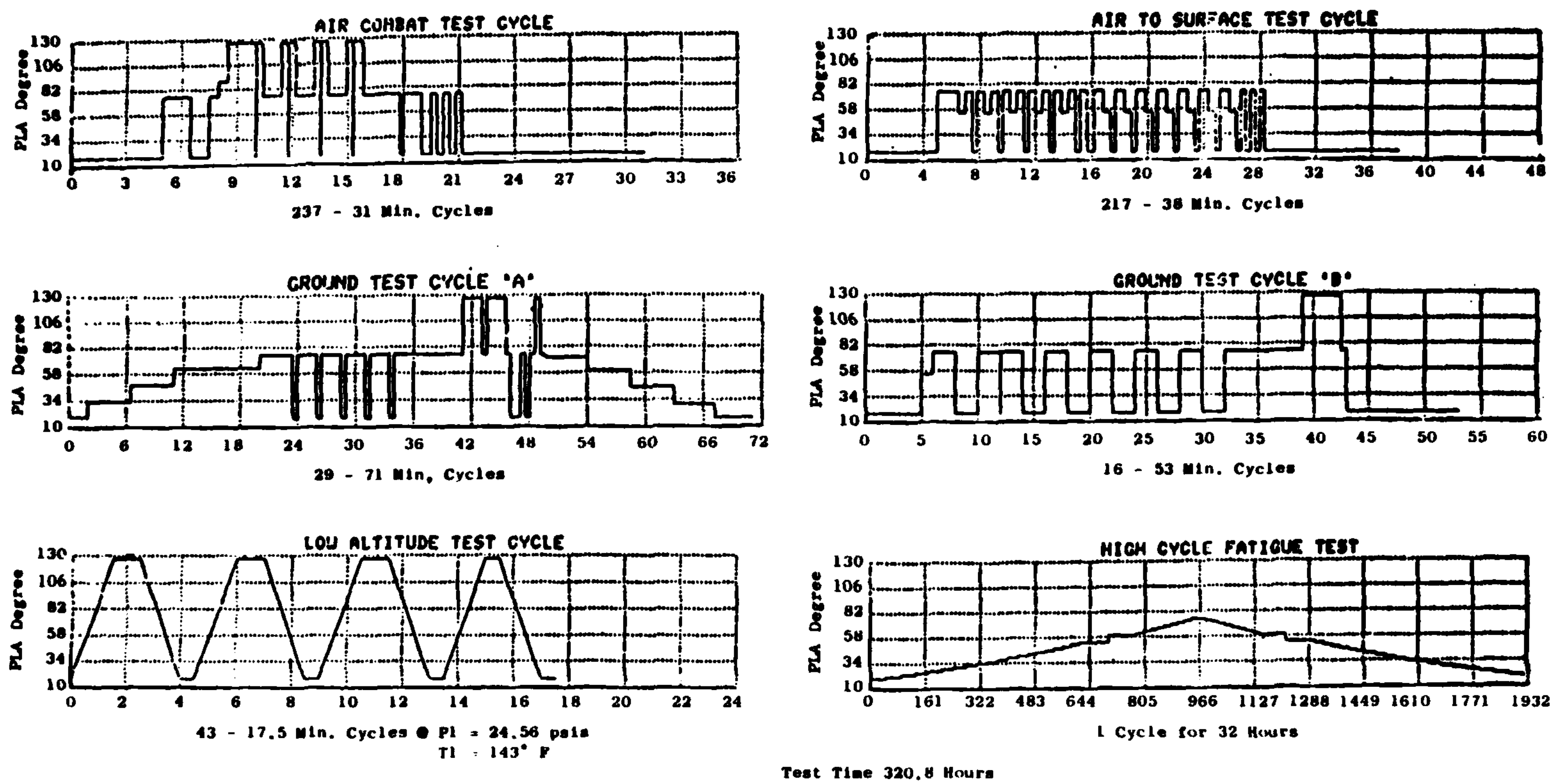


Figure 4-13. Accelerated Mission Test IV.

Table 4-III. F101 DFE Mission/AMT Summary.

	Design Cycle and F-14 Mission	F-16 Missions	AMT IV	AMT III
EMT (Equiv. Mission Hrs)	2000	2000	2018	2000
EMT Per Mission	1.75	2.01	1.86	2.10
No. of Missions	1144	995	1084	954
Total LCF	1144	995	1084	954
Total FTC (Includes LCF)	15878	12470	12768	12402
TAC Cycles	4828	3863	4007	3816
Total TAMP - Hrs.	275	199.7	237.4	333.9

these parts. Figure 4-14 is a sample for the HP turbine rotor blades, plotted as a Weibull curve on probability paper. It is shown that at 2600 hours, half of the blades would not yet have been removed for being beyond serviceable limits. Such characteristics are key inputs, to the calculation of component failure rates as a function of component age, for use in weapon systems operation and support calculations.

The failure distributions of the identified life limiting parts will be updated as the development program progresses and the factory and flight test data becomes available. These updated values will in turn be used in the Operation and Support Cost Analysis Program (OSCAP) to project in-service operating costs and maintenance spare parts requirements for the F101 DFE.

4.2.6 Life Cycle Cost

Life Cycle Cost (LCC) is defined by AF Regulation 800-11, "Life Cycle Cost Management Program" as "The total cost of an item or system over its full life. It includes the cost of acquisition, ownership (operation, maintenance, support, etc.), and, where applicable, disposal." Acquisition Cost is defined as "The cost of research, development, test, and evaluation (RDT&E), production or procurement of the end item, and the initial investments required to establish a product support capability (e.g., support equipment, initial spares, technical data, facilities, training, etc.)." Ownership Cost is defined as "The cost of operation, maintenance, and follow-on logistics support of the end item and its associated support systems. The terms 'ownership cost' and 'operating and support cost' are synonymous."

The engine sub-system contributes to aircraft system LCC with engine-oriented elements for engine RDT&E, engine acquisition cost, and engine product support costs. Each computation of a system or sub-system LCC requires establishment of a scenario including ground-rules for such items as: program timing, RDT&E completion, unit system (subsystem) cost, quantity of system (sub-system), annual flying hour and mission profiles, number of depots and bases, fuel and labor costs, etc.

The F101 DFE development program has concentrated on those elements which have the most significant influence on engine LCC - the cost drivers - and will thus provide a predictable engine contribution to system LCC for fighter aircraft programs and scenarios over their normal 15-20 year life. This section discusses the engine subsystem cost drivers, demonstrates methods of their computation and means for inclusion of the resultant data in any USAF-selected system LCC scenario.

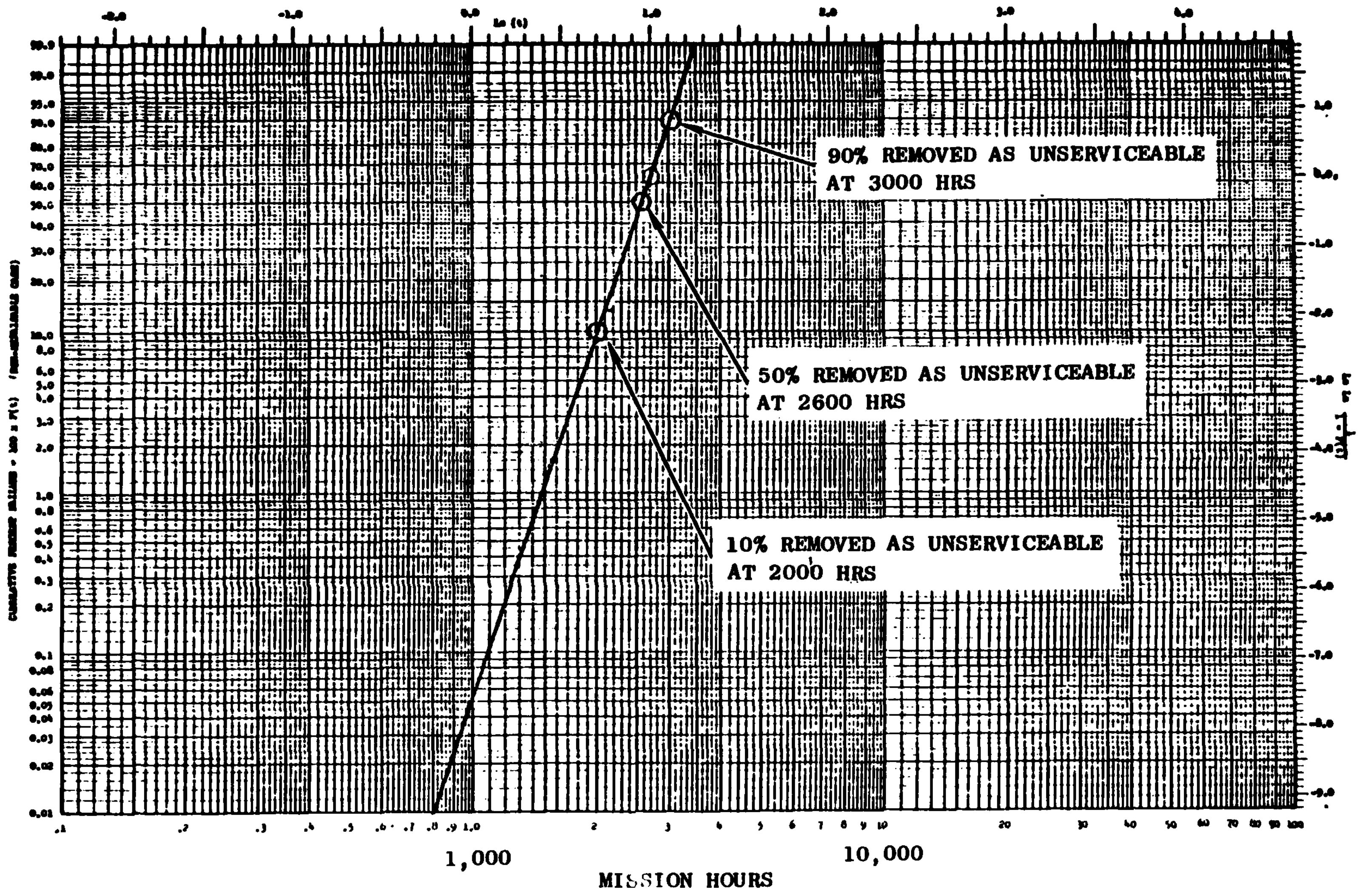


Figure 4-14. A Typical Weibull Distribution for HP Turbine Blades. (1979)

The total cost (LCC) of an engine over its full life includes several engine and engine-related elements. Specifically these are:

- <u>Engine Contractor</u>
  - Development, including test and evaluation
  - Installed/Spare Engines
  - Production Tooling
  - Training
  - Support Equipment
  - Program Management
  - Data
  - Spare and Repair Parts
  - CIP
- <u>Government and Weapon System Contractor</u>
  - Fuel
  - Personnel Training
  - Transportation
  - Mod Kits
  - Development Test Facility Operation (AEDC, Edwards)
  - Program Management
  - Maintenance Labor
  - Military Construction/Facilities
  - Engine Portion of Aircraft Flight Testing

Some of the above elements are performed/paid for by the Government or by the Weapon System Contractor and are generally not available to this Contractor, and, except for fuel, cannot be reasonably estimated for computation of "engine-related" LCC. In some program scenarios, the USAF has supplied additional specific elements (transportation, Government test facility costs) for specific program calculation. This discussion will not include such elements except where generally available.

Government data on the J79 engine shows that over 90 percent of the engine-related program cost is associated with 4 principal "cost drivers" (See Figure 4-15):

- Fuel
- Installed Engine/Spare Engines
- Maintenance Labor
- Spare/Repair Parts

Initial studies of F101 DFE program cost estimates indicate that the same 4 principal "cost drivers" are applicable. Accordingly, the discussion in this section is limited to those elements which comprise most of the costs forecasted to be incurred by the Procuring Service.

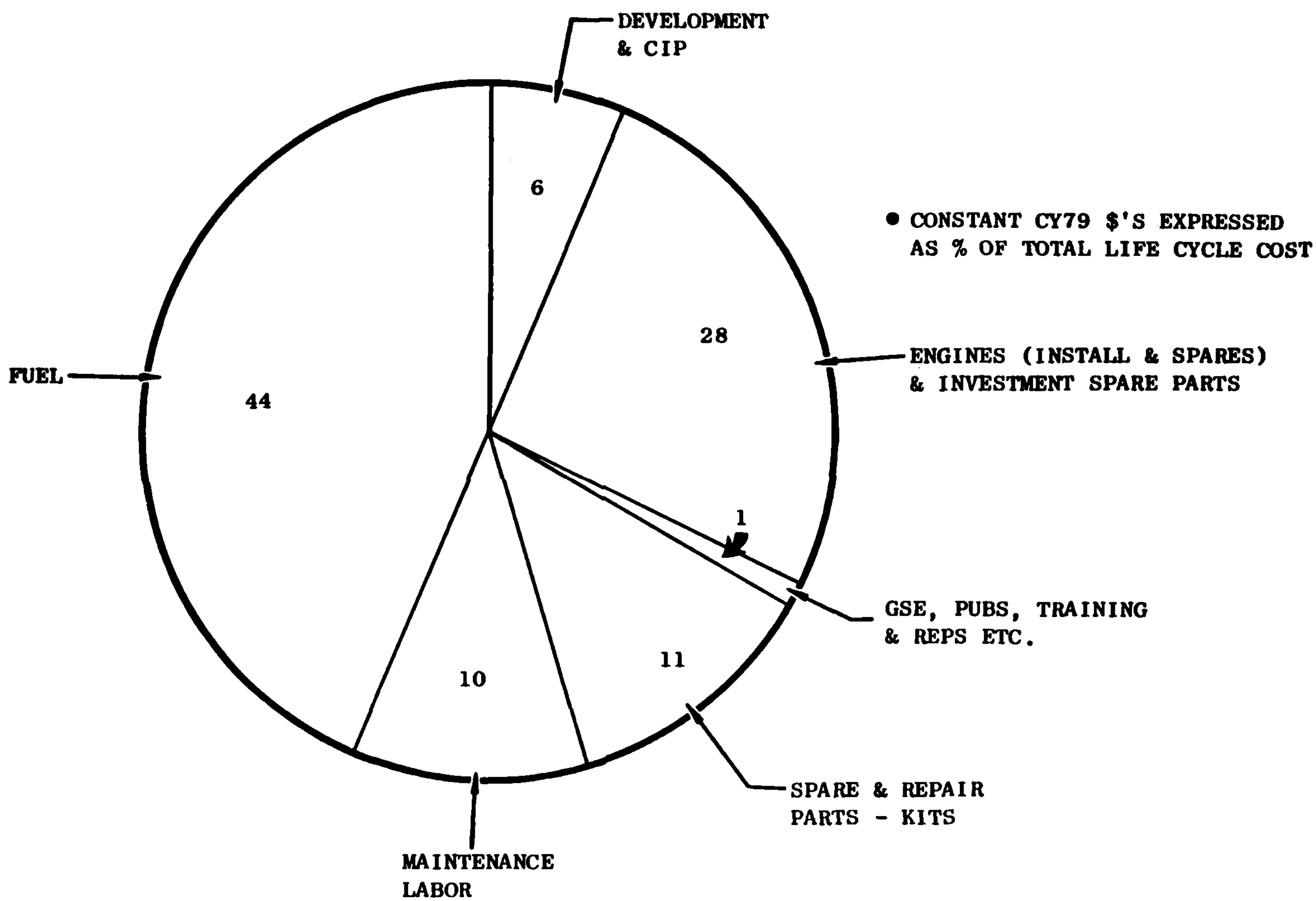


Figure 4-15. Life Cycle Cost For J79 Engine (1952-1980).

Measurements and Goals

Measurements - The Contractor's Military Engine Division (MED) has conducted research to examine the service record of all General Electric military engines and to express that record in terms of a series of common measurements which seem to have the most significance to operating costs, mission readiness, and successful mission completion. Each measurement was dissected into the principal hardware causes. The data provide a new and comprehensive perspective of the relative merits of MED's products, their trends, and the hardware components contributing to adverse cost and mission capability.

These measurements have resulted in a different design and development philosophy being applied to the F101 DFE:

- Simplicity, through advanced technology.
- Back-off from the "ultimate" technical performance.
- Achieve production performance before first flight.
- Prove early maturity before production.

The LCC goals for the F101 DFE complement and incorporate the Military Engine Division's results continually into planning and monitoring the F101 DFE Program. Identification of limiting hardware component life permits design and evaluation effort to be applied during full scale development to resolve such limitations.

Later, it is planned that these Goals and Measurements will be invaluable in planning and carrying out cost reduction programs, logistics forecasting, and CIP, as well as making projections for potential growth engines.

Goal Tracking - The measures and LCC goals will be tracked from the values shown in the next paragraph in accordance with the following status and update techniques.

- Maintenance-related Goals - since hardware failures or life-limited hardware are the principal causes of maintenance events, the Contractor's development efforts are concentrated on extra-severity testing to establish failure modes and life limits. Test data provide the component life information for use in the Operation and Support Cost Analysis Program (OSCAP) model. Tracking of these goals, will be carried out by periodic updating of the OSCAP input based on both factory experience and program scenario changes. The OSCAP output provides the basis for analysis of changes and impact of the Goals.

- Fuel Consumption Goal - the fuel consumption goal will be primarily influenced by the unit cost of fuel and the composite mission definition for the aircraft. When changes to these USAF-furnished inputs are provided, an update of the goal can occur.
- Production Unit Cost Goal - this goal can be tracked by periodic update of the estimated 250th unit cost. Such updates will include the effect of design changes, make/buy decisions, economic changes to labor and material costs, cost reduction programs, and co-production program changes. Concurrently, overall quantity changes resulting from customer installed engine schedule revisions, or spare engine requirements calculations can be factored into the impact of the baseline average unit cost.

Goals - Under the current Limited Development Program (Contract F33657-79-C-0176), the Contractor will submit engine total LCC dollar reports based upon scenario and program ground rules established by ASD/YZKA. SPO supplied schedules, composite mission, and relevant planning ground rules will be "priced" in accordance with Contractor estimates of RDT&E, Production and Operation and Support costs. The sum of these values for the period(s) to be specified will represent the projected total LCC for the F101 DFE operating in the F-16 Weapon System and can be compared by the USAF with the LCC of other engine alternates using the same scenario and ground rules.

