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ASSESSMENT OF AUGMENTED ELECTRONIC FUEL CONTROLS FOR MODULAR ENGINE DIAGNOSTICS AND CONDITION MONITORING

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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

The work reported herein is part of a continuing effort of the Applied Technology Laboratory, US Army Research and Technology Laboratories (AVRADCOM), to conduct investigations directed toward advancing the state of the art of diagnostics for Army aircraft. Technological advances continue to afford the Army the opportunity to improve the maintenance and support requirements for gas turbine engines. It is the intent of this organization to apply these technologies in a timely, productive, and cost-effective manner.

The object of this particular effort was to establish the requirements and to define the approaches to be used to include condition monitoring and on-condition maintenance features in the design of advanced electronic control systems for helicopter turboshaft engines. Although the investigation is considered to be generic in nature, the General Electric T700 gas turbine engine was used to derive real world experience and to evaluate applicability to an existing Army helicopter gas turbine engine. The T700 engine is being employed on the Army's UH-60A BLACK HAWK helicopter (Sikorsky) and on the advanced attack helicopter (AAH) under development by Hughes Helicopters.

The findings of this report are being used to identify the parameters necessary for fault isolating the module and line replaceable unit (LRU) level and to assess the impact of integrating diagnostic and condition monitoring (D&CM) functions with a full authority digital electronic fuel control.

Although it has been shown that fault isolation by means of an electronic diagnostic system is feasible, it has not yet been established that the D&CM system to accomplish diagnostics would be cost effective. Future efforts are planned to assess the cost effectiveness and to conduct trade-off studies of potential engine D&CM systems and their impact on Army aviation maintenance philosophies.

The technical monitor for this contract was Mr. G. William Hogg, Aeronautical Systems Division.

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A T700 functional baseline FADEC control design was established which contained approximately 70% of the parameters planned for diagnostics and condition monitoring. An integral part of the GE FADEC system is Failure Indication and Corrective Action (FICA), based on extended Kalman-Bucy filtering techniques. An important part of this study was to adapt FICA to a turboshaft engine. This effort showed by computer simulation that the system could detect single and multiple control sensor failures, and could make corrections which would permit continued satisfactory engine operation by the use of simulated control sensor signals estimated by FICA. Indication of failed sensors by FICA and indication of computer failures through self-test provide inherently significant D&CM capability. The FICA system also calculates intermediate engine parameters, such as T3 and T4.1, allowing more complete hot part life calculations.

General Electric's (GE's) experience with the T700-GE-700 turboshaft engine and other engine condition monitoring activities was used to determine the diagnostic functions desired. Fault isolation to the LRU and module levels is discussed and preliminary lists of parameters required for implementation on both FADEC and non-FADEC-equipped engines are provided. Further study and analysis, however, is necessary to verify the system effectiveness.

Integration of the FADEC and D&CM systems at the outset of the control design provides the potential for maintenance payoffs associated with D&CM at reduced development and procurement cost. It is concluded in this report that:

1. The FADEC system can inherently accomplish the D&CM functions of engine history calculations, detection of most control sensor failures, and detection of some control system failures.
2. The FADEC system should accomplish all D&CM signal processing except vibrations.
3. D&CM functions such as a HIT check, tracking oil pressure and detection of overtemperature, filter bypasses, and chip detection indications should be integrated into FADEC.

To continue the momentum of this program, it is recommended that the following steps be taken in the near future:

1. A detailed study (to be followed by a test phase) of a D&CM system to achieve the specific goal of fault isolation to the Module and LRU level for a T700 Engine on-the-wing in a cost effective manner.
2. A digital, engine-mounted history recorder containing important basic elements should be designed, fabricated, and engine tested to demonstrate integration of engine history and health in a unit using FADEC technology.
3. A study should be initiated to increase FADEC system ability to detect and provide corrective action for control system failures not detected by FICA or self-test, thereby increasing D&CM capability.

