F100 Engine Diagnostic System (EDS)—Summary of Results

James A. Boyless*
US Air Force Academy, Colorado
and
Dwelle C. Butts†
Wright-Patterson AFB, Ohio

An Engine Diagnostic System (EDS), proposed for the F100 engine, was tested in five specifically modified Tactical Air Command F-15A aircraft during a two-phase 16 month flight evaluation period at Langley AFB, Va. The first phase was conducted from March 1980-Dec. 1980 with phase two continuing until June 1981. After almost 4,000 engine operating hours and more than 1,000 flights, EDS successfully demonstrated four of five original design requirements. The requirements demonstrated included recording engine operating time and cycle data, event detection, engine trim, and trend and performance data collection. The diagnostic and troubleshooting goal was not fully demonstrated. In this paper the majority of the data presented covers the first phase, March-Dec. 1980.

Introduction

The U.S. Air Force On-Condition Maintenance (OCM) concept, defined in AF Regulation 66-14, establishes equipment condition as the prime determinant of maintenance need. To adequately perform OCM, engine maintenance management tools such as oil analysis, borescope inspection, parts tracking, periodic and phase inspection, monitoring, and diagnostics must be utilized. Of these, monitoring and diagnostics are by far the most difficult to implement. Monitoring and diagnostics development activities have encompassed aircraft/engine systems from the F-100/J57 to the recent F-15/F100. With each system, various parameters, both airframe and engine, have been used to provide information and engineering in order to establish a feedback loop for future engine development. A review of the F-15/F100 Engine Diagnostic System (EDS) is presented.

Background

History

As gas turbine technology increased complexity, so too did the need to assist maintenance personnel in the performance of their tasks. In addition, logistic requirements called for improved data in connection with engine life usage (e.g., information pertaining to engine operating time and cycle), thus necessitating a method for automatic data acquisition. Preliminary studies by the Air Force Aero Propulsion Laboratory indicated that an Advanced Fighter Diagnostic System (AFDS) could prove feasible for an advanced jet engine design.[1] The AFDS study defined both the hardware and software requirements[2], as well as researching existing capabilities. Follow-up studies of these existing capabilities showed that the F100 engine, in both the F-15 and F-16 aircraft, was well suited for an engine diagnostic system application. The F100 engine's complexity and its operational environment were ideal for testing and evaluating a diagnostic system.

System Description

The diagnostic system envisioned for the F100 engine, referred to as the F100 Engine Diagnostic System (EDS), was composed of airborne and ground elements.[3] The airborne element, shown in Fig. 1, consisted of six primary components: engine and aircraft sensors, multiplexers, data processor, status panel, advisory lights pilot option switch, and transfer receptacle. The ground element consisted of two primary components: the data collection and diagnostic display units (also shown in Fig. 1). A further description of each component follows.

Presented as Paper 81-1448 at the AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colo., July 27-29, 1981; submitted Aug. 25, 1981; revision received July 16, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Assistant Professor.
†Program Manager, Aeronautical Systems Division.

Airborne Element

Engine and Aircraft Sensors

Initial failure mode and effects analysis and cost effective analysis on the F100 engine showed that 38 engine and aircraft parameters should be included in the EDS. Tables 1 and 2 depict these parameters and the type of sensor or source used to acquire the data for diagnostics.

The use of existing engine inlet temperature, fan turbine inlet temperature, exhaust nozzle throat area, low spool rotor speed, high speed rotor speed, anti-ice command signal, fuel derichment signal, main oil pressure, EEC levels I, III, and III faults, and existing aircraft flow-meter precluded the need for additional EDS transducers.

Engine Multiplexer (EMUX)

The engine multiplexer unit—developed under Air Force contract—collects, conditions, and multiplexes sensor signals serially to the onboard Data Processor Unit (DPU). The EMUX replaces both the present F100 Event History Recorder (EHR) and the junction box (J-Box) for engine aircraft electrical connections. The unit is fuel-cooled using existing EHR cooling lines and is hard-mounted in the area vacated by the J-Box. It also sets a built-in-test maintenance indicator on the EDS status panel should it fail during operation.