The Contractor has prepared preliminary data based upon the SPO-furnished scenario and ground rules and developed one set of LCC goals at maturity for the F101 DFE which are shown in Table 4-IV below ($ values are expressed in CY 1979 $). These results have not yet been verified by ASD/YZ and subsequent changes in mission severity, duration, mix and production timing/concurrency will affect the precise value of the goals. Thus, the set shown below is included for reference purposes only. Additionally, for information and comparison, available Contractor data for the J79-17 engine is also shown.

Table 4-IV. Selected F101 DFE Goals.

	F101 DFE	J79-17
• Shop Visit Rate, per 1000 engine flight hours	<2	2.8
• Line Replaceable Unit Rate, per 1000 engine flight hours	1.4	5.0
• Maintenance Man Hours, per engine flight hours	1.9	3.4
• Parts Consumption Cost, per engine flight hour	$115	$97
• Mean Time Between Maintenance Actions, hours	175	74

LCC Goal Description - The Shop Visit Rate, Line Reparable Unit Rate, Maintenance Manhour Rate, and Parts Consumption Cost Rate goals measure the resources (manpower, money, facilities) required by the customer to maintain the fleet in a high state of readiness at affordable cost. The Mean Time Between Maintenance Actions goal measures the availability and operability of the engine.

These goals have been selected as some representative measures of the engine's overall reliability and durability, as well as "affordability." Each goal represents a key recurring "cost of ownership" parameter, and provides management visibility as to status toward achievement of commitments to the Customer. Further, these Goals provide both absolute and relative projections of the "cost of ownership", when converted to cost elements which can provide the basis for annual price projections over the period of ownership.

Significance of Selected Goals - Shop Visit Rate (SVR) is the most significant measure of total labor and material recurring maintenance cost. Obviously, when the engine stays "on the wing", costs are minimum. Whenever the engine goes to the Intermediate Maintenance Shop, the labor is significant to remove, part repair or subassembly replacement, test, and reinstall. Most engine removals generate component or subassembly returns to depot level for repair, thus incurring additional labor. Condemnation of reparable spare parts and the scrapping of expendable parts plus soft consumables occur during each shop visit. When the entire engine or individual modules go to depot level, cost to repair ranges from 10 percent of the cost of the engine, and up, depending on the range of repair required. RAND studies, commercial experience, and Air Force Logistics Command research indicate that the average shop visit costs 10 percent of the engine price.

LRU Removal Rate is primarily a measure of the reliability of controls and accessories, and secondarily, a measure of the amount of labor required for troubleshooting and removal/replacement at the flight line. Reliability of controls and accessories are, of course, a significant measure of the ability to perform assigned missions. Material costs to repair and depot labor are only significant on a few LRU's, such as fuel controls and other complex control components.

MMH Rates are a direct measure of cost. Base Level Maintenance manhour rates are important as they affect manning levels, which impacts training needs, recruitment, and retention; while depot manning does not suffer the retention problems of the uniformed branch, low and constant manhours leads to a stable, economical work load.

Parts Consumption Cost Rate is a direct reflection of the cost of maintenance, i.e., durability as well as reliability. It is of major importance, because excessive parts consumption diverts funds from primary mission accomplishment.

Mean Time Between Maintenance Actions (MTBMA), which includes both engine/LRU removals and the need for other corrective maintenance, is primarily a measure of the engine availability.

Example of SVR Goal Significance - The results of a General Electric study of Total Maintenance Cost (normalized to engine cost) and Shop Visit Rate (data source primarily USAF Actuarial Reports), including all engine returns to the intermediate or depot shop - scheduled and unscheduled - engine and non-engine caused - excluding only convenience scheduling, is plotted in Figure 4-16. Since the historical data is gathered from several sources with some timing and fund allocation differences, the plot should be interpreted as a trend line with a "band" of total maintenance costs on either side. This plot conclusively supports the premise that field experience shows engine maintenance cost is proportional to the number of times an engine is removed and sent to the maintenance shop.

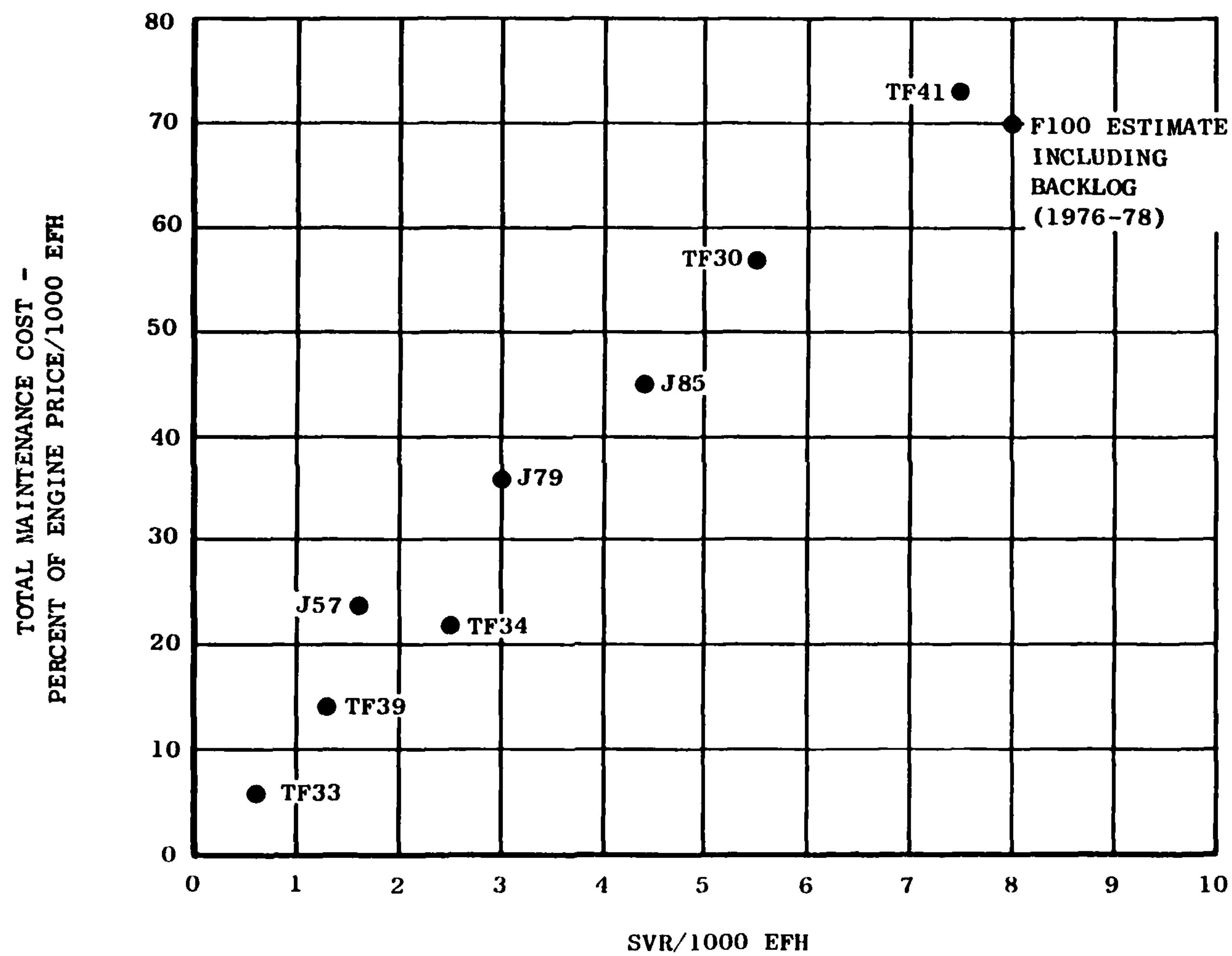


Figure 4-16. Engine Maintenance Cost vs. SVR. (Reference 3)

The component life distributions discussed in Section 6.0 are the foundation for the analysis of relative mission severity and the subsequent calculation of engine removal rates. The major emphasis in the F101 DFE program to determine component wearout phenomena is merited since total maintenance cost to the user is so heavily influenced by the engine removal rate (SVR).

Data Base

Establishment and tracking of the measures and LCC Goals requires the application of different methodology techniques for the Maintenance-related goals.

Maintenance Related Goals - Cost estimates for operation and support activities are best calculated with a mechanized model for ease in handling the large volume of data involved. The Contractor has developed a digital computer model called Operation and Support Cost Analysis Program (OSCAP) for application to O&S cost calculations. Figure 4-17 schematically shows the input/output data provided by OSCAP.

OSCAP/OPSEV Description - The General Electric Company has used a digital computer model called Operation and Support Cost Analysis Program (OSCAP) to generate the support cost forecasts for the F101 DFE engine. Along with OSCAP, another computer program called Operational Severity (OPSEV) is used to assess the relative severity of different types of engine operation (development test vs. aircraft mission mix, etc.), to generate input for the OSCAP program. The use of the OSCAP and OPSEV computer programs for the generation of O&S forecasts for the F101 DFE engine is shown in Figure 4-18.

OPSEV - The OPSEV program relates two or more types of engine power level versus time profiles and calculates, for the significant engine components, the expected failure rate ratio using one set of profiles as a base.

The program breaks the profile up into steady state and cyclic portions and through a set of stored modifier curves counts "equivalent" time of a reference power setting and "equivalent" numbers of reference cycles in each set of missions. From these data the component severities are determined.

The OPSEV computer program compares the relative severity of different types of engine operation, i.e., a set of planned aircraft missions vs. a set of factory test cycles/design requirements. The severity is defined as the ratio of failure rates, under stabilized conditions, of a fleet of engines operated to the power

INPUT

Scenario

- Aircraft delivery schedule
- Planned utilization - Flight hours per calendar interval per aircraft
- Base activation schedule
- Attrition rate
- Foreign object damage rate
- Scheduled maintenance inspections/servicing

Component Data

- Component life distributions (wearout) phenomena)
- Learning curve parameters ("K" values for random distress)
- Assembly/disassembly manhours
- Repair manhours
- Repair material

OUTPUT

- Shop Visit Rate
- Maintenance labor cost
- Maintenance material cost (consumed spares)
- Pipeline spares cost
- LRU rate
- MMH/EFH
- MTBMA

Figure 4-17. OSCAP Program Elements.

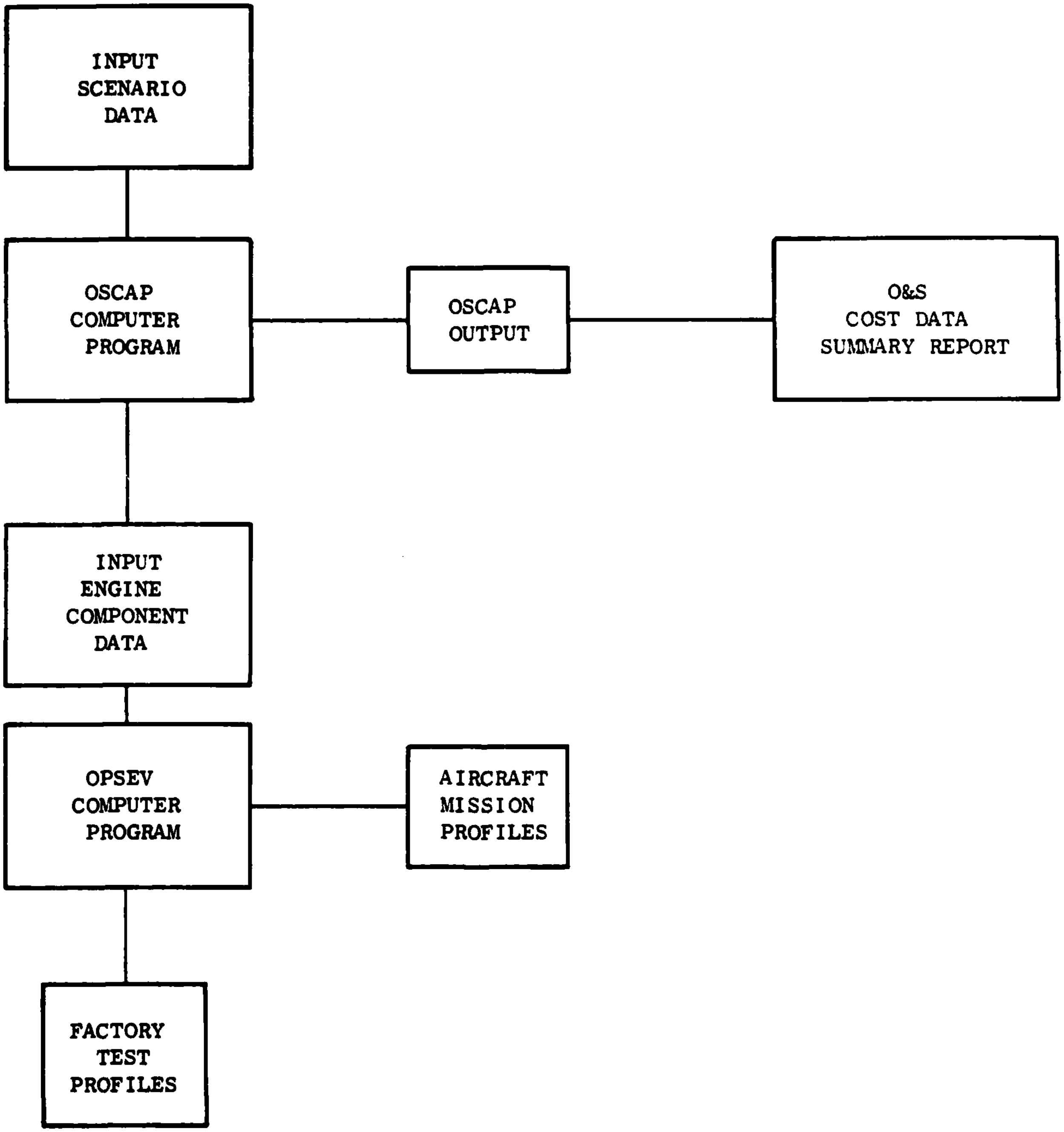


Figure 4-18. Computer Program Usage - O&S Cost Forecasting.

level profiles of the mission set vs. the base line cycle. The OPSEV program permits the relative assessment of various types of planned usage, and, therefore, can be employed to make trade studies away from the baseline due to changes in life distributions (wearout phenomena)[1], and learning curve parameters (random distress).

From the OPSEV program the expected engine removals and shop visits are projected. On the basis of probability theory, allowance is made for multiple components to be distressed with only one engine removal being counted. For instance the situation may occur where a combustor, HP turbine blades, and LP turbine blades, etc., may be simultaneously distressed "beyond operable limits" on the same engine and only one engine removal will occur for a defined primary cause.

An engine goes to the shop if the component assigned as the cause for removal can only be replaced in the shop. Once in the shop, the secondary damage is assessed and shop practice is applied to determine the components requiring secondary maintenance to be performed. The secondary maintenance may involve cleaning, inspection, scrapping or repairing of these components. When the secondary maintenance actions are defined, the last step is to accrue costs.

OSCAP - The OSCAP program input can be segregated into two major categories which are scenario data and engine component data. The key scenario data consist of:

- Aircraft delivery schedule.
- Planned utilization -- flight hours per calendar interval per aircraft.
- Base activation schedule.
- Attrition rate.
- Foreign object damage rate.
- Scheduled maintenance inspections/servicing.
- Etc.

---

[1]The fraction failed vs. component age is forecasted using Weibull techniques to provide input data. A typical Weibull plot is shown in Fibure 4-14, where percent of components failed is plotted against cumulative hours at failure. Initial analytical projections are periodically updated as engine test data results become available.

The key engine component data required for OSCAP includes:

- Component life distributions (wearout phenomena) for selected missions.
- Learning curve parameters ("K" values for random distress).
- Assembly/disassembly manhours.
- Repair manhours.
- Repair material.
- Shop turn times.
- etc.

For each primary and secondary maintenance action, the labor and material costs are accrued for assembly/disassembly, repair, test, etc. If a primary failure occurs on an LRU, then the cost for replacement is accrued in the unscheduled "on-wing" maintenance category. Also included in "on-wing" maintenance is all scheduled maintenance for routine periodic inspections and servicing.

Spare parts are calculated based upon demand and the shop turn times for a desired input fill rate. Spare costs are separated into two categories: the first is part of unscheduled material cost and represents the consumed spares; the second part is in the investment category and represents pipeline spares.

These data are assembled for a baseline set of aircraft missions and the OSCAP program will calculate for any number of years the expected O&S costs per year. Key costs outputs from the OSCAP program are:

- Shop Visit Rate.
- Maintenance Labor Cost.
- Maintenance Material Cost (consumed spares).
- Pipeline Spares Cost.
- Etc.

Data Base - The Contractor has established a data base of F101, CFM56 and F101 DFE engine experience, starting in 1970 with the initial core engine design. At the end of CY 1979, the data base was:

- 30,000 core test/flight hours.
- 1500 mission hours demonstrated on the hot section.
- 4000 mission hours demonstrated on the core disks.

- Fan and compressor stresses measured throughout the envelope.
- Engine stability demonstrated with screens.
- Augmentor operation demonstrated throughout the envelope.

This existing data base will be expanded through the remainder of the F101 DFE development program. Analysis of the testing to be conducted in the remainder of Phases I, IA and IB and that proposed to be added in Phase IC (including the optional F-15 flight test program) shows that the engine will enter product verification with:

- Core 35000 hours total.
- TAC cycles 40,000 total.
- Hot section 2000 mission hours.
- LPT disks 4000 mission hours.
- Operability demonstrated in F-16, F-14, F-15.

This data base is judged to be relevant in establishing both initial and mature LCC goals, status reports, and related tracking and analysis. The F101 DFE has already demonstrated durability characteristics normally associated with several years of post qualification-service.

5.0 ANALYTICAL TOOLS AND METHODOLOGY

This section describes the four computer models and the methodologies used in this program. The four computer models used were: The F-16 ADA aircraft performance model, the engine performance deck, the OPSEV (Operational Severity comparison program) and the OSCAP (Operation Support Cost Analysis Program).

5.1 F-16 ADA AIRCRAFT PERFORMANCE MODEL PROGRAM

The F-16 ADA aircraft performance model computer program is a parametric program capable of calculating climbs, cruise accels and maneuvers for variable aircraft weight. The program models the aircraft through a set of tables which include aircraft drag polars, C_L vs alpha, drag polar corrections for Reynolds No. effects and $C_{L\ max}$ as a function of Mach number. Engine cycle data is accessed from a table of previously created values which can be directly output from an engine cycle deck run. This allows any engine or cycle variation to be run by simply designating the appropriate cycle data file. The engine data can be adjusted for installation effects by taking installed thrust directly from the cycle deck or by using the aircraft tables in the program. These tables contain inlet recovery vs mass flow, angle of attack effect on recovery, inlet bleed vs Mach No., inlet spillage drag versus capture ratio and afterbody drag.