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INTRODUCTION AND SUMMARY

The Army's emphasis on improved maintainability, reliability, and life-cycle costs for its fleet of new T700 turboshaft engines has resulted in dramatic improvements. Modularity in the basic engine design which permits major assemblies such as the gas generator or power turbine to be replaced in the field, elimination of rigging and trimming after accessory replacements, and remarkable improvements in the remove-and-replace times for key control and accessories Line Replaceable Units (LRU's) are achievements already accomplished. The benefits of these maintainability features, however, may be further enhanced if the Army's ability to correctly identify the faulty engine module or LRU can be improved. This report describes two means of improving the LRU and module fault detection and isolation: (1) adoption of a Full-Authority Digital Electronic Control (FADEC) with built-in D&CM capability, and (2) integration of advance electronic condition monitoring with existing engine control systems.

The digital computation used in a FADEC system allows the use of built-in failure indication and corrective action (FICA) circuits to enhance control system reliability without the use of redundant sensors. The predicted reliability of the proposed FADEC approach can be compared to that of the present T700-GE-700 engine* control system by looking at the maintenance removals. Due to the simplification of the hydromechanical unit (HMU), and any other features such as the self-testing of the electronic control unit (ECU), significant reductions in maintenance removals can be predicted (see Table 1).

TABLE 1. RELIABILITY COMPARISON

	Maintenance Removals per 10,000 Engine Flight Hours		
Component	T700 Engine	FADEC System	Remarks
Hydromechanical Unit (HMU)	4.3	1.3	FADEC HMU less complex and less susceptible to contamination.
Electrical Control Unit (ECU)	2.2	1.5	FADEC ECU benefits from digital schedule computations, temperature compatible materials, automated assembly, and self-testing.
Engine History Recorder (EHR)	0.7	0.5	FADEC ECU incorporates the Engine History Recorder electronic section.
Sequence Valve (SV)	1.3	1.3	No change.

*T700 refers to the T700-GE-700 engine throughout this report.

This improved reliability level can be translated to a reduction in maintenance for these same components, as shown in Table 2.

TABLE 2. MAINTENANCE INDEX COMPARISON

Component	Man-Hours per 10,000 Engine Flight Hours T700 Engine	 FADEC System
Hydromechanical Unit (HMU)	153	22
Electrical Control Unit (ECU)	365	208
Engine History Recorder (EHR)	67	28
Sequence Valve (SV)	31	31
Total Control System	616	289

These comparisons show that the FADEC can ultimately improve the overall engine control system reliability and maintainability. This significant impact is increased by the system weight and cost reduction due to the fact that much of the needed D&CM sensors and computational capability is provided free in a FADEC-based system.

This study was an investigation of the requirements to accomplish D&CM objectives in the presence of the expanded number of available signals provided for future FADEC applications. With FADEC, every engine sensor signal required for control system operation is available in a usable digital format and available in one location for diagnostic use. In addition to providing more signals for engine diagnostics, the FADEC system has a failure indication and corrective action (FICA) capability. The FICA strategy for turboshaft application is defined in the study.

Preliminary estimates indicate that as many as 33 engine parameters may be required to detect and isolate to the LRU and module level the most common faults predicted to occur in service with either the current T700 engine or a future FADEC-equipped T700. The FADEC-equipped engine, however, would have 21 of these signals available in digital form, 4 in analog form and would require only 8 new sensors. The current T700 engine has 16 analog signals that could be made available for D&CM, would require 17 new sensors and, of course, has no digital signals. In addition, at least ten of the available analog signals would require electrical circuit isolation.

Because of the extensive engine and off-engine hardware and software that may be required for module and LRU fault isolation, detailed trade studies are required to provide data for sound decisions on the degree to which electronic fault isolation can be accomplished within practical and economic limits.

The need for additional sensor development was studied and though all sensors for FADEC development are available, recommendations are made for the development of several special sensors as well as for cost reduction of digital pressure transducers.

TASK I - DIAGNOSTIC FUNCTION IDENTIFICATION

Engine diagnostic and condition monitoring systems mounted on board aircraft are implemented in a variety of designs for both military and commercial aircraft. These systems are designed to detect incipient failures, measure life used, troubleshoot and identify faulty modules or components, and detect mechanical and performance degradation.