Data Processor Unit (DPU)

The DPU is an airframe-mounted, air-cooled, central processor unit consisting of an Intel 8080 computer, core memory, and interface circuits. Both cooling and electrical power are provided by the aircraft. This unit is the nerve center of the in-flight monitoring system. It is programmed through software logic to detect a limit exceedance, set maintenance indicators, and store data surrounding the limit exceedance for later collection/diagnosis.

Aircraft Components

There are four aircraft components that are integral parts of the EDS: the cockpit advisory lights, pilot option switch, status panel, and transfer receptacle. The advisory lights and pilot option switch are located in the cockpit. Should a Fan Turbine Inlet Temperature (FTIT) anomaly occur, the lights turn on, thus giving the pilot a visual warning of a temperature excursion. The pilot option switch, upon activation, will take a snapshot of data at that point in time. It is used at the pilot's discretion.

To aid flight line-personnel in aircraft turnaround, an EDS status panel is located in an existing maintenance access door in the lower left fuselage. The panel has flag indicators specifying either to Go or No-Go status for the aircraft, as well as maintenance-advisories. Should there be a No-Go status or a maintenance-advisory, then the flight personnel would transfer the data via the transfer receptacle. The transfer receptacle, located in the same access door as the status panel, quickly connects the DPU to either the DCU or DDU for extraction of stored data. Average transfer time is six seconds. Collection or diagnostic operations can be performed at the aircraft with the collection unit or the diagnostic display unit.

Ground Element

Data Collection Unit (DCU)

The DCU is a small lightweight portable battery-powered unit that collects data from the DPU. The collected data is then transfered to either a DDU Or auxillary ground processor for analysis and engine life usage data records. The unit can store 10-15 flight records. For increased maintainability, the DCU uses interchangeable modules with the DPU and DDU.

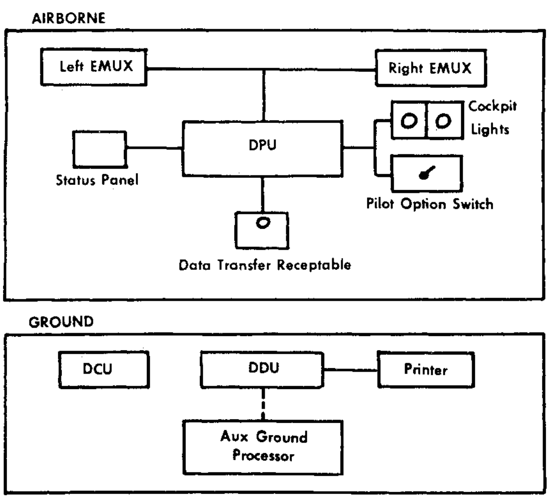

Fig. 1 System elements.

Diagnostic Display Unit (DDU)

The DDU is a more sophisticated portable unit capable of collecting not only up to five flight records but, also, diagnostics at the aircraft. It has an alphanumeric display screen and keyboard for interfacing with maintenance personnel. Personnel can prompt the unit via the keyboard for any of the stored data and recommended repair procedures. The unit uses interchangeable modules with the DPU and DCU and can be both battery-powered and 115 volts AC with adapter.

System Capabilities

The entire engine diagnostic system is designed to perform in five specific areas. These areas include engine operating time and cycle recording, event detection, engine trim, trend and performance data collection, and diagnostics and troubleshooting. To perform in all areas, collection of inflight data is a prerequisite. How collection of data occurs for all areas is shown in Fig. 2. For diagnostics and troubleshooting, event detection is vital. EDS detected events are of two types; No-Go events and maintenance-advisory events. No-Go events would set the No-Go indicators on the status panel and would specify that an event has been detected requiring grounding of the aircraft and maintenance prior to the next flight. Maintenance-advisory events are those events not serious enough to ground the aircraft but requiring maintenance when the aircraft is available. Maintenance-advisory events are also indicated by a light on the data collection unit.