The only input required to run the program is the appropriate engine cycle data file as previously mentioned, the particular cycle data case numbers to be used, and the aircraft weights desired.

The output in Table 5-I is typical of that available from the program with the capability of running ten different aircraft weights in succession. Maneuver specific power curves are available and can also be computer plotted as shown in Figure 5-1. The program can also machine plot the climb, cruise and accel results with the use of supplemental programs.

This program is used for comparative performance in a mission segment like accel for changes in aircraft weight, engine cycle design or aircraft configuration. It cannot calculate an entire mission, takeoff to landing, but does calculate the individual segments that make up the total mission. The user must assimilate these mission segments together and do the iteration to

Table 5-I. Typical Aircraft Performance Model Output.

*****************CONSTANT MACH/ALT CRUISE*****************

MO	ALT	VT	WT
0.880	43000.0	851.887	24500.0

FNIN (LB)	SFCIN (LB/HR/LBF)	RF (NMI)	TCR (MIN)	DCR (NMI)	WFCR (LB)
2354.2	0.893	5883.20	0.	0.	0.
2348.3	0.893	5884.38	1.43	12.02	50.0
2342.5	0.893	5885.55	2.86	24.07	100.0
2336.6	0.894	5886.69	4.30	36.14	150.0
2330.8	0.894	5887.82	5.73	48.24	200.0
2325.0	0.894	5888.93	7.18	60.37	250.0
2319.1	0.894	5890.01	8.62	72.53	300.0
2313.3	0.894	5891.08	10.07	84.71	350.0
2307.4	0.895	5892.12	11.52	96.92	400.0
2301.6	0.895	5893.15	12.98	109.16	450.0
2295.8	0.895	5894.15	14.43	121.42	500.0

******************** CONSTANT MO CLIMB ********************

MAX ALT IS LESS THAN 45000.0

MACH= 0.900 WT= 30302.0

ALT (FT)	VT (FPS)	ROC (FPM)	TCLIMB (SEC)	DCLIMB (NMI)	WFCLIMB (LB)
0.	1004.78	8293.	0.	0.	0.
5000.0	987.36	12697.	29.90	4.822	94.7
10000.0	969.62	13603.	52.74	8.407	166.1
15000.0	951.56	12794.	75.40	11.893	231.9
20000.0	933.14	9913.	102.26	15.972	298.7
25000.0	914.36	7329.	137.85	21.317	369.5
30000.0	895.18	5041.	188.07	28.745	448.4
35000.0	875.58	2940.	268.84	40.478	547.7
40000.0	871.25	941.	479.28	70.702	750.0
45000.0	0.	0.	0.	0.	0.

********************** ACCELERATION **********************

ALT= 30000.0 WT= 23000.0

MO	FNIN (LB)	D (LB)	TACCEL (SEC)	DACCEL (NMI)	WFACCEL (LB)
0.900	12663.6	2538.7	0.	0.	0.
1.000	14326.9	5095.1	7.313	1.137	57.237
1.100	16291.8	7675.3	15.220	2.496	126.893
1.200	17333.6	9056.9	23.589	4.072	207.955
1.300	18113.9	10467.9	32.435	5.882	298.581
1.400	19257.4	11926.5	41.800	7.952	400.996
1.500	19800.6	13731.5	52.225	10.426	524.215
1.600	20247.7	15810.0	65.445	13.781	691.850

************************* MANEUVER *************************

ALT	MACH	WT
30000.	0.900	22000.0

G	ALPHA (DEG)	FNIN (LBS)	DRAG (LBS)	PS (FPS)	TR (DEG/SEC)	RAD (NMI)
1.00	2.32	12663.58	2454.00	415.00	0.	********
2.00	4.38	12663.58	3998.20	351.09	3.57	2.37
3.00	6.50	12663.58	6982.30	227.86	5.82	1.45
4.00	9.29	12663.58	12044.73	18.42	7.98	1.06
5.00	13.16	12663.58	20241.42	-321.87	10.09	0.84
6.00	17.74	12663.58	33440.31	-869.90	12.18	0.69
7.00	21.14	12663.58	51506.75	-1515.21	14.27	0.59
7.85	25.17	12642.28	69300.69	-2354.25	16.03	0.53
4.07	********	********	********	0.	8.13	1.04

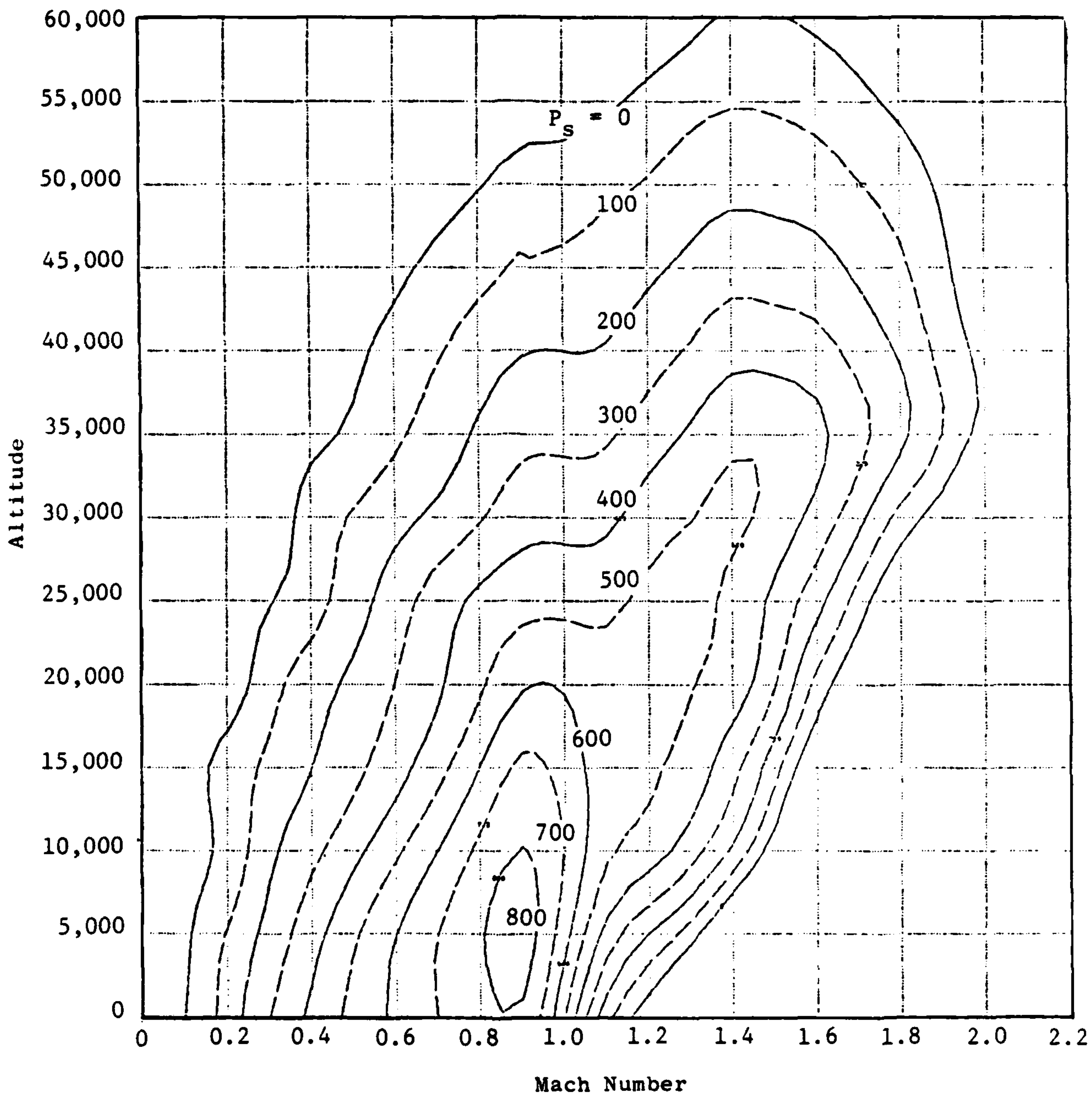


Figure 5-1. Typical Specific Power Curve from Aircraft Performance Program (1g).

construct the total mission. The program eliminates all the error laden interpolation and iteration required for each segment. This program makes it possible to accurately and rapidly evaluate the effect on total aircraft performance changes in engine cycle design as well as aircraft configuration.

5.2 F101 DFE CYCLE PERFORMANCE DECK

Engine cycle F-16/F101X-254/HAJ/F-16/MAP PGRF deck defines the steady state performance of the base F101 DFE in this study. The deck contains steady state component characteristics and steady state control schedules. It is capable of calculating inlet spillage drag. The deck required input data are: Flight point (Mach No. and altitude), power setting, ambient condition and power extractions (shaft horsepower and bleed). The deck output are thermodynamic data throughout the engine, thrust and specific fuel consumption.

5.3 OPERATIONAL SEVERITY ANALYSIS PROGRAM (OPSEV)

The Operating Severity Analysis Program (OPSEV) predicts the relative effect of various engine operating profiles on the failure rates of the major components of an engine. The cyclic and steady state portions of the failure rate of each major component (or component category) are related to the specific engine parameters that influence their failure characteristics, and tradeoff curves are used to predict the relative severity for each profile as seen by each component. The tradeoff curves are derived based on experience and general failure physics.

Figure 5-2 is a simplified flow diagram of the OPSEV program. The figure shows that both new mission and reference mission characteristics are input requirements. All new missions and the reference are subdivided into segments as shown in Figure 5-3 representing various thrust settings and transients occurring during the mission. The engine cycle parameters are obtained for each segment of each mission. The engine is divided into 25 major subassemblies. The parameters that affect each subassembly and the failure rate of each engine subassembly during each of the mission segments are determined analytically using the appropriate cycle parameters and material property characteristics for each subassembly. It should be noted that all major sections of the engine are considered and not just the hot section parts.

In calculating the individual failure rates, both cyclic and steady state

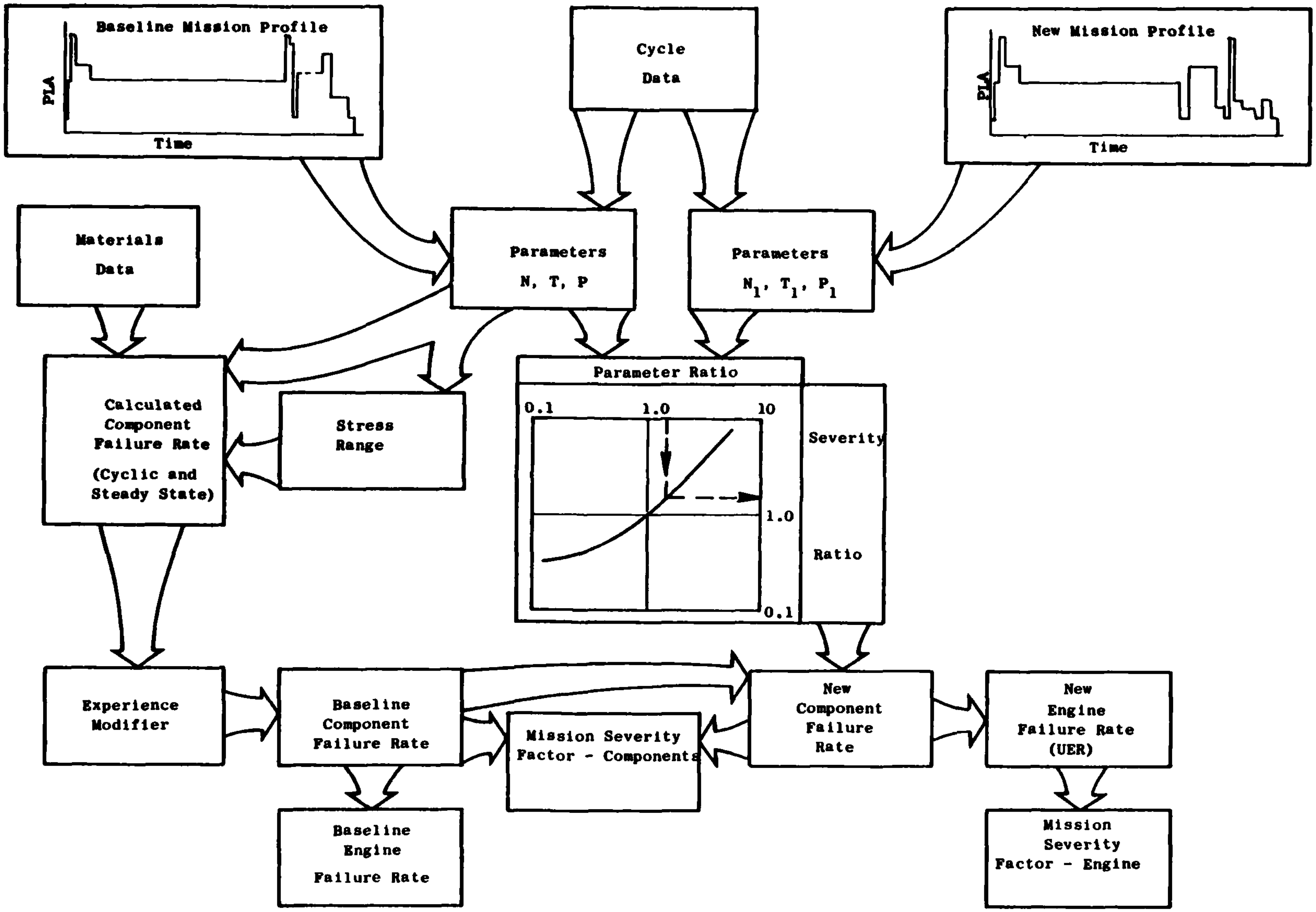


Figure 5-2. Operational Severity Analysis.

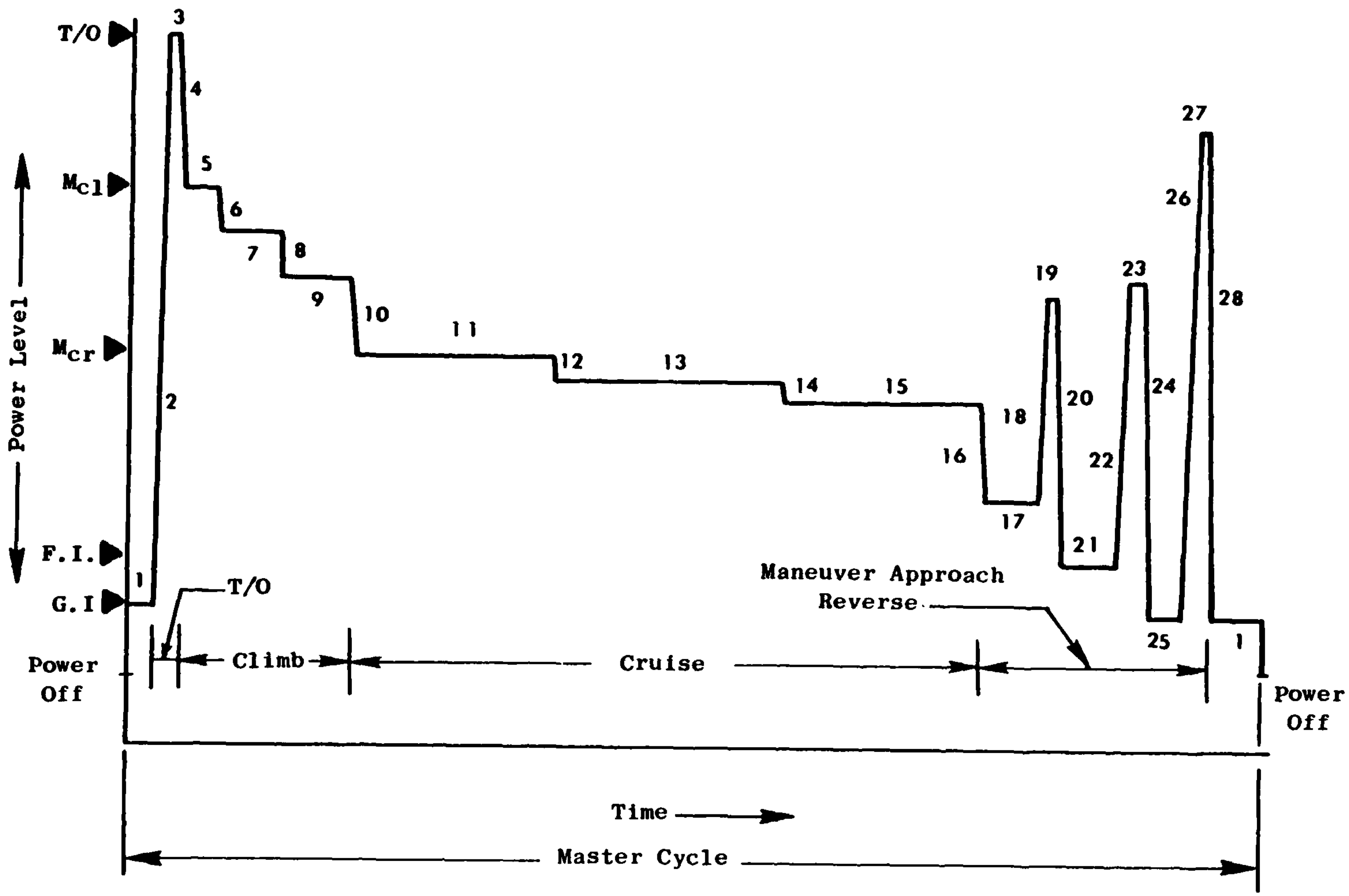


Figure 5-3. Typical Mission Segments Used in Severity Model.

effects are considered. A few of the component severity function curves are shown in Figure 5-4. When all the failure rate calculations for the individual mission segments and subassemblies are completed, the subassembly failure rates are combined into total engine failure rates for each mission, and these totals are then used to determine the relative severity between the various missions. A severity factor is the ratio of failure rates or unplanned engine removal rates between the new and reference missions.

Since low cycle fatigue (LCF) is so important in engines and is so different from steady state, time-oriented failure mechanisms in its sensitivity to operating profile shapes, it is split apart and treated separately in OPSEV. Thus:

$$S_{n/r} = \frac{\lambda_n}{\lambda_r} = \frac{\lambda_{cyc_n} + \lambda_{ss_n}}{\lambda_{cyc_r} + \lambda_{ss_r}}$$

Where:

$S_{n/r}$ = Severity ratio of new to reference mission

λ_n = Failure rate of new mission

λ_r = Failure rate of reference mission

λ_{cyc} = LCF failure rate

λ_{ss} = All other failure rate

The LCF failure rate is further subdivided into portions that are dominated by different performance parameters. Usually, this involves a speed sensitive portion, a pressure sensitive portion, and a temperature sensitive portion.