Because the military aircraft D&CM environment is different from the commercial in almost every aspect, the military services are developing their own D&CM concepts by performing studies and building and flying development systems. General Electric is contributing to these efforts under contracts with all three services. The information contained in this report utilizes this ongoing GE-Military D&CM experience.

PRELIMINARY PARAMETER SELECTION FOR FAULT DETECTION AND ISOLATION OF CURRENT PRODUCTION T700 LINE REPLACEABLE UNITS AND MODULES

Table 3 is a preliminary or candidate list of the engine and aircraft parameters believed necessary for LRU and modular fault detection and isolation to a high degree of effectiveness. Detailed studies and analyses are required to develop a more definitive parameter listing and a quantitative measure of diagnostic effectiveness for a D&CM system using the listed or similar parameters. It should be pointed out that because engine faults detectable only by visual inspection (which includes borescopy) can comprise 10-15% of all engine field events requiring maintenance actions, electronic diagnostic systems cannot be expected to detect and isolate more than 85-90% of the field or organizational level failures. Effectiveness of Fault Detection (FD) and Fault Isolation (FI) is defined as follows:

$$\text{FD\%} = \frac{\text{No. of failure events detected correctly by D\&CM} \times 100}{\text{No. of actual failures experienced}}$$

$$\text{FI\%} = \frac{\text{No. of failure events that have occurred} \times 100}{\text{No. of maint. actions to correct*}}$$

*A maintenance action can be an engine, component, or module replacement or adjustment.

A further refinement can be made if it is specified that only events resulting in an in-flight power loss - automatic or voluntary (by pilot action) - are to be considered. Such a restriction would tend to make any D&CM system appear to be more effective in Fault Detection.

TABLE 3. MINIMUM CANDIDATE PARAMETERS FOR LRU & MODULE FAULT DETECTION AND ISOLATION - NONFADEC T700

	Gas Gen. Speed	Power Turb. Speed	G.G. Turb. Disch. Temp.	No. 1 Eng. Torque	No. 2 Eng. Torque	Pressure Altitude	Comp. Inlet Press.	Anti-Ice Valve On-Off	ECU Input to HMU-TM current	Power Turb. Speed-Demand	HMU F/B to ECU LVDT	Sequence Valve O/S Signal	VG Position LVDT	Comp. Disch. Press.	Alternator Power-ECU	Fuel Press. - Boost Pump	Fuel Filter / Bypass	Load Demand Signal	Compressor Inlet Temp.	Overspeed Test	Power Available Spindle	Lube Press. Differential	Lube Temp.	Master Chip Detector	Lube Filter Bypass	IPS Blower P/T	IGN Exciter Output	AGB Vibration	Comp. Disch. Temp.	Fuel Flow	Customer Bleed-On/Off	Vibes.-Exh. Frame	Fuel Temp.	TOTALS
	NG	NP	T4.5	Q1	Q2	PO	PT2	AI	WFD	NPD	WFFB	OS	VG	PS3	ALT	FP	FWF / BP	LDS	T2	OST	PAS	PL	TL	MCD	FL/ BP	IPSP	IGN	V	TS3	WF	CB	V2	TF	
Signals - Existing	x	x	x	x	x			x	x	x	x	x			x		x			x			x	x	x									16
- New						(2) x	x						x	x		x		x	x		x	x				x	x	x	x	x	(2) x	x	(2) x	17
																																		33
Control & Fuel(1) System-LRU's	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	(2) x	x	x									(4) x	(4) x			21
Oil-Wetted Part LRU's	x																					x	x	x	x								x	6
Other LRU's															x											x	x							3
Modules																																		
Performance	x	x	x	x		x	x	x					x	x				x	x		x								x	x	x			15
Vibration	x	x																										x				x		4
Oil Debris																								(3) x										1
Life Usage	x		x			x													x										x					5

NOTES: (1)At least 10 control signals require electrical isolation by means of buffer circuits.
(2)Signals required from airframe mounted sensors.
(3)Isolation of OWP failure to module assumed to be by visual inspection of the six scavenge screens.
(4)Primary requirement is for modular fault isolation. Might be used for controls if applicable.