Flight Evaluation

Objective

Validation of the functional capability of EDS to record engine operating time and cycle data, detect events, perform engine trim, record trend and performance data, conduct diagnostics and troubleshoot over a period of 3000 engine operating hours was the objective of the flight evaluation.[4]

Method

Five Tactical Air Command F-15A aircraft and 11 F100 engines would be specially modified with EDS equipment. These aircraft were to average between 45 and 60 engine operating hours per month. Time and cycle recording functional capability would be accomplished automatically by the EDS. Transfer of the recorded data would take place from the DDU to a teletype in the proper format of the present Modular Engine Time/Cycle Accumulation Record. The present Maintenance Action Cycle used at Langley would be integrated with the EDS. During the test the crew chief would check the EDS status panel to determine aircraft availability (Go/No-Go). If the status panel indicated an event, the flight dispatcher would send a technician with the DDU or DCU. The information would be reviewed and validated by the

Table 1 EDS engine parameters

Parameter	Source	Parameter	Source
Augmentor fuel pump discharge		Fuel pump inlet temperature	
Augmentor permission fuel		Main oil	Thermocouple
Burner[a]		Compressor exit static	
Fan/core mixing[a]		Fan exit duct	
Fan exit duct[a]			
Fuel pump boost	Pressure transducers	Diffuser case	
Fuel pump inlet		Gearbox case	Vibration transducer
Fuel pump discharge		Inlet case	
Main breather			
No. 4 bearing scavenge			
Rear compressor variable vane		Power level angle	Position transducer
Augmentor zone 1 fuel	Pressure switch		

[a]Contains temperature compensating circuitry.

propulsion maintenance unit with advice and/or assistance provided by the EDS team.

Validation of the data included an in-depth critique of the in-flight data. There were five categories in which the data would be grouped: Hits, Good, False (I & II), and Misses. A "Hit" is an event declared only by EDS and confirmed by the present reporting system, i.e., a pilot or maintenance write-up. A "Good" is an event not declared by EDS nor reported by the present system, i.e., "Good" flight. A "False I" is a false event declared by EDS and not by the present reporting system, while "False II" is false but known "fix" is in work

Table 2 EDS aircraft sensors

Parameter	Source
Angle of attack Pressure altitude	Air data computer
Total fuel flow	Fuel flow transmitter
Weight on wheels	Nose landing gear relay
Engine inlet total pressure Mach No.	Derived

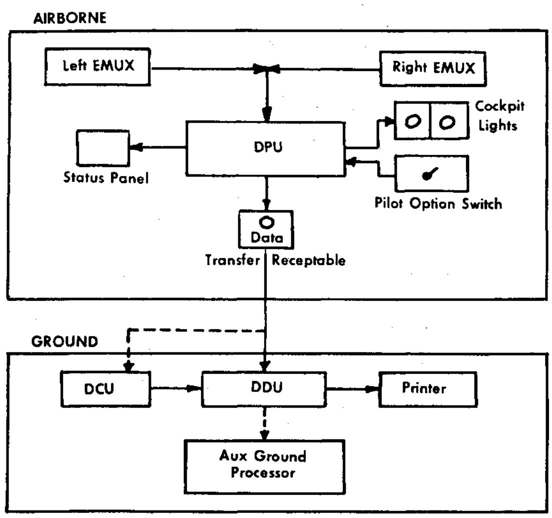

Fig. 2 EDS data collection.

to remedy the cause. A "Miss" is a pilot or maintenance write-up not detected by EDS when it should have been.

Engine trim, both installed and uninstalled, would be performed using EDS instead of the present M-37 test-stand or trim-pad trim procedures. The time required to trim would be carefully monitored for analysis. EDS would collect trend and performance data automatically when engine stabilization and Power Level Angle criteria were met. Finally, diagnostics and troubleshooting were to be evaluated by careful review of actual equipment usage by maintenance personnel. If maintenance was declared once an event detection occurred, the procedure called for the repairman to use the DDU. When validation of the event occurred, the DDU would be used to diagnose or "troubleshoot" the malfunction. Maintenance records would be screened and data collected which expressed the amount of time needed to troubleshoot and diagnose malfunctions.