By definition, the value of the severity for the reference case is always taken as unity. Therefore, the severity of a new mission operating profile is more or less severe than the known reference case. As an example, an overall engine severity of 2.0 means that the total predicted UER rate per engine flight hour in the new mission profile is twice that of the reference usage. The fact that the model is capable of discriminating among individual components is of prime importance since consumption and spare parts provisioning are based on component usage and not directly to total engine severity.

A cycle counting method is used in OPSEV which assumes that damage per cycle is a unique function of stress range which in turn is assumed to be a unique function of the normalized range of the selected parameter (Figure 5-4).

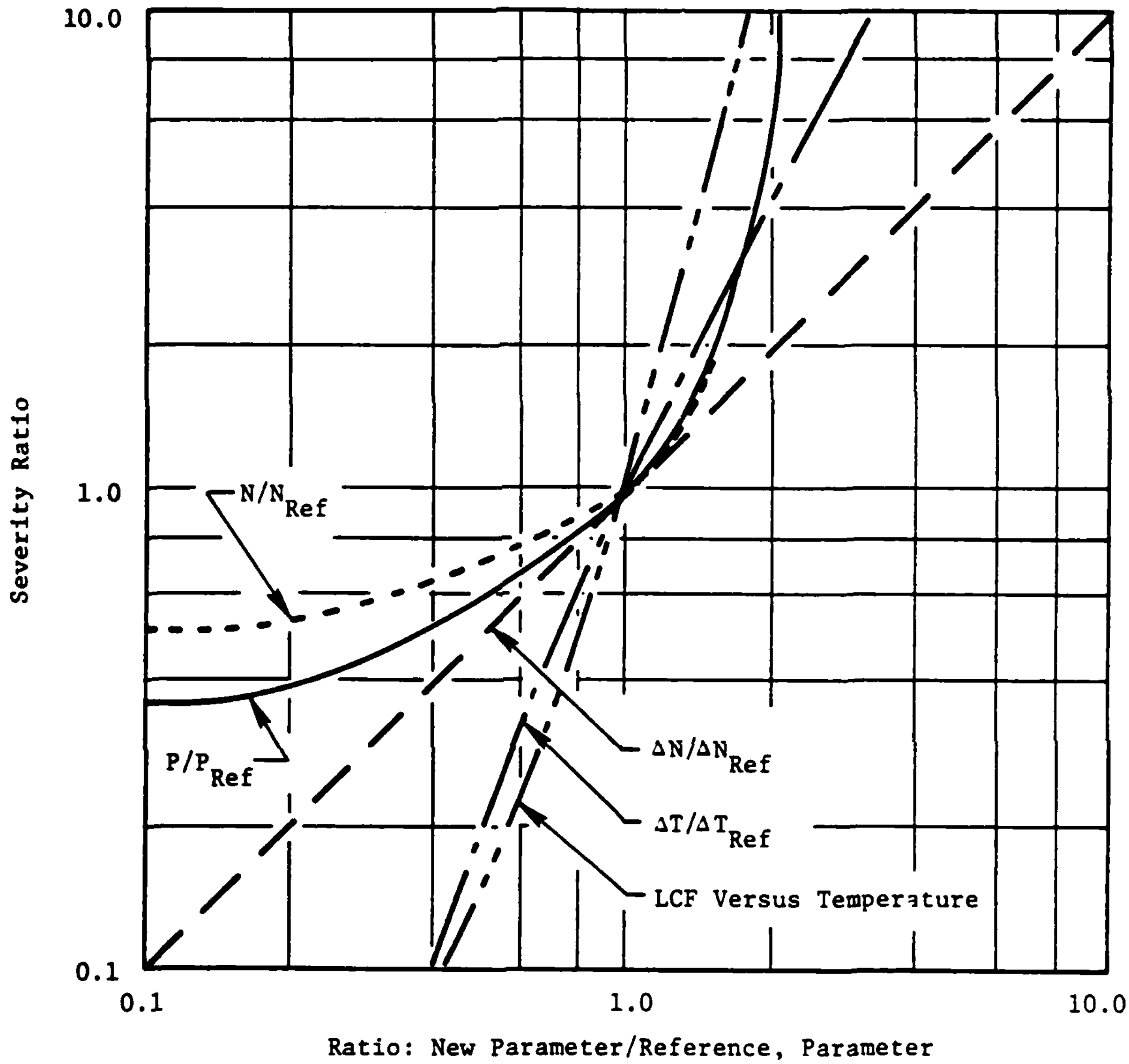


Figure 5-4. Severity Function Curves.

A "master cycle" is defined as an excursion from prestart to reference conditions and back to prestart. Every parameter excursion, from a "peak" to a "valley" (or a valley to a peak), is evaluated as a half cycle. The selected LCF severity function is used to convert normalized parameter range values to fractions of a half master cycle. Small cycles are screened out and ignored to assure maximum sensitivity to the larger cycles upon which they are superimposed. These fractions of a half master cycle are summed over each profile and divided by the profile time to obtain a cyclic density. The LCF severity is the ratio of these cyclic densities. Note that for long steady state profiles, the cyclic density becomes very small, and the LCF severity is inversely proportional to the profile time.

Steady state severity is calculated as the time-weighted average of the severity ratios calculated for the time phases in the profile. Each phase severity ratio is the product of up to three factors, each of which is calculated from the normalized parameters and the pertinent tabulated severity function.

A typical OPSEV printout is shown in Table 5-II. The example shown used a reference mission depicting the CF6-50 engine as used in the commercial fleet. The current UER rates by component cause of this commercial reference mission are shown under Column 7. The OPSEV predicted UER rates for the new mission, Column 8, are ratioed to the reference values to obtain the individual component severities shown in Column 9.

Columns 2 through 6 inclusive are the proportional component allocations affecting predicted UER events and are based on the operational profile of the new mission. The allocations are called failure rate fractions and are divided into steady state and cyclical portions. These two portions are inherent in the total regime of engine operation. The steady state failure rate fraction, by component, is shown in Column 5.

The cyclic parameters of speed, pressure and temperature are shown in Columns 2, 3 and 4 respectively. Since cyclic failure mechanisms differ from those of steady state in their sensitivity to operational mission profiles, the cyclic parameters are segregated from steady state and treated separately in OPSEV.

Table 5-II. Typical OPSEV Printout.

1) REFERENCE AND CALCULATED FAILURE RATES
BY COMPONENT
2) CALCULATED FAILURE RATE FRACTIONS
3) COMPONENT AND ENGINE SEVERITIES

COMPONENT NO.	(1) NAME	FAILURE RATE FRACTIONS (2) SPEED	(3) PRESS	(4) TEMP	(5) STEADY STATE	(6) TOTAL	(7) FAILURE RATES REFERENCE	(8) MISSION	(9) SEVERITY
1	FAN ROTOR	0.017255	0.001855	0.	0.028618	0.047728	12.1	14.1	1.168737
2	FAN STATOR	0.	0.006025	0.	0.042240	0.048264	13.1	14.3	1.091656
3	LPT ROTOR	0.013491	0.	0.017163	0.008292	0.038947	6.8	11.5	1.697055
4	LPT STATOR	0.	0.006004	0.016721	0.007608	0.030334	5.3	9.0	1.695828
5	COMPR ROTOR	0.116972	0.008553	0.009700	0.094638	0.229864	51.3	68.1	1.327655
6	COMPR STATOR	0.	0.017429	0.002471	0.051645	0.071545	19.6	21.2	1.081565
7	HPT ROTOR	0.036482	0.	0.038849	0.020036	0.095367	16.0	28.3	1.766072
8	HPT STATOR	0.	0.	0.027922	0.020025	0.047947	9.2	14.2	1.544221
9	MN COMBUSTOR	0.	0.	0.145606	0.109030	0.254637	50.5	75.4	1.494036
12	CONT/AMBIENT	0.	0.	0.	0.040061	0.040061	12.6	11.9	0.942074
13	CONT/NON-AMB	0.	0.	0.	0.003449	0.003449	1.1	1.0	0.928967
15	BRG/SEALS/HP	0.	0.	0.	0.004688	0.004688	1.5	1.4	0.926083
16	CONT/CYCLIC	0.029532	0.	0.	0.013751	0.043283	8.6	12.8	1.491239
19	MN IGNITION	0.057963	0.	0.	0.	0.057963	8.2	17.2	2.094429
20	FAN FRAME	0.	0.001886	0.	0.013220	0.015106	4.1	4.5	1.091656
22	COMP RFRAME	0.	0.007336	0.011093	0.004326	0.022756	4.4	6.7	1.532393
23	TURB MDFRAME	0.	0.004418	0.024609	0.012932	0.041959	7.8	12.4	1.593892
25	INLET GRBOX	0.073240	0.	0.	0.109522	0.182762	47.6	54.2	1.137657
26	BRG/SEALS/LP	0.	0.	0.	0.050163	0.050163	16.5	14.9	0.900807
	** TOTALS **	0.344935	0.053506	0.294134	0.634245	1.326821	296.3	393.1	1.326821

The three cyclic performance failure rate fractions in Columns 2, 3 and 4 are added together and then summed with the steady state parameter to obtain the total failure rate fraction per component. For example, Item 5, Compressor Rotor, indicates failure rate fractions of 0.116972, 0.008553 and 0.009700 for the cyclic effects of speed, pressure and temperature, respectively. Continuing, Column 5 shows a failure rate fraction for steady state of 0.094638. All four values when summed are equal to the total failure rate fraction for the component, in this example 0.229864, as shown in Column 6. The compressor rotor here contributes 17.3% of the total engine predicted failures (0.229864/1.326821 = 0.173).

Note that the value for the total engine failure rate fraction, bottom of Column 6 (1.326821), is the same as the overall severity for the new mission, bottom of Column 9. This is a result of the total engine failure rate fraction and is defined as 1. The new mission UER rates may be determined from the products of the severities and respective reference mission UER rates, Column 7. Using the compressor rotor as an example, the product of the total component severity (1.328 - Column 9, Line 5) and the reference UER rate (51.3 - Column 7) yields (68.1 - Column 8) the new mission compressor rotor UER rate.

The new mission severity, by component and for the total engine, is the ratio of the new mission UER rate to the UER rate of the referenced mission. For the compressor rotor, the severity value is 1.327655, as indicated in Column 9 (51.3/68.1 = 1.33).

Several limitations are present in the use of the OPSEV program. A few of these are:

- OPSEV cannot make corrections for differences in engine ages, maturity level, or failure definition. Where differences are known to exist, separate correction factors must be applied.
- Where all components of an engine are not common to two types of operation (such as the turbine rear frame of the LM2500 which is the prime propulsion system for marine applications when compared to the TF39), OPSEV must be applied to the common components only.

5.4 OPERATIONAL SUPPORT COST ANALYSIS PROGRAM (OSCAP)

OSCAP is a time-share program written in FORTRAN to calculate the Operating and Support costs for a fleet of engines. Figure 5-5 shows the four major parts of this program.

Engine Removal Generator (ERG) - This subroutine calculates the expected number of engine removals in each time interval due to FOD and those which are due to engine causes. The engine-caused events are calculated for two types of parts — those which fail from random causes alone, and those which fail from both random and such life-limiting causes as LCF, creep and stress rupture. The failures due to random causes follow "learning curve" types of functions as shown in Figure 5-6. The life-limiting failure modes are calculated by keeping track of the component age distribution and interacting this with the input failure versus age Weibull distribution function as shown in Figure 5-7. The overall failure rate for a component is the sum of the random and life-limiting events in each interval.

The engine-caused removal rate is calculated by correcting for the probabilities that failed components may occur simultaneously on the same engine. A given engine can only be removed once for a single recorded cause.

Resultant Maintenance Action Calculator (REMAC) - This subroutine calculates, for each of the engine removal events, the number of parts which are removed from the engine and processed through the shop.

Maintenance Event Processor (MEP) - For each part identified by REMAC, the labor and consumable material expended for repair are accumulated. Also, the number of scrapped items is tallied. All tallies are by program interval.

Life Cycle Cost Post Processor (LCCPP) - Costs are calculated by program interval for 17 categories identified by the ASD/YZ report on LCC issued by the joint DOD-Industry committee in February 1977. A summary for the program output categories is shown in Table 5-III.

5.5 METHODOLOGY

Methodology as used in this program encompasses the problem statement, assumptions and calculation sequence. In performing quantitative trade studies of very complex problems such as those addressed in this program, one of two

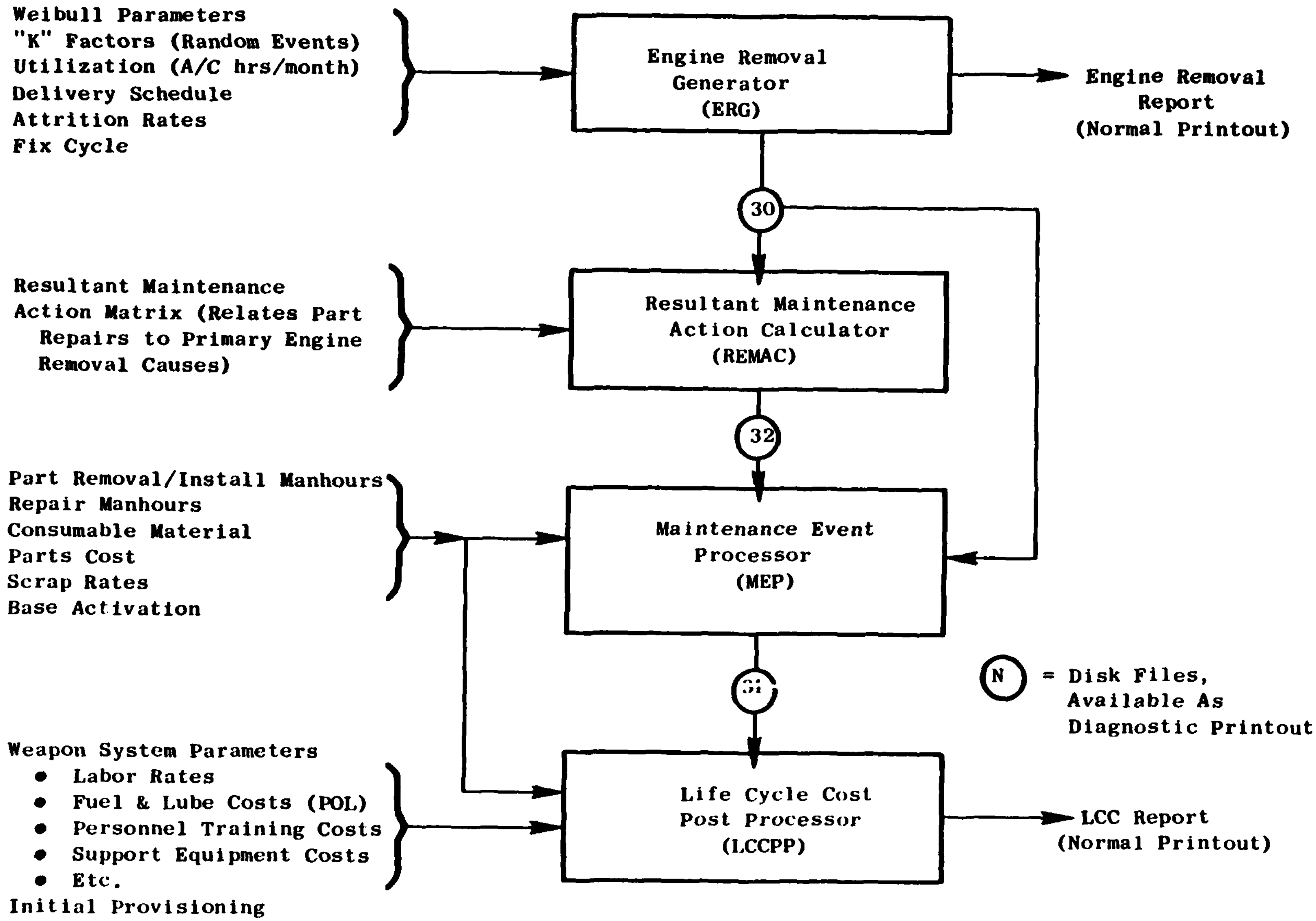


Figure 5-5. OSCAP Flow Diagram.

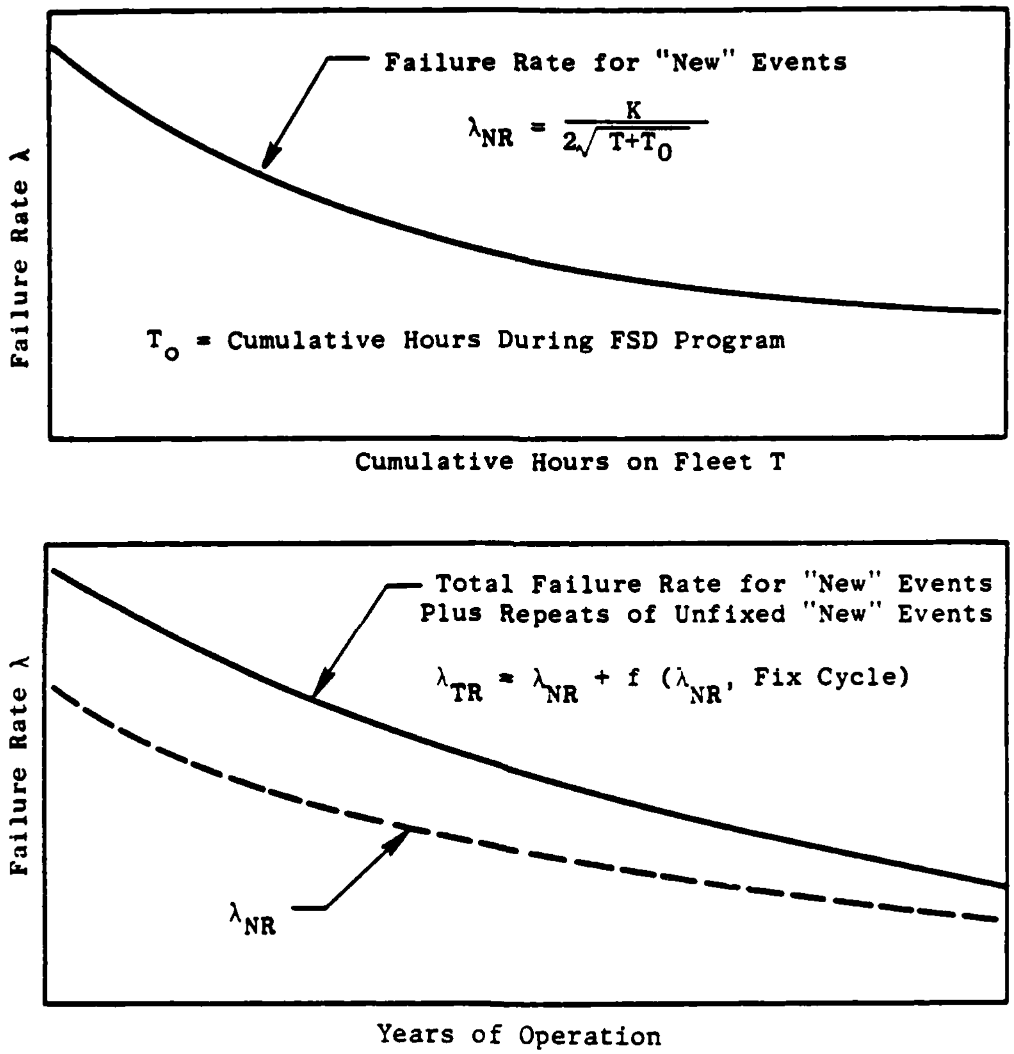


Figure 5-6. Component Failure Rate Calculation (Random Events).