The maximum detection and isolation effectiveness rates for a D&CM system on the current T700 engine are estimated to be 85 to 90% for detection and 75 to 80% for isolation. Studies are required to determine whether the achievement of these rates would be cost effective. For comparison, the predicted rates for two GE designed augmented turbofan engine D&CM systems are as follows:

	FD%	FI%	#Parameters
Engine X	95%(1)	71.3%	44
Engine Y	89%	75.1%(2)	43

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(1) Count only events causing 10% power loss or more.

(2) Includes use of GSE - electrical circuit tester.

MODULES

The T700 engine is comprised of four modules: cold section (compressor and output section), hot section (combustor and high pressure turbine (HPT)), low pressure turbine (LPT) module, and accessory module (accessory gearbox (AGB) and most controls and accessories). For troubleshooting purposes, the accessory module is excluded from consideration since all its components except the AGB are LRU's that would be fault isolated and replaced separately as required.

Modular troubleshooting consists of detecting a fault, then isolating the fault to one of three modules. This may involve one or more of four diagnostic techniques, depending upon the problem: performance measurement, vibration measurement, life used measurement, and oil debris monitoring. Candidate parameters for modular troubleshooting are shown on Table 3. It is interesting to note that although 15 parameters may be required, only three would be unique to modular isolation. The relative predicted engine-caused failure rates for the three modules of interest as a percent of total engine events (as discussed later in this section under the heading of "Comparison of Predicted and Actual Distribution of Field Events"), excluding the module related oil-wetted part events, are as follows:

Compressor	9%
Hot Section	9.6%
Power Turbine	4.6%

Modular Performance Fault Isolation: Considerable savings in support costs may be possible if performance data taken electronically in flight or during ground tests would identify the module(s) responsible for low engine performance of an installed engine. In the case of the T700, a study was completed in Nov. 1977 which defined an analytical technique and the additional engine instrumentation required by the METS (mobile engine test stand) to isolate engine performance degradation to one of the three performance critical modules, which are the compressor high pressure turbine and power turbine. The METS method, which was evaluated as capable of "reasonable success" in fault isolation at maintenance bases, is not considered practical for installed engines because of the added instrumentation required, including accurate airflow instrumentation. Another approach applicable to on-the-wing fault isolation which has been studied requires much less added instrumentation than the METS and no airflow measurements. This method is a candidate for further analysis and evaluation for installed engine modular performance determination and is the basis for the parameter selection shown on Table 3.

The difficulty of conducting the performance diagnostic function in an acceptable manner is fully appreciated. More than 75% effectiveness in this type of fault isolation is probably not achievable due to unmeasurable leakage and cooling flow variations, and instrumentation error even if a practical method is developed. In addition to these difficulties is added the fact that overall engine performance is very sensitive to small changes in component performance. For example, the effect of module thermodynamic efficiency on overall engine performance for the T700 engine is approximately as shown below. A 10% loss in engine power would result from any one of the following reductions in component performance:

Power Turbine Efficiency	10%
Compressor Efficiency	2.6%
Gas Generator Turb. Eff.	2.5%
Leakage	3.0%

Modular Vibration Fault Isolation: The use of externally mounted accelerometers to detect power turbine, high pressure turbine, and compressor rotor out-of-limits unbalance is feasible. Two accelerometers, one mounted on the AGB and one on the exhaust frame, will detect a one-per-revolution unbalance condition on either rotor. Signal conditioning equipment unique to the accelerometers is required, including charge amplifiers, high and low pass filters, and tracking filters to track the two rotor speeds. Since rotor unbalance problems on the T700 engine are most easily detected during start-up acceleration, fault isolation could be performed during low power runs.