Results

The Flight Evaluation Phase (FEP) test results are based on the period March-Dec. 1980.[5] The FEP, because of software complexity, was divided into a debug and an actual validation period. The debug of the software lasted from March 1 to Aug. 31. During this period, approximately 1700 engine operating hours were flown by test aircraft, providing software testing and modification for the validation phase. Between Sept. 1 and Dec. 12 an additional 880 hours were accumulated, during which time five specific areas of the EDS were tested. As listed previously, these areas are engine operating time and cycle data recording, event detection, trend and performance data collection, diagnostics and troubleshooting, and engine trim.

Automatic recording of engine operating time and cycle data was accomplished during the FEP. Approximately 600 EDS automated forms from in-flight and ground data were recorded. These automated forms represented a successful transfer information rate of approximately 89% during the first phase of the FEP.

The event detection design requirement was successfully demonstrated. At the beginning of the FEP, 13 events were programmed through software logic into a decision matrix. The decision matrix used combinations of parameter inputs and limit exceedance levels. The two levels of events used during the FEP were No-Go and maintenance-advisory. At the start of the FEP there were 11 No-Go events and, as evaluation continued, it became clear that many of these events did not require immediate maintenance of the aircraft (See Table 3). There were five No-Go events redesignated as maintenance-advisories and main fuel pump deterioration

Table 3 Event menu

	Flight evaluation			
	Start		End	
Event types	No-Go	Maintenance advisory	No-Go	Maintenance advisory
Hot start	X		X	
N2 overspeed	X		X	
FTIT overtemp	X		X	
FTIT spread out of limits	X			/
Oil pres out of limits	X		X	
Scav pres over limits	X			/
Vibs over limits	X		X	/
EEC fault	X	X[a]		/[a]
Engine stall	X	X[b]		/
Augmentor blowout		X[b]		
	X	mislight		/
Rcvv out of limits		X		/
Main fuel pump deterioration		X		
Main fuel pump failure	X		X	

[a]If cleared by pilot. [b]If out of envelope.

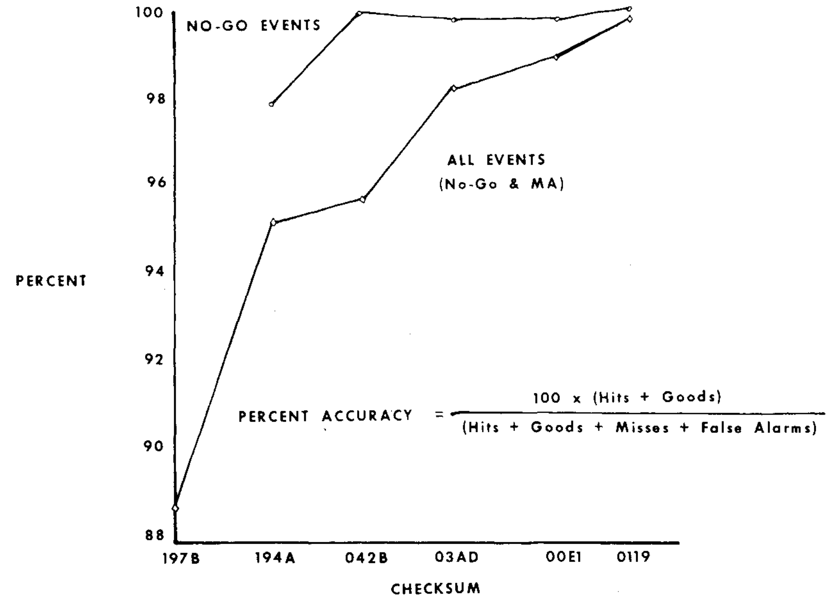

Fig. 3 Event detection accuracy.