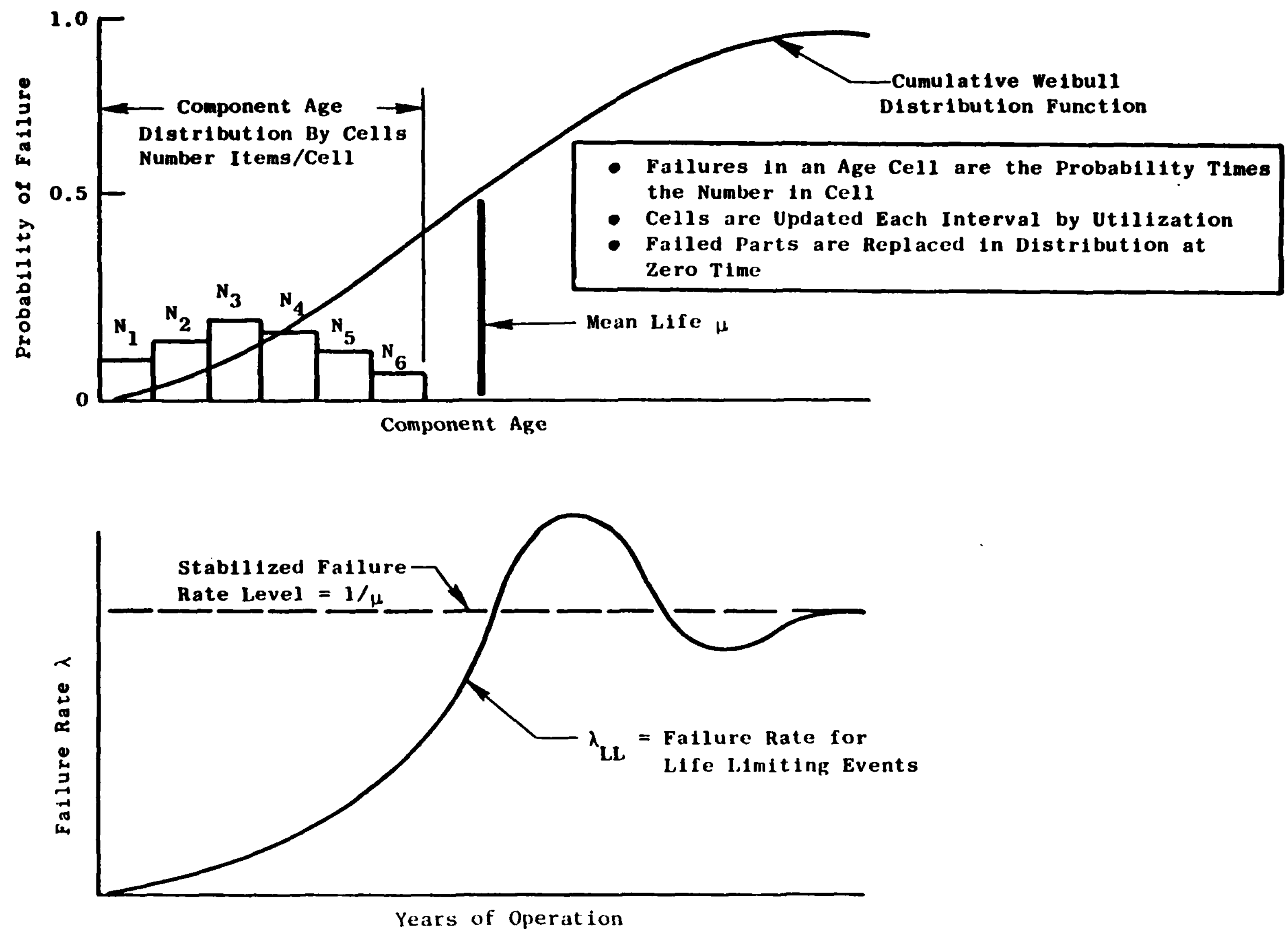


Figure 5-7. Component Failure Rate Calculation (Life Limiting Events).

Table 5-III. Fleet Statistics.

SUMMARY FOR 28 YEARS

FLEET STATISTICS

NO. A/C
NO. ENG.
CUM ENG. FLT. HRS.
NO. OF BASES
NO. ENG. LOST BY ATTRITION

ENGINE LEVEL STATISTICS

ENG. CAUSED UER RATE/1000 EFH
FOD UER RATE/1000 EFH
SCHED. REMOVAL RATE/1000 EFH
TOTAL REMOVAL RATE/1000 EFH

F101X/F-14 O&S LCC DEFINED BY ASD/YZ EQUATIONS

	DOLLARS	$/EFH
DETAILED ENGINE DESIGN COST		
ENGINE MANUFACTURING COST		
COST OF ENGINE SPARE SECTIONS		
PECULIAR SUPPORT EQUIPMENT COST		
SPECIAL TEST EQUIPMENT COST		
PACKAGING AND SHIPPING COST		
CONTRACTOR TEST COST		
GOVERNMENT TESTING COST		
TRAINING COST		
CONTRACTOR FIELD SUPPORT COST		
DATA COST		
RECURRING INVENTORY MANAGEMENT COST		
ENGINE SCHEDULED MAINTENANCE COST		
ENGINE UNSCHEDULED MAINTENANCE COST		
RECURRING MAINTENANCE MANAGEMENT DATA COST		
SYSTEM ENGINEERING/PROJECT MANAGEMENT COST		
POL COST		
TOTAL O&S LCC		

SCHEDULED MAINTENANCE

TYPE INSP.	NO. PERF.	TOTAL MAN-HRS.	$/EFH
PRE-FLT.			
POST-FLT.			
SOAP			
TURNAROUND			
SERVICING			
PHASE INSPECTIONS			
50 HOURS			
100 HOURS			
500 HOURS			

UNSCHEDULED MAINTENANCE

COST ELEMENT	ORGANIZATIONAL		INTERMEDIATE		DEPOT	
	$(T)	$/EFH	$(T)	$/EFH	$(T)	$/EFH
LABOR						
REPAIR MAT'L						
PARTS CONSUMED						

TOTAL UNSCHEDULED MAINTENANCE COST = $

things can happen: The problem can be defined in such detail that obtaining answers takes a long time and is very costly, or the problem can be oversimplified in the name of expediousness so that the results have little meaning. From an engineering standpoint, it is recognized that there is some middle-of-the-road approval which results in meaningful results with a reasonable economy of effort. The question is how to determine this optimal procedure.

Several methodologies were exercised in the course of this program to assess their relative merit. They will be presented and discussed in the Trade Study section.

6.0 TRADE STUDIES

A total of five trade studies were performed using the baseline system and analytical tools previously described. The objectives of these studies were first to evaluate methodologies for performing the quantitative trade studies and second to address problems that are germane to current aircraft system concerns. The studies performed were:

1. Turbine Rotor Inlet Temperature Derate
   a - Preliminary Design Methodology
   b - Detailed Design Methodology
2. Mission Change
3. Aircraft Weight Change
   a - For Constant Range Mission
   b - For Constant Combat Capability Mission

6.1 TURBINE ROTOR INLET TEMPERATURE DERATE

The technical problem addressed was to estimate the effect of several turbine rotor inlet gas temperature ($T_{4.1}$) derate schedules on aircraft performance and engine life and shop visit rate (SVR).

Experience in commercial and transport aircraft has shown that significant reductions in Operating and Support costs can and have been realized by derating the engine thrust, that is, operating the engines at a thrust level somewhat lower than it had been developed to deliver (see Reference 1). Figure 6-1 shows the effect of (UER), which is a direct contributor to Operating and Support costs. The dashed lines are analytical estimates while the solid line is a curve fit of the available historical data. Excellent correlation between the analytical estimates and the historical data were obtained. These results show that for a 7.5% thrust derate, the UER rate was reduced by 12% for a four hour flight and for a 10% thrust derate, the UER rate was reduced by 25% for a 1.6 hour flight.

The question addressed in this study was: Could similar Operating and Support cost savings be obtained for advanced lightweight fighter aircraft weapon systems without greatly restricting their flight performance characteristics? The broad range of flight altitudes and Mach numbers over which a

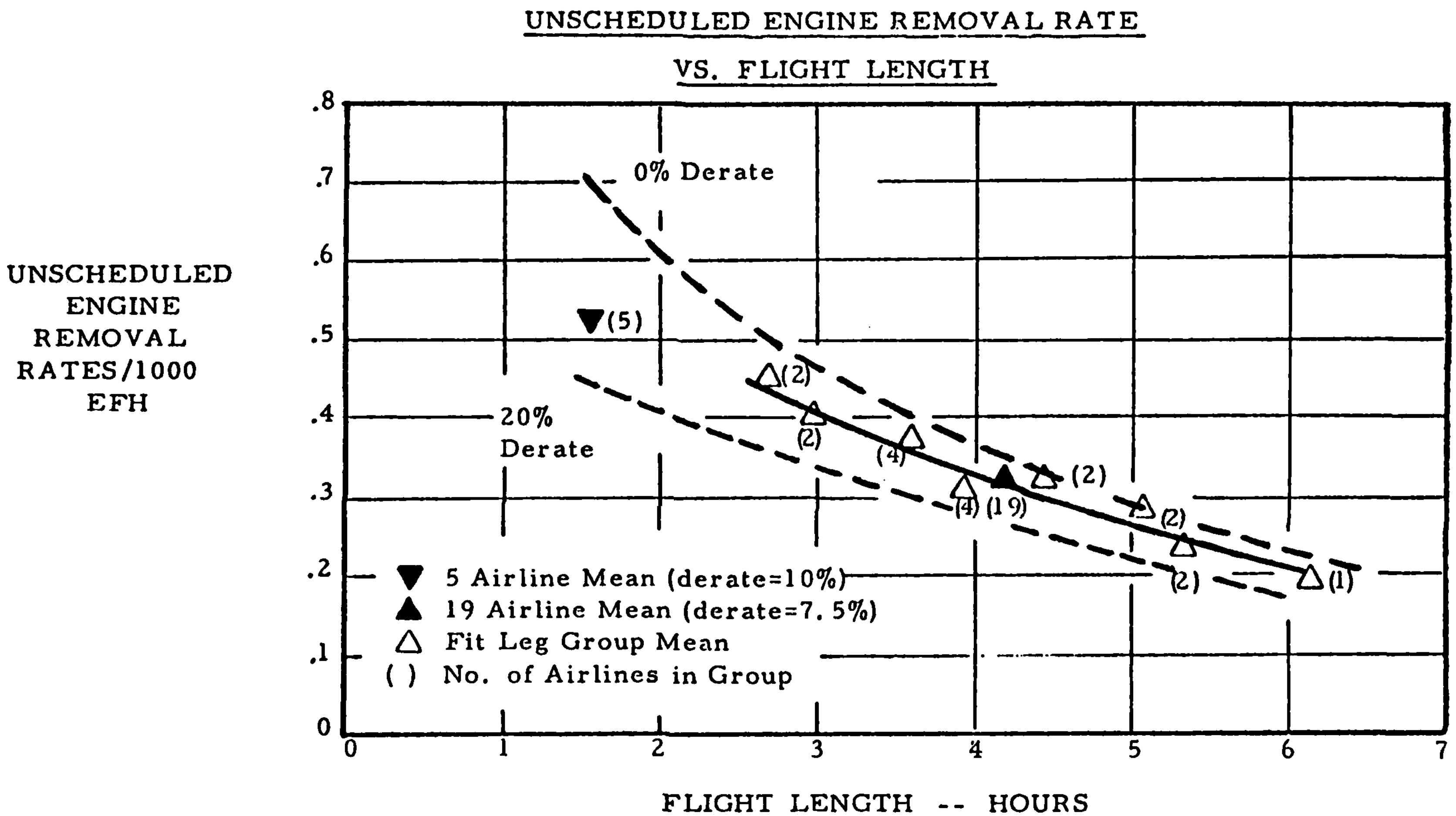


Figure 6-1. Effect of Thrust Derate on the CF6-50 UER.

fighter must operate to satisfy its diverse mission requirements results in many short missions with a very large number of throttle movements compared to the typical commercial or transport missions. Thus, the answer to this question is not immediately obvious and required a significant amount of engineering study to answer.

Two methodologies were used to quantify this problem. The first will be referred to as the Preliminary Design Methodology (PDM) where design approximations are made. This allowed an expeditious evaluation of a large matrix of variables. The second will be referred to as the Detailed Design Methodology (DDM) which addressed the problem in great detail with no simplifying assumptions.

6.1.1 Preliminary Design Methodology (Study No. 1)

Problem Definition: Determine the effect of several different control set points that derate turbine rotor inlet temperature ($T_{4.1}$) on the engine component usage severity, engine Operating and Support cost parameters and aircraft flight performance.

Data Input: Baseline Aircraft and engine as described in Section 4.0.

Assumption: Base power schedules which were determined using the base cycle deck, base aircraft model and base missions can be used to calculate component severities and Operating and Support cost parameters for the new control set points, i.e., the effect of new control set point has negligible effect on aircraft mission capability.

Calculation Approach

1. Define two new control set points that reduce turbine rotor inlet temperature ($T_{4.1}$).
2. Define control limits that maintain the same operability limits as base cycle for new $T_{4.1}$ derate cycles.
3. Incorporate new cycle decks with aircraft performance model and for each cycle, calculate the following aircraft performance parameters: Cruise specific fuel consumption, maximum service ceiling altitude, maximum Mach No. capability at sea level at intermediate power, and at 30,000 ft and 40,000 ft at max afterburner thrust, acceleration

times from M_0 = .9 to 1.6 and 1.7 at both 30,000 and 40,000 ft and climb time from sea level to 20,000, 30,000 and 40,000 at a constant Mach No. of .90.

4. Using OPSEV, calculate engine component severities relative to base mission mix and base cycle for the new cycles and the base mission mix.
5. Use OPSEV results to modify base engine component Weibulls.
6. Using OSCAP, calculate Operating and Support cost parameters of engine shop visit rate (SVR), materials cost, maintenance index, engine spares cost and component spares cost for each cycle using the F-16 base use scenario.

Results: Figure 6-2 shows the $T_{4.1}$ vs T_2 characteristics of the two derate cycles plus the base cycle. Note that at 30,000 ft altitude, the $T_{4.1}$ vs T_2 characteristic of all three cycles are the same at T_2 levels below 520°F.

The results of the study are summarized in Table 6-I. It was found that cruise specific fuel consumption and max altitude ceiling were not affected by the derates. Component severities are shown relative to the base configuration, thus a severity of less than 1.0 implies that the cycle-mission evaluated is less severe than the base cycle-mission. Aircraft performance and Operating and Support cost parameters are shown in terms of percent change relative to the base configuration. The results of this study indicate that the candidate control set points do reduce the component severities and Operating and Support cost parameters; however, the aircraft performance parameters are also reduced. Figure 6-3 shows the trends in aircraft performance change as a function of the change in shop visit rate. Shop visit rate was used as the Operating and Support parameter since it has been found that total maintenance costs are linearly related to SVR. Figure 6-3 shows that on a percentage basis, the improvement SVR is greater than the loss of all the aircraft performance parameters shown except acceleration time from Mach .9 to 1.7 at 30,000 ft for both candidate control set points. However, the rate of change in SVR to aircraft performance is greater for the 50° $T_{4.1}$ derate than the 100° $T_{4.1}$ derate.