Regarding the detection of incipient bearing failures, experience has shown that accelerometers are not suitable for this role.

Modular Oil-Wetted Part Fault Isolation: Bearing, gear, spline or seal problems that generate magnetic debris particles in the oil will be detected by the master chip detector. Examination of the six scavenge screens at the scavenge pump inlets will, in many cases, indicate the source of the debris. If this is inconclusive, slave magnetic chip detectors can be inserted at the scavenge pump inlets for more effective debris capture during ground runs. Permanent installation of indicating and chip detectors in each line would not be recommended. Permanent installation of manually read magnetic plugs might be considered, if proven cost effective.

Modular Life Usage Monitoring: The measurement of low cycle fatigue based on gas generator speed excursions and stress rupture life usage based on cumulative time - T4.5 temperature measurement can provide a valuable prognostic tool for scheduling borescope inspections or module replacement. When LCF and stress rupture life limits become well established for several critical hot and rotating parts, these life usage measures can direct maintenance actions to specific modules with favorable reliability, maintainability and life-cycle cost impacts.

LINE REPLACEABLE UNITS (LRU'S)

Table 4 lists the 23 T700 engine components classified as LRU's by the T700 PIDS Appendix 50[1]. The LRU tabulation is arranged in order of decreasing predicted failure rate to show the LRU's with the highest potential payoff for D&CM at the top. Also shown is a preliminary estimate of the most effective D&CM technique for fault isolating each non-FADEC T700 LRU. Of special interest is the observation that only 16 LRU's or 70% are strong candidates for fault isolation by electronic D&CM monitoring. The remaining LRU failures are isolated by ground electrical circuit checks or visual inspection. In terms of number of failure events per 10 hours diagnosed electronically the percentage is higher - 279/331 - or 84%.

Reference to Table 3 indicates that as many as 17 additional signals, most of which require added engine sensors, may be required to achieve the maximum practical D&CM fault isolation capability. Most of these sensors would become LRU's also subject to failure and requiring fault isolation logic.

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[1] PRIME ITEM DEVELOPMENT SPECIFICATION (PIDS) FOR T700-GE-700 TURBOSHAFT ENGINE, General Electric Co., Lynn, MA., U.S. Army Specification No. AMC-CP-2222-02000A, page 213.

TABLE 4. D&CM PRIORITY LIST FOR LINE REPLACEABLE UNITS
T700 LRU(1) PREDICTED FAILURE RATES AT MATURITY

		Potential Fault Isolation Method			
		FR/10^6 Hours (2)	D&CM	Ground Support Equipment	Manual/ Visual
1.	Electrical Control Unit	105	X		
2.	Hydromechanical Control Unit	42	X		
3.	Thermocouple Harness (T4.5)	19		X	X
4.	Anti-Icing Starting Bleed Valve	17	X		
5.	Lube/Scavenge Pump	17	X		
6.	Fuel Filter Assy.	16			X
7.	Sequence Valve	14	X		
8.	Fuel Boost Pump	13	X		
9.	Ignition Exciter	12	X		
10.	Oil Filter Bypass Sensor	12	X		
11.	IPS Blower	10	X		
12.	Torque Sensor	8	X		
13.	Np Sensor	8	X		
14.	Wiring Harnesses	7		X	
15.	Igniters	7		X	
16.	Primer Nozzles	6	X		X
17.	Engine History Recorder	4			X
18.	Alternator Stator	4	X	X	
19.	Chip Detector	4	X	X	
20.	Radial Drive Shaft	3			X
21.	Oil Filter	2			X
22.	Oil Cooler	2	X		
23.	Ignition Leads	2	X	X	

(1)LRU's defined by PIDS Appendix 30

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[2] T700 BI-MONTHLY RELIABILITY PROGRESS REPORT, General Electric Co., Lynn, MA., U.S. Army Contract No. DAAJ01-72-C-0381, CDRL Item A060, 20 May 1974

Oil-Wetted Parts (OWP)

Monitoring of oil-wetted parts can isolate oil system problems to oil system LRU's such as pump, filter and cooler as well as detect non-LRU problems such as incipient bearing, seal, AGB and spline problems. As indicated later in this section under the heading of "Comparison of Predicted and Actual Distribution of Field Events", oil-wetted part problems are predicted to comprise about 19% of the problems to be encountered at organizational level. Of greater impact is the potential to prevent secondary engine damage and mission aborts by early warning of impending OWP problems. As Table 3 shows, only six monitored parameters are required to perform these functions. Assuming the existence of a D&CM system, OWP monitoring should be very cost effective.