Table 4 Evaluation summary

Engine No-Go	Hot start	2
	Oil temperature	2
	Oil speed	0
	Oil pressure	4
	EEC	24
	MFP Failure	9
Maintenance Advisory	Stall	21
	FTIT spread	85
	Scavenge pressure	9
	Aug BO/ML	2
	RCVV	46
	VIBS	42
Records	Trend	183
	Performance	67

was deleted. The five event changes were the result of refining the software logic. Logic changes, necessitated by numerous false events during throttle transients, received distinctive identifiers called checksums. The checksums were printed out with each data package transferred from the DPU. Using each checksum as a reference point, Event Detection Accuracy reached 99% (See Fig. 3) by the end of the debug period.

Using the last operable checksum, 0119, the entire evaluation period was reviewed and summarized as shown in Table 4. Of the 12 events continuously monitored by EDS, there were five events that were detected on numerous flights during the evaluation period.

Stall occurrences were very prevalent during the evaluation. Assessment of the EDS data revealed that few stalls were reported by the pilot and most of the stalls detected were associated with augmentor operation.

FTIT spread occurrences were also numerous during the evaluation with 85 being reported. FTIT is sensed by seven thermocouples equally spaced around the circumferences of the engine at a station between the high pressure and low pressure turbines. The individual sensed values are averaged and used by the engine control to establish the engine's maximum power output, as determined by the maximum allowable operating temperature.

During the FEP, there were 46 occurrences of RCVV out of-limits. Rear Compressor Variable Vane (RCVV) detection is totally contained within the EDS and the pilot is unaware of any RCVV out-of-limits indication. RCVV limits incorporated in the EDS logic are broader than allowed in present technical orders, primarily to accomodate the wider range of TT2.5 (Fan Exit Duct Temperature) encountered in flight compared to the test stand. RCVV angle is not scheduled uniquely by controller but varies with TT2.5. When RCVV limits are checked at idle (Electronic Engine Control-on), the normal indication is 8708 to 9268 rpm. It the normal indication is not met, further RCVV schedule adjustment is required.

More than 40 vibration occurrences were recorded during the FEP. Vibration occurrences were detected for inlet and diffuser case as well as for the gearbox. These vibration areas are monitored for limit exceedance programmed in the DPU. The limits selected for EDS are identical to the M-37 test-stand values for uninstalled engines.

There were 24 EEC occurrences reported. The EDS is programmed to detect EEC faults in three different ways. Fault I is a failure of one of the two EEC N1 sensor signals and can be cleared by the pilot. Fault II is an exceedance of Power Level Angle (PLA) position, Compressor Inlet Variable Vane, or Mach number position resolver range checks. Fault III can be a failure of both N1 (Low Spool Rotor Speed) signals, a TT2 (Fan Inlet Temperature) or N2 (High Spool Rotor Speed) signal exceeding the maximum upper limit above PLA, selected processor calculation failure, or selected drift signal range check exceedance. These results demonstrate the successful capability of EDS to detect events.

EDS recorded trend and performance tracking data whenever the power level was stabilized in certain portions of the flight envelope. A total of 183 trend/performance data sets were recorded, representing approximately 20% of the total engine flights. The limited quantity of trend data was due to the requirement that the power setting be stabilized for 180 s at Power Level Angle (PLA) ranges as low as 30 deg. This was found to be incompatible with actual usage in the TAC environment. Analysis revealed that 74% of trend data points lie in the lower PLA range (30-40 deg). This range is in the idle reset area where the augmentor nozzle is wide open, thus producing data scatter due to differences in nozzle area. In order to increase the number of data points and reduce data scatter experienced in low PLA ranges, a change in constants was approved which increased PLA threshold to 60 deg and reduced stabilization time to 35 s for trend and 30 s for performance.