A stability analysis was performed to assure that the candidate control set points are viable potential solutions. The effect of reduced $T_{4.1}$ cycles on the fan and compressor surge margins was made. The results of these

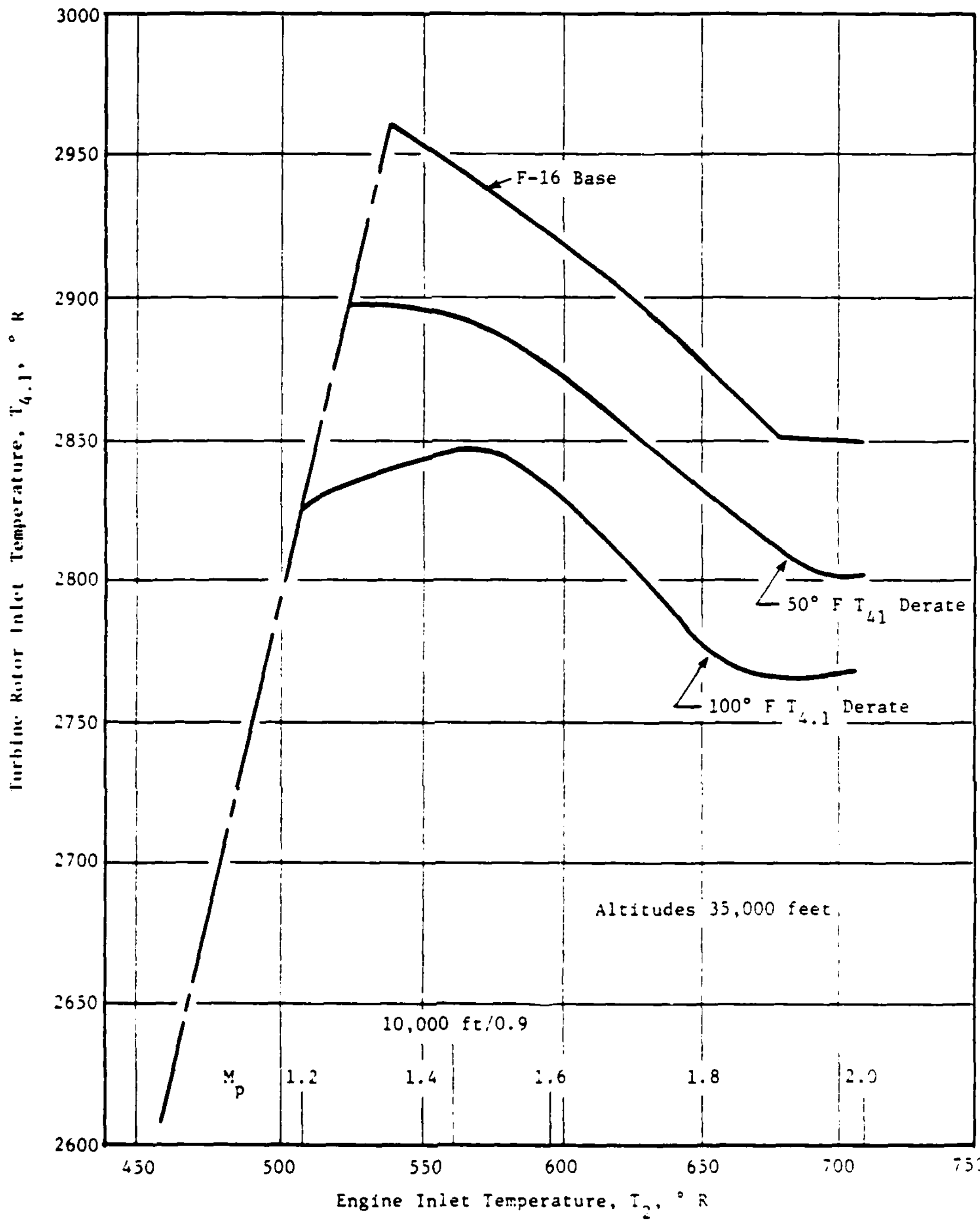


Figure 6-2. Comparison of Derate Cycles with Base Cycle (Study No. 1).

Table 6-I. Turbine Rotor Inlet Temperature Derate Results (Study No. 1).

Cycle Set Point	Base Cycle	Flat Derate	100° $T_{4.1}$ Flat Derate
Relative Severity Ratios			
Overall Engine	1.0	.961	.882
Fan Rotor		.995	.90
Compressor Rotor		.996	.922
Compressor Stator		.968	.878
Combustor		.919	.787
HPT Rotor		.932	.788
HPT Stator		.915	.751
LPT Rotor		.932	.853
LPT Stator		.922	.824
Afterburner		.943	.869
Exhaust Nozzle		.941	.851
A/C Performance			
Max Mach No. (% change)*			
S.L Dry		0	0
30'K - Max A/B		(2.14)	(4.6)
40'K - Max A/B		(1.13)	(3.28)
Acceleration Time (% change)*			
M .9 to 1.6 @ 30'K		8.21	20.60
M .9 to 1.7 @ 30'K		11.80	30.78
M .9 to 1.6 @ 40'K		4.32	11.50
M .9 to 1.7 @ 40'K		6.21	15.87
M .9 to 1.8 @ 40'K		9.15	24.27
Time to Climb (% change)*			
M .9 (SL to 20'K)		1.46	6.18
(SL to 30'K)		.96	4.23
(SL to 40'K)		.54	2.38
Operations & Support Summary (% change)*			
Shop Visit Rate	Base	(10.98)	(25.61)
Material Costs		(9.07)	(25.66)
Maintenance Index		(6.72)	(18.49)
Eng Spares		(3.48)	(13.81)
Component Spares		(.46)	(1.91)

( )* indicates decrease

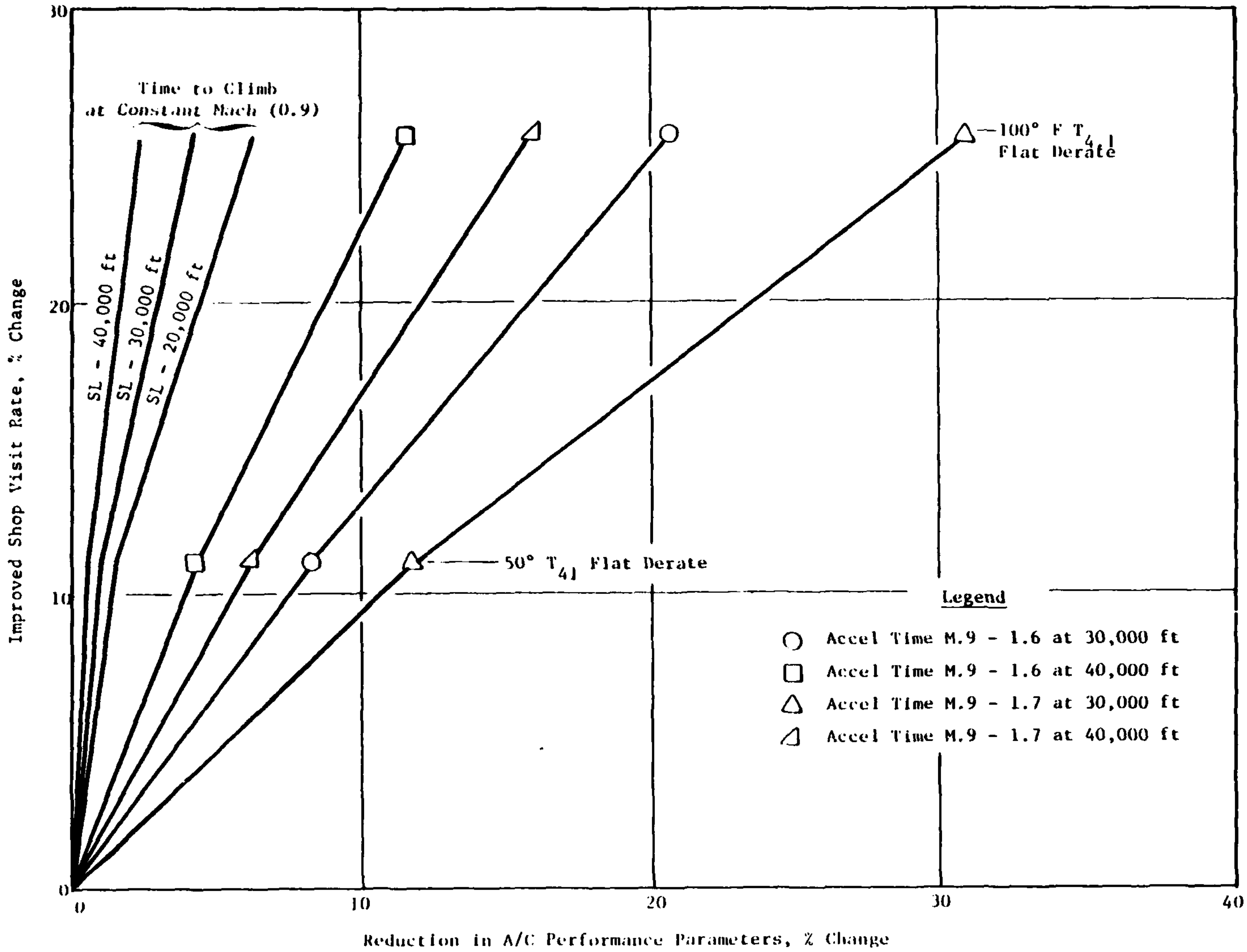


Figure 6-3. Trends in A/C Performance as a Function of SVR Change (Study No. 1).

analyses indicated that the surge margin of these compression units were essentially unaffected by the derates. Figures 6-4 and 6-5 show the fan and compressor surge margins for the base and 100° F derate cycles. Figure 6-6 shows that the flow reduction of the derate cycle improves compression unit stability due to the associated reduction of flow distortion from the inlet. The effect of the flow reduction on augmentor stability/capability at high altitude-low Mach number conditions was also evaluated. The results of this evaluation showed that no stability/capability problems were anticipated. Thus, from a stability standpoint, the two candidate $T_{4.1}$ derate set points appear to be viable candidates.

In summary, the PDM results showed that both candidate $T_{4.1}$ derate control set points have acceptable stability, reduce engine component life consumption, SVR and aircraft performance parameters. Prior to arriving at conclusions and recommendations based on this study, the second study will be presented since it addressed the same problem but used the Detailed Design Methodology (DDM).

6.1.2 Detailed Design Methodology (Study No. 2)

Problem Definition: Same as Study No. 1.

Data Input: Same as Study No. 1.

Assumptions: None

Calculation Approach

1. Define two new control set points that reduce turbine rotor inlet temperature ($T_{4.1}$).
2. Define control limits that maintain the same operability limits as the base cycle for the new $T_{4.1}$ derate cycles.
3. Define one mission that is to be used to evaluate changes in aircraft performance component severities and O&S cost parameters. Define one aircraft performance figure of merit.
4. For each control set point cycle, including the base cycle, determine power schedules and performance figure of merit.

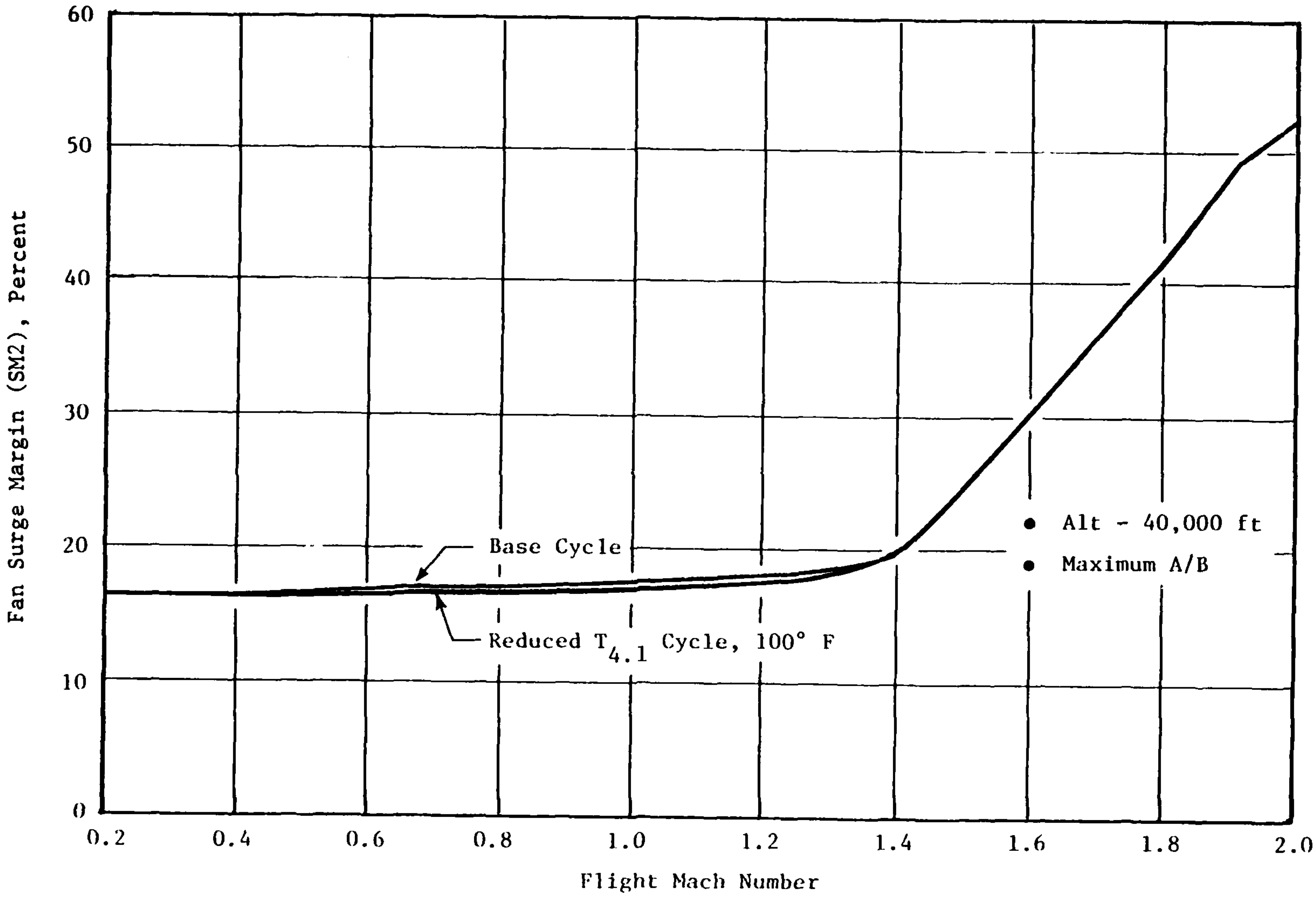


Figure 6-4. Fan Surge Margin Characteristics for Derate Cycle.

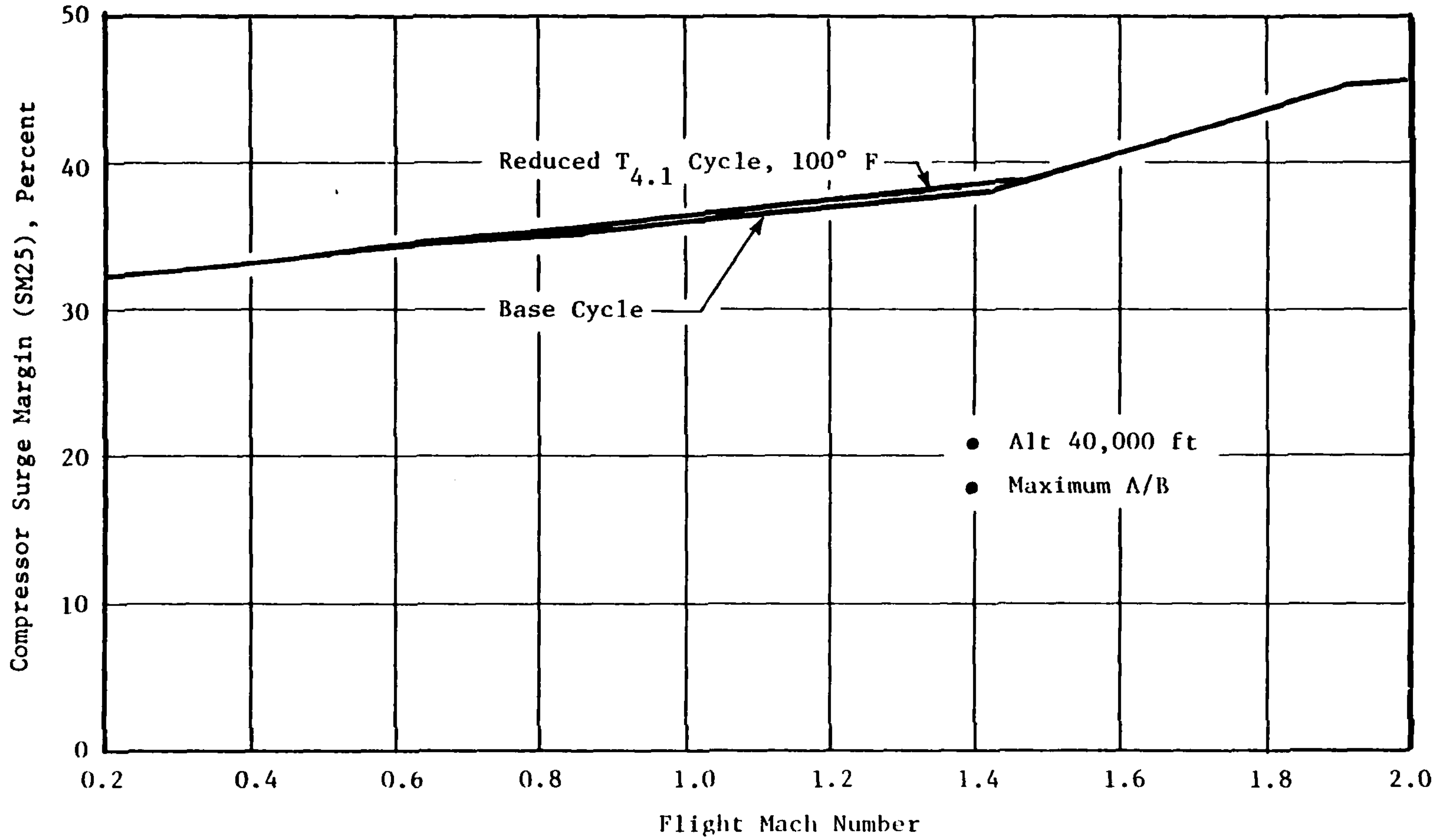


Figure 6.7. Compressor Surge Margin Characteristics for Derate Cycle.