Control LRU's: The need for a detailed analysis of the non-FADEC T700 control diagnostic system becomes clear when studying Table 3. Twenty-one candidate parameters of the 30 listed may be required for control and fuel systems diagnosis. Six of these parameters would require new sensors and several more would require electrical isolation or buffering to prevent the D&CM system from causing spurious signals to be fed into the engine's control. A trade study which considers projected system effectiveness, life-cycle cost effects, and reliability and maintainability impact is required in order to quantify these factors and provide a sound basis for future actions.

An indication of the computer logic required for control fault isolation can be obtained by reference to the T700 Maintenance Instructions TM55-7840-248-23, 31 May 1978.[3] The troubleshooting procedure block diagrams comprise [illegible] pages of troubleshooting logic, 48 of which are concerned with fuel and control system problems. A D&CM computer system comprising signal conditioning and fault detection circuitry in the airborne system plus fault isolation logic and display facilities, probably in a ground-based unit, would be necessary to provide the maintenance messages for LRU fault isolation. The analysis and trade study would determine how much of this logic would be feasible to include in the airborne D&CM system and how much in the ground unit.

Other LRU's

Separator blower failures can be detected and isolated with either a differential pressure or temperature sensor.

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[3] Aviation Unit and Intermediate Maintenance Instruction, General Electric Co., T700-GE-700 Engine, TM55-2840-243-23, 31 May 1978

Wiring harness and connector problems require circuit checks with ground equipment for isolation.

Engine history recorder problems become obvious when recorded data is analyzed.

Ignition system problems can be detected by monitoring ignition exciter output by an induction coil around the ignition leads. Isolating the problem between leads and igniters, however, probably requires ground circuit checks.

Sensors: Logic can be programmed into a D&CM airborne computer to make gross signal validity checks of most engine analog signals. The logic will determine if each signal is within the min-max band for an engine running between ground idle and high power conditions. Signal errors due to sensor calibration shifts, however, would not be detected as they would with a FADEC/FICA equipped engine as discussed later in Section V.

T700-GE-700 ENGINE FIELD FAILURE ANALYSIS

An analysis of all General Electric Field Service Reports (GE DV-7) has been made covering UTTAS and AAH flight testing of the T700-GE-700 engine between October 1974 and June 1977. The testing included more than 11,000 hours of T700 engine operation.

The failure rate of the unqualified T700-GE-700 engines is not of interest for this analysis, but the distribution of failures is important since it is an indication of the areas of greatest payoff for diagnostics and condition monitoring. Distribution of the 197 failure events resulting in an engine or component removal is shown in Table 5.

Table 5 shows that:

1. There was a low incidence (3%) of performance problems. In the six performance events there was no consistent degradation versus time effect. Time-since-new (TSN) varied from 1.5 hours to 143 hours. Longtime factory engines with more than 600 hours had no discernible performance degradation.

2. There was a predominance of controls and fuel system problems (53%). Further review of the details shows four components (HMU, ECU, SV, and primer nozzles) accounting for over 60% of all events in this category. With a FADEC system, the incidence of control failures should be significantly reduced, as shown in Table 1.

3. OWP problems accounted for 19% of the total failure events. This proportion, however, does not accurately reflect the critical nature of OWP problems. Such problems, if undetected early in their failure state, can and typically do lead to catastrophic failure with extensive associated secondary damage.

TABLE 5. DISTRIBUTION OF T700-GE-700 ENGINE FAILURE EVENTS

Failure Events	Percent
Performance