The diagnostic and troubleshooting capability of EDS was partially demonstrated. Both EDS on-site and maintenance personnel used EDS on a daily basis to confirm detected

Table 5 Potential engine "saves"

Event	Engine S/N	Pilot report	Corrective action
Oil pressure low	311	Yes	Serviced oil tank
Scavenge pressure high	470	No	Vacuum check, No. 4 compartment Found foreign material in oil system
Oil temperature	330	Yes	EDS detected oil temperature higher than reported by pilot. EEC changed
FTIT spread	160 311 330	Yes[a]	Borescope every 50 flight hours as precaution until phenomenon and consequences can be quantified
Failed FTIT probe	311 694 694	N/A	Replaced No. 4, verified No. 4, verified No. 5, verified
Failed cockpit Warning light		No	Non bill of material relay panel Blocked EEC failure warning to cockpit

[a] FTIT spread monitored only in EDS equipped aircraft.

Table 6 Maintenance "Saves"

Engine S/N	Pilot assessment	EDS record
694	Mismatch throttles to match rpm	Pilot option data record confirmed mismatch in rpm, FTIT, PLA rigging
470	No complaints	Repeated EEC level 1 faults
639	N/A	Several false RCVV events on recent flights, TT2.5 error, missing AP2 plug
722	Low thrust rpm instability	Low out of trim pilot option record
801 (528)	A/B blowout on both engines	801 ok. 528 "hardlight-blowout" followed by stall. EPR high 0.11
311	A/B blowout, took pilot option	Stall following augmentor "hardlight-blowout." RCVV's out of band, axial on stall, RCVV and pilot option events
907 (528)	A/B blowout on both engines	907 ok. 528 "hardlight-blowout" followed by stall
722	Augmentor anomalies on three FLTS. Second FLT double hard, light on burners	Stalls in augmentation on 722

events. During the FEP it was decided that, once confirmation of an event occurred, maintenance action would be recommended based on the severity of the event.

Finally, EDS engine trim capability was demonstrated. Both uninstalled and installed engine trim was performed using EDS. After five partially successful attempts at uninstalled trim, software changes were made and testing continued. Installed engine trim was successfully demonstrated after several attempts. The entire trim procedure with exception of Engine Pressure Ratio (EPR) check was performed. EPR check was not accomplished due to a false sensor reading.

Discussion

The value of EDS cannot be underestimated. This was one of the first fully-automatic engine monitoring systems that demonstrated capabilities in five distinct areas. The success of EDS in these areas can be shown by both potential engine and maintenance "saves". Tables 5 and 6 show these engine and maintenance saves credited to EDS during the flight evaluation. Engine saves included a high-scavenge pressure event of which the pilot was unaware. Had the discrepancy continued, the engine could have suffered catastrophic failure. But the most obvious save for maintenance was the prevention of misdirected maintenance. Whereas four of the eight pilot assessments included dual engine anomalies, EDS confirmed that only one engine had the anomaly.

There were two areas in which the pilot was unaware of any discrepancies. One area, FTIT spread, is a non-reportable item, that is, only EDS can monitor a non-uniform temperature spread from the seven installed probes. The second area is RCVV excursions. These excursions, dependent on TT.5 input, indicate that actual flight operation rather than ground test stand, is perhaps the best area to monitor.

Conclusions

The F100 Engine Diagnostic System was designed to complement the present On-Condition Maintenance concept espoused by AFR 66-14. It successfully demonstrated four of five general design requirements. The EDS was used successfully for validating needed maintenance and preventing unnecessary maintenance. There were also significant areas of interest for design engineering as a result of actual in-flight monitoring of the F100 engine. After the initial phase of the F100 Engine Diagnostic System (March-Dec. 1980) there were several significant accomplishments. Four of the five general design requirements were successfully demonstrated: automatic recording of engine operating time cycle data, event detection, engine trim, and trend and performance data collection. Over 1,000 flights—the equivalent of almost 4,000 engine operating hours—provided an in-depth look at 38 engine and airframe parameters. In retrospect, the expectations of the EDS were very high, yet, in general, they were reached during the first phase.