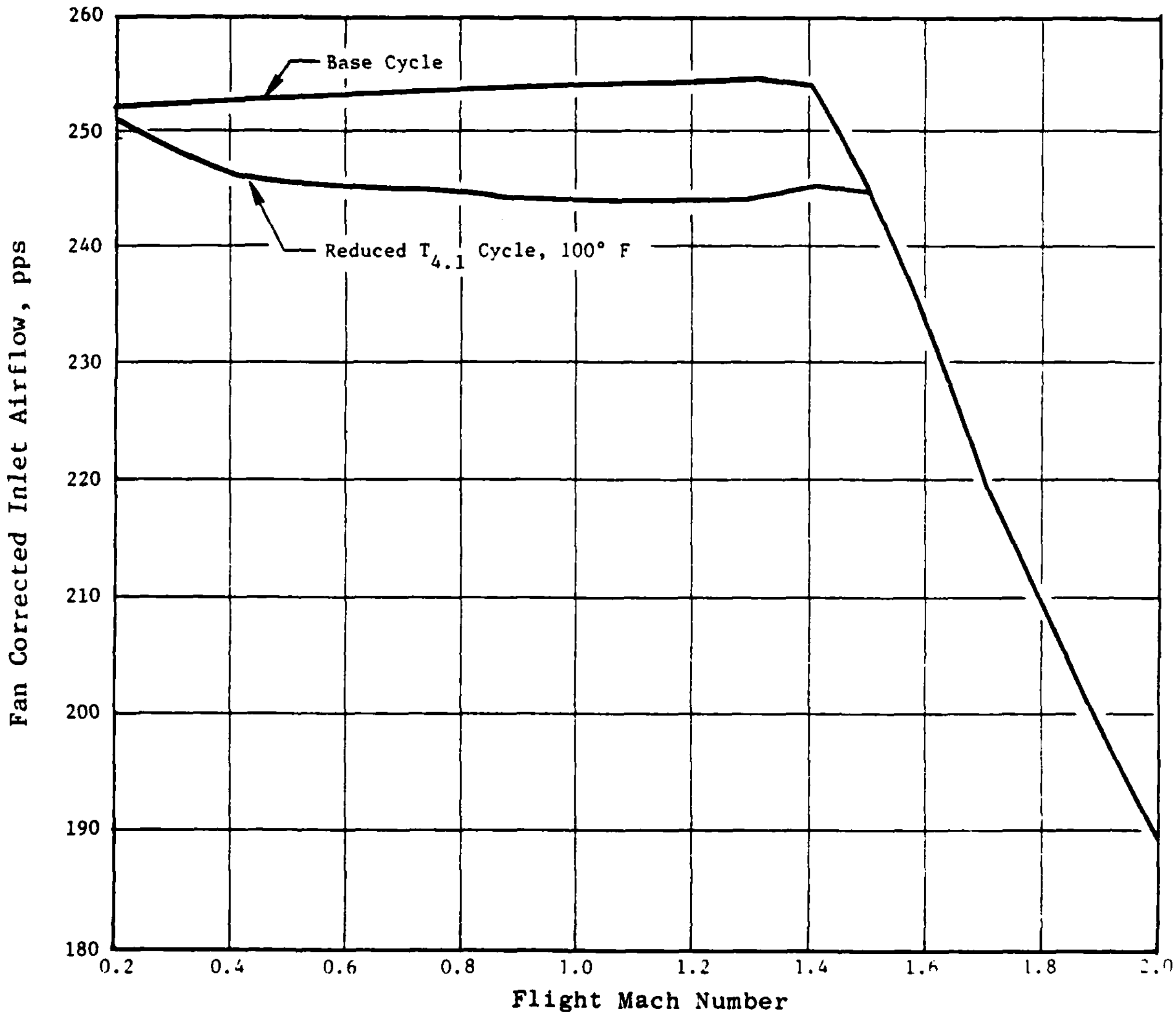


Figure 6-6. Flow Characteristics for Derate Cycle.

5. Using OPSEV, calculate engine component severities relative to the base mission and base cycle for the new mission-cycles.

6. Use OPSEV results to modify base engine component Weibulls.

7. Using OSCAP, calculate O&S cost parameters.

Results: Figure 6-7 shows the $T_{4.1}$ vs. T_2 characteristics of the two new derate cycles plus the base cycle and the 100° $T_{4.1}$ derate cycle used in Study Number 1. Note that in the first study the 100° $T_{4.1}$ derate had a transition from the base cycle then maintained an essentially constant 100° F difference from the base cycle in the T_2 range of 580° R to 710° R. For the purposes of discussion, this cycle will be referred to as the 100° F flat derate (FD). By contrast, the two new cycles defined for this study have a linear decrease in derate as T_2 increases so that they have zero derate at T_2 = 710° R. For the purposes of discussion, these cycles will be referred to as the 50° F selective derate (SD) and the 100° F selective derate (SD), where the 100° F SD has a common transition with the 100° F FD. The stability of these cycles was found to be the same as those studied in Study Number 1. Figure 6-8 shows the percent change in thrust of these three derates as a function of altitude for a constant Mach number.

Figure 6-9 shows the mission selected for this study. This basic mission was an air-to-air combat mission with a fixed mission radius. Combat was at a constant altitude and at maximum afterburner (A/B) thrust. The combat segment of the mission consisted of a M .9 to 1.6 acceleration followed by a fixed number of supersonic turns than as many subsonic turns as the remaining fuel would allow. All turns were performed at the maximum sustained turn rate possible. Cruise out and back were at constant Mach number and optimum cruise sfc altitude. For each engine cycle, the mission radius and fuel usage were held constant and the change in combat turns determined.

Table 6-II summarizes the results of Study Number 2. The results of both studies conducted show that $T_{4.1}$ derate control set points can reduce the rate of engine component life consumption and O&S cost parameters. However, Study Number 2 indicates that the improvement in SVR for the common 100° F FD case studied is lower when the DDM is applied. The reason for this is the fact that the derate cycles result in changes in power schedules because of

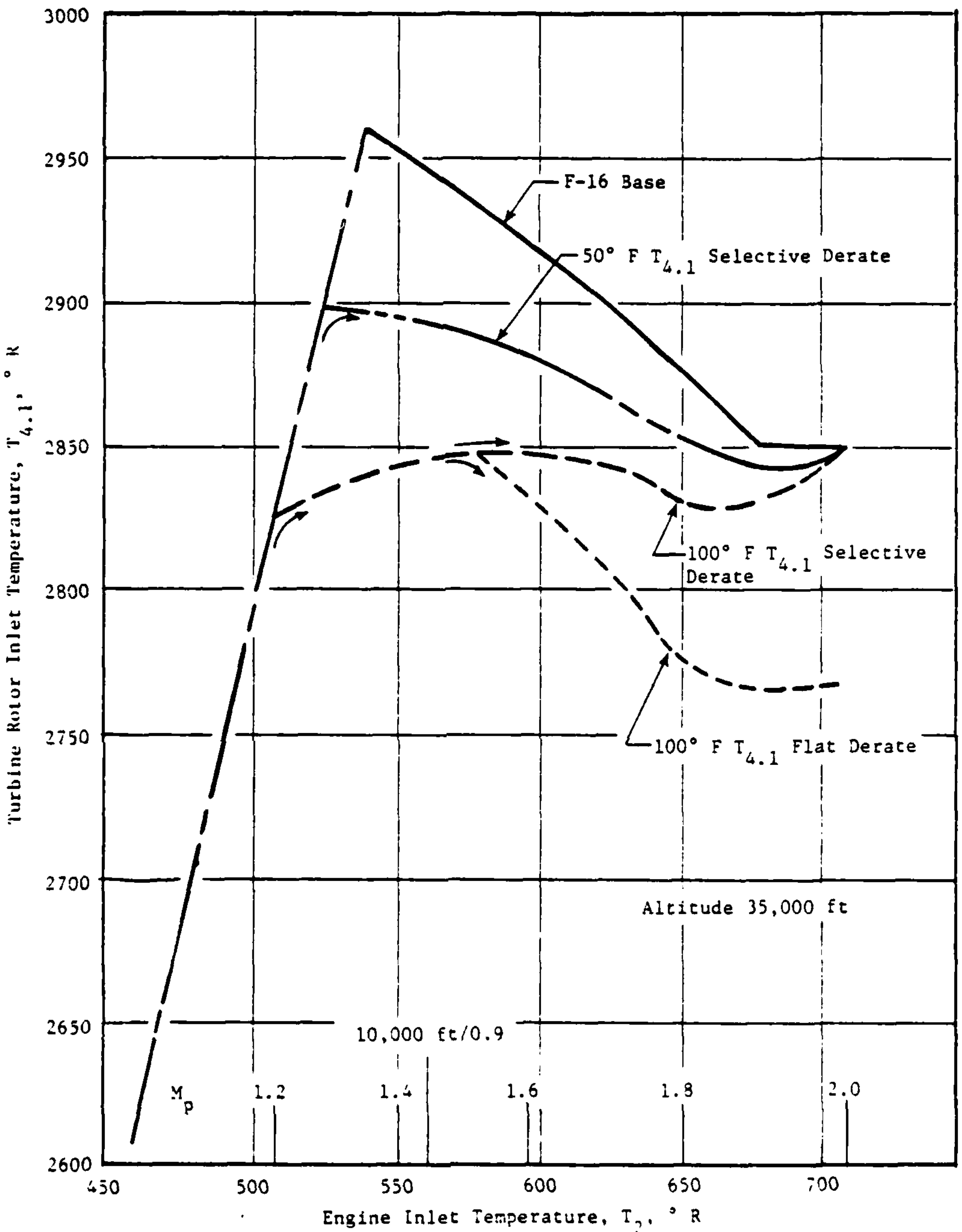


Figure 6-7. Comparison of Derate Cycles with Base Cycle (Study No. 2).

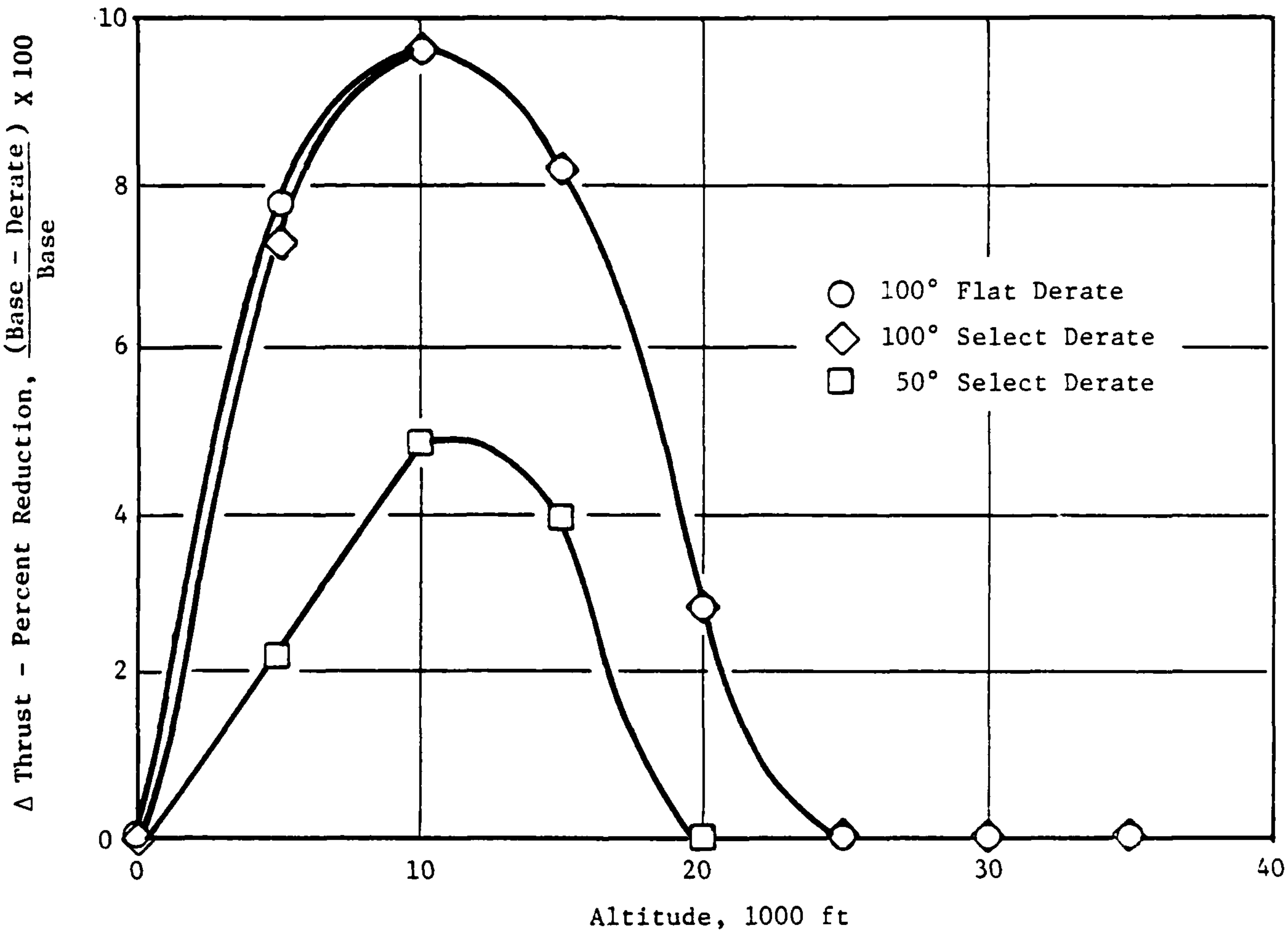


Figure 6-8. Thrust Characteristics of Derate Cycles (Study No. 2).

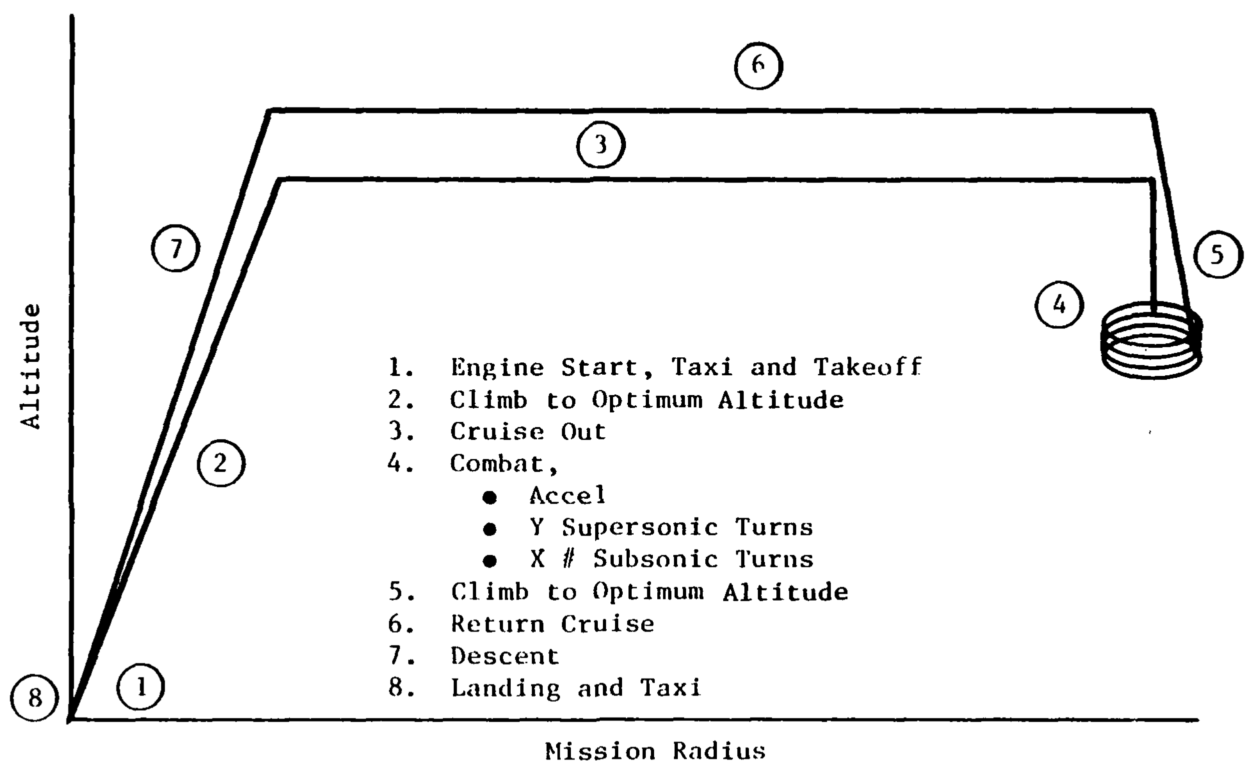


Figure 6-9. Mission Definition (Study No. 2).

Table 6-II. Turbine Rotor Inlet Temperature Derate Results (Study No. 2).

Cycle	Base	50 SD	100 SD	100 FD
Relative Severity Ratios				
Overall Engine	1.0	.996	.976	.957
Fan Rotor		1.00	.965	.951
Compressor Rotor		.994	.977	.957
Compressor Stator		.991	.974	.945
Combustor		.97	.928	.879
HPT Rotor		.97	.92	.877
HPT Stator		.973	.926	.877
LPT Rotor		.964	.914	.882
LPT Stator		.965	.921	.875
Afterburner		.981	.959	.944
Exhaust Nozzle		.994	.968	.945
Shop Visit Rate (% increase)	0	(2.2)	(7.9)	(12.0)
Aircraft - Mission Performance				
Range	Base	Base	Base	Base
Total Fuel	Base	Base	Base	Base
No. Mo.9/30' K turns % increase	Base	(8.5)	(9.6)	(9.6)

their .educed aircraft performance capability. Thus, the assumption made in Study Number 1 was not very good.

These are several conclusions that can be drawn from these two studies. They are: first the methodology used in the study can have a large impact on the magnitude of the answers. For example, the percent reduction in SVR calculated using the PDM was 25.6% while it was only 12% using the DDM. Second, it has been demonstrated that quantitative studies can be performed that reflect the trades between engine life and aircraft system performance parameters for changes in control set points. Third, the capability of performing these studies was highly dependent on the fact that a well defined baseline system could be defined. Definition and modelling of the base system took much more time and effort than the trade studies. And fourth, the analyses described here are not sufficient for making a decision as to whether to implement a $T_{4.1}$ derate. Serious consideration of this decision would require that additional derate control set points be identified and evaluated and that they be studied for the full mission mix. Further, that the results of such a detailed study be compared with the defined system requirements which must be used as the measure of system capability acceptance.

6.2 MISSION STUDIES (STUDY NO. 3)

Problem Definition: Determine the effect of several mission mixes on the life consumption rate of the base engine components.

Data Input: Baseline aircraft and engine as described in Section 4.0. Two mission mixes, the F-14 mission mix and the F-16 mission mix as defined by General Dynamics.

Background: When this program was initiated, it was intended to obtain an F-16 mission mix from General Dynamics as part of their subcontract commitment to the "Design Analysis and Critical Component Development Program" (F33615-78-C-2007). In this effort, General Dynamics defined seven stick missions and their mix plus flight tapes from the F-16 that would allow General Electric to attempt to construct realistic missions by superposing actual flight data throttle movements into the legs of the missions. Just prior to the completion of this effort, the Air Force F-16 SPO identified the missions and mission mix defined in the base aircraft system.

The purpose of presenting this study in this report is to emphasize what is considered an important factor that must be recognized in any future trade study; namely, that an operational aircraft will be used as deemed necessary by the Air Force command who in no way is restricted to fly only those missions defined in the weapon system development process. In addition, it is very difficult to construct realistic flight missions from composites of design stick missions and segments of flight tapes.

Assumptions: None

Approach

1. Determine power schedules for missions using the base cycle.
2. Using OPSEV, calculate engine component severities relative to the base mission mix and base cycle for the new missions and base cycle.
3. Use OPSEV results to modify base engine component Weibulls.
4. Using OSCAP, calculate O&S cost parameters.

Results: Figures 6-10 and 6-11 show the power schedules for the F-14 and F-16 missions defined from General Dynamics data, respectively. Table 6-III defines the mission mixes. Table 6-IV summarizes the results which show that using the F-16 weapon system to fly the F-14 mission mix would result in a significant increase in SVR. And, if the General Dynamics mission mix had been used as the base instead of the Air Force SPO mission mix, the predicted SVR would be 40% lower.

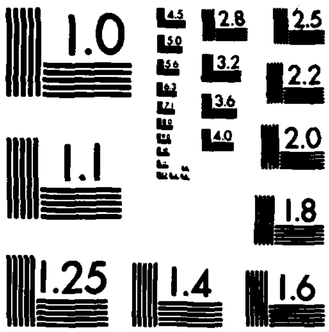
These results show the importance of identifying realistic mission mix definitions early in the development process. To date, the best method of accomplishing this appears to be by knowing how current fighters are being used for complete missions. This was accomplished on the F-14 using flight monitoring techniques on a number of aircraft that flew complete missions.

6.3 AIRCRAFT WEIGHT INCREASE STUDIES (STUDY NO. 4 AND STUDY No. 5)

One of the most frequent occurrences in a weapon system development is a shrinking of the system thrust to weight ratio. The causes for this shrinkage

AD-A127 740 PERFORMANCE LIFE AND OPERABILITY TRADE-OFFS IN VCE CONTROL LOGIC DESIGN..(U) GENERAL ELECTRIC CO CINCINNATI OH AIRCRAFT ENGINE BUSINESS GR.. 2/2

UNCLASSIFIED R G STABRYLLA AUG 81 R81AEG266 F/G 21/5 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

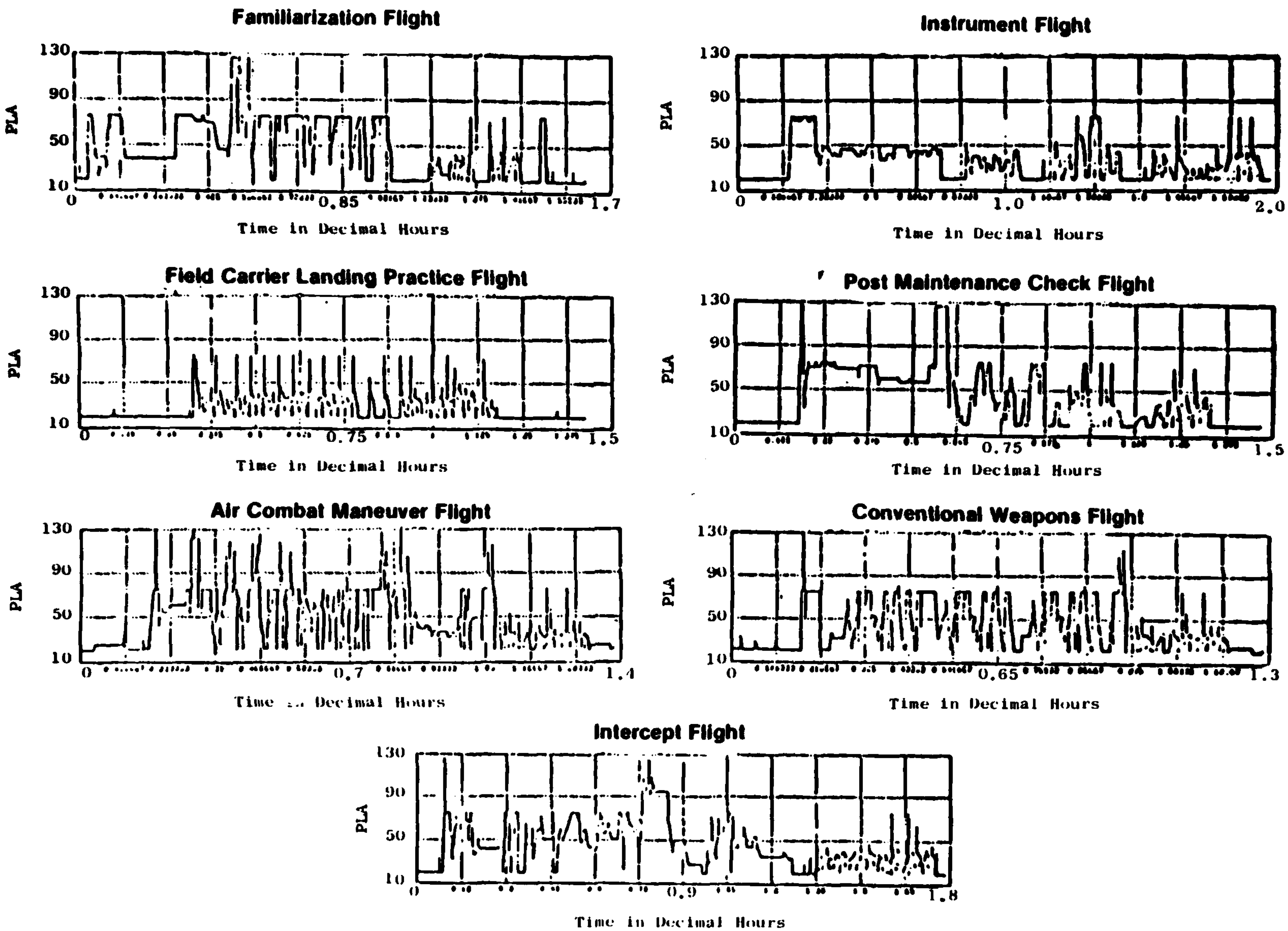


Figure 6-10. F-14A Mission Power Schedules.

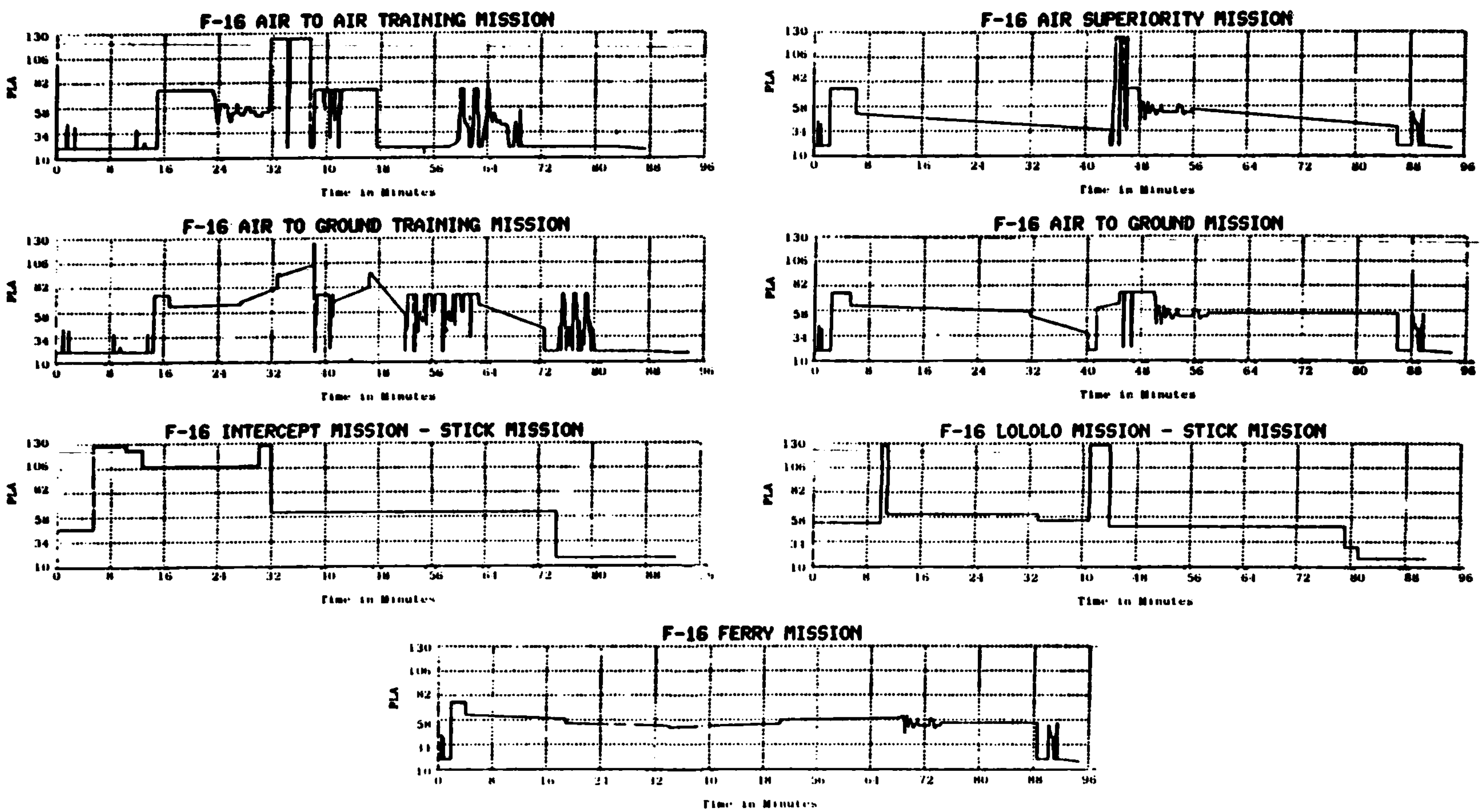


Figure 6-11. F-16 Mission Power Schedules (Reference G.D. Missions).

Table 6-III. Comparison of Mission Mixes.

F-16 Base Mission Mix

Mission	% Use	No. Sorties	Mission Length (Min)
Air to Surface (ATS)	45	409	132
Air Combat (ACM)	44.2	431	123
Functional Check Flt (FCF)	2.8	60	56
Test Stand Test (TST)	8.0	95	98.9
Total	100	900	

F-16 Mission Mix (Ref G.D.)

General Dynamics (5+2) Missions (F-16 DMM)

Mission	% Use	No. Sorties	Mission Length (Min)
Training			
• Air to Air (ATA)	30	576	87
• Air to Ground (ATG)	30	363	128
Combat			
• Air Superiority (ASM)	13	75	228
• Intercept	2	31	94
• LoLoLo	10	187	83
• Air to Ground (AGM)	10	58	224
• Ferry	5	22	293
Total	100	1312	

F-14 Mission Mix

Mission	% Use	No. Sorties	Mission Length (Hrs)
Familiarization	13.95	93	1.50
Instrument	23.38	122	1.92
Field Carrier Landing Practice	17.67	186	.95
Post Maintenance Check	1.70	14	1.22
Combat Maneuvers	13.70	111	1.23
Conventional Weapons	14.98	107	1.40
Intercept	14.62	82	1.78
Total	100.00	715	

Table 6-IV. Study Number 3. Effect of Mission Mix on Component Severity and SVR.

Mission Mix	F-16 Base	F-16 G.D.	F-14
Relative Severity Ratios			
Engine	1.0	.45	1.19
HPT Rotor	1.0	.98	1.25
Combustor	1.0	.73	2.0
Severity Ratio (cyclic/total)			
Engine	.88	.66	.90
HPT Rotor	.94	.88	.95
Combustor	.90	.76	.92
SVR (% change)	-	(~4.0)	30.0

( ) indicates decrease

are numerous, i.e., increased payload requirements, overweight airframe, increased electronics, engines with low thrust, etc. A quick review of historical data shows no less than five weapon systems that showed programmed and unprogrammed weight increases that ranged from 15 to 30%. The five systems are the commercial 747, the B-1 Bomber, the F-111 multirole aircraft and the YF16 and YF17 fighters. Since increased weight appears to be a common phenomenon, it was identified for evaluation in this program.

Both Studies Number 4 and 5 address this problem. However, the methodologies differ. In Study Number 4, the mission range and total full usage were held constant and the number of subsonic turns was determined while in Study Number 5, the full usage and subsonic turns were held constant and range was determined. All other portions of the methodologies used were the same.

Problem Definition: Determine the effect of aircraft system weight increase on aircraft mission performance capability, on component severities and SVR.

Inputs:

- o Base weapon system

Assumptions: None

Approach

1. Define one mission that is to be used to evaluate the effects of aircraft dry weight increases of 10 and 20%.
2. Determine two aircraft performance figures of merit to be evaluated.
3. Calculate mission for each weight increase and base weight.
4. Calculate power schedules.
5. Using OPSEV, calculate component severities.
6. Use OPSEV results to modify base engine component Weibulls.
7. Using OSCAP, calculate SVR.

<u>Results</u>: The mission defined in Study Number 2 was also used in these studies. The results of the studies are summarized in Table 6-V. For the constant range and fuel usage case (Study Number 4), the SVR and component severities were essentially contant as weight increased; however, the number of subsonic turns decreased by 19% and 63% for the 10% and 20% weight increases respectively. For the constant fuel usage and combat capability case (Study Number 5), the severities and SVR increased significantly while the mission range decreased 31% and 59% for the 10% and 20% weight increases, respectively. A review of the OPSEV analyses showed that in Study Number 4, the cyclic content of three missions increased slightly while the steady-state high temperature content decreased slightly, resulting in essentially constant component severities. On the other hand, in Study Number 5, the cyclic severity content increased significantly due to the fact that there are more shorter missions in 2000 flight hours. In addition, the total amount of time accumulated at high temperature conditions also increased. Thus, it was concluded that the trends identified are realistic. Further since all studies used the base cycle control set point, no change in operability is anticipated.

The results of these studies indicate that the increased aircraft weight alone does not necessarily result in a change in SVR. However, this, in combination with the mission usage, can have a dramatic effect on SVR. Further, it must also be recognized that the two cases selected for study probably represent the outer boundaries of reality. Further, in the real world, an additional option that could conceivably be considered is to increase the system thrust by increasing $T_{4.1}$ and shifting the compressor operating line (reducing surge margin). This new control set point option could also be considered, but it would be very difficult to quantify the SVR associated with engine stalls. The models being used cannot address this failure mode.

Table 6-V. Aircraft Weight Increase Results (Studies Numbers 4 and 5).

Aircraft Weight	Base	Study No. 4 +10%	Study No. 4 +20%	Study No. 5 +10%	Study No. 5 +20%
Severity Ratios					
Overall Engine	1.0	.996	.998	1.171	1.388
Fan Rotor		1.003	1.008	1.255	1.564
Compressor Rotor		.999	1.004	1.264	1.591
Compressor Stator		.991	.993	1.232	1.531
Combustor		.99	1.00	1.24	1.557
HPT Rotor		.99	1.00	1.294	1.658
HPT Stator		.994	1.004	1.234	1.538
LPT Rotor		.998	1.003	1.293	1.652
LPT Stator		.987	.987	1.261	1.590
A/B		.999	.973	1.268	1.604
Exhaust Nozzle		.988	.976	1.28	1.630
Aircraft Performance					
Range		Base	Base	(31.2)*	(59.0)
Total Fuel		Base	Base	Base	Base
No. M.9/30' K turns		(19.15)	(62.76)	Base	Base
SVR (% change)	Base	0	0	50	100

* ( ) indicates decrease

7.0 CONCLUSIONS

The results of VCE Controls Analysis Study indicate that trades can be made; however, no one procedure is adequate for all studies. Sound engineering judgment is needed to set up trade boundaries so the results reflect the actual problem.

Initial studies were performed assuming that PLA vs. time for a mission was constant independent of derate. Results showed reductions in severity, i.e., component life usage, that were in the 10-20% range. Performance studies were carried out by evaluating various figures of merit, i.e., SFC, accel, climb, etc., for the new set point.

Next the study evaluated methodology. The approach taken was to evaluate specific mission performance in terms of combat capabilities for a fixed fuel and mission range. Power requirements were identified for each derate case and life analyses performed using these power schedules. This approach allowed comparison of combat capabilities with component life ratios, showed smaller savings in life consumption. This result appears realistic. Thus, one must conclude that for initial trends, the initial approach is adequate; however, the more detailed approach is necessary if a more accurate answer is needed.

The next evaluation performed was aimed at assessing the usefulness of the tools in evaluating the effect of aircraft changes on engine life. The problem identified was to evaluate the effect of aircraft weight increases. Two approaches to evaluate this question were carried through. The first was to hold range and fuel usage constant and let combat capability decrease. The second approach held fuel and combat capabilities constant and allowed range to change.

The results of these two studies were quite different, and the responsible Air Force management team would have to decide which solution most realistically represented the real world.

In conclusion, the results of the present study indicate that:

- A quantified range of system performance and engine life trade options is available through control set point selection; however, operability must be maintained in the system context.

- Engine life can be predicted for evolving missions and aircraft characteristics with reasonable accuracy.
- The usefulness of the analytical capabilities is strongly dependent on the accuracy of the individual models. The individual aircraft performance model, the cycle deck, the OPSEV, and the OSCAP models must be formulated to represent the specific weapon system being studied. Preferably, their modeling should reflect test data whenever possible, i.e., wind tunnel or flight aircraft data, AMT-IV durability data, etc.
- The decision making potential of these tools must be based on the capability to relate the calculated results to the military requirements and their evolution.
- Great care must be exercised in formulating the calculation methodology to assure it represents an accurate simulation of the preceived problem.

Finally, assurance of the engine product can be achieved through

- understanding of military requirements and their evolution
- proper and sufficient development testing
- engineering based analytical procedures suitable for absorbing the test data and making verifiable projections of system life characteristics.

8.0 RECOMMENDATIONS

It is recommended that:

- A Systems Perspective always be maintained in Control Requirements Definition.
- Operability margins be positive if engine life is to be predictable.
- These analytical techniques be made available to organizations responsible for predicting engine parts usage.
- The military customer use these techniques to provide performance/life trade options.

9.0 REFERENCES

1. Troha, W., and Stabrylla, R., Effects of Aircraft Power Usage on Turbine Engine Relative Durability and Life, AIAA/SAE/ASME, 16th Joint Propulsion Conference, Paper No. AIAA-80-1115, June 30 - July 2, 1980.

2. Akimov, V.M., Starik, D.E., et al., The Economic Efficiency of Raising the Flying Life and Reliability of Gas-Turbine Engines, Ekonomicheskaya Effektivnost' Povysheniya Resursa i Nadezhnosti Gazoturbinnykh Dvigateley, 1972, pp. 1-170, English Translation FTD-MT-24-291-73.

3. Spencer, R.L., The Engineering Basis for the Application of Life Cycle Cost or Supportability Criteria to Gas Turbine Engines, Fifth International Symposium on Airbreaking Engines, February 16-21, 1981, Bangalore, India.

*USGPO:1983-659-062-865