The first phase of the FEP brought many changes to the software logic which gradually increased the event detection accuracy of the EDS to 99.7%. In several areas the findings were significant.

1) Fan Turbine Inlet Temperature spread occurrences were unexpected. Actual cause and effect are still under investigation but, as a precaution, the 100 h borescope interval was halved to 50 h. Three inspections on engines have revealed no major problems to date.

2) Stalls were also numerous and analysis showed that they were associated with augmentor sequencing. A stall counter was added to the logic to record the number of stalls encountered during a flight. At this time, the engine manufacturer continues to study this problem.

3) Rear Compressor Variable Vane scheduling is still being investigated. As transient phenomena, RCVV's may or may not impact engine performance. All that is known now is that engines are being "scheduled" at or near the upper limit of the RCVV band.

4) Vibrations continue to be investigated. At present the data indicates that inlet case vibrations cannot be fully monitored using unistalled M-37 test-stand limits.

5) It is well understood that pilot workload may preclude the detection of engine anomalies unless there are audible and vibratory cues. Often, excessive temperatures and oil pressure fluctuations may go unnoticed during evasive maneuvers. An engine diagnostic system programmed to detect these events as well as others will aid pilots and maintenance personnel in correctly determining the condition of an engine. It will also provide a tool for maintaining engines more efficiently.

6) EDS has been used during the FEP phase as an engineering tool to further understand engine performance. A weight-on-wheels (WOW) activation switch for data collection has been added to record data at takeoff—a predetermined repeatable point. Also, the pilot option switch has been often used to take data when event logic needed refinement. This snapshot of data often revealed discrepancies in the logic, thus leading to corrective action.

7) Finally, EDS has demonstrated that it can assist maintenance personnel in the repair of the F100 engine.

References

[1]MDC A3726, "Preliminary Investigation of AFDS Hardware Requirements," McDonnell Aircraft Co. Report, 1976.

[2]MDC A4270, "F100 EDS Hardware and Software Definition Phase," McDonnell Aircraft Co. Report, 1976.

[3]Carlson, R., et. al., "Report to Scientific Advisory Board on Turbine Engine Monitoring Systems," Aeronautical Systems Div., AF Systems Command, Wright-Patterson AFB, Ohio, 1979.

[4]MDC A5566, "Flight Evaluation Plan," McDonnell Aircraft Co. Report, 1976.

[5]Boyless, J.A. "F100 Engine Diagnostics System Status-to-Date," *Conference on Aircraft Engine Diagnostics,* NASA CP-2190, 1981.

From the AIAA Progress in Astronautics and Aeronautics Series . . .

AERO-OPTICAL PHENOMENA—v. 80

Edited by Keith G. Gilbert and Leonard J. Otten, Air Force Weapons Laboratory

This volume is devoted to a systematic examination of the scientific and practical problems that can arise in adapting the new technology of laser beam transmission within the atmosphere to such uses as laser radar, laser beam communications, laser weaponry, and the developing fields of meteorological probing and laser energy transmission, among others. The articles in this book were prepared by specialists in universities, industry, and government laboratories, both military and civilian, and represent an up-to-date survey of the field.

The physical problems encountered in such seemingly straightforward applications of laser beam transmission have turned out to be unusually complex. A high intensity radiation beam traversing the atmosphere causes heat-up and breakdown of the air, changing its optical properties along the path, so that the process becomes a nonsteady interactive one. Should the path of the beam include atmospheric turbulence, the resulting nonsteady degradation obviously would affect its reception adversely. An airborne laser system unavoidably requires the beam to traverse a boundary layer or a wake, with complex consequences. These and other effects are examined theoretically and experimentally in this volume.

In each case, whereas the phenomenon of beam degradation constitutes a difficulty for the engineer, it presents the scientist with a novel experimental opportunity for meteorological or physical research and thus becomes a fruitful nuisance!

412 pp., 6 × 9, illus., $30.00 Mem., $45.00 List

TO ORDER WRITE: Publications Order Dept., AIAA, 1633 Broadway, New York, N.Y. 10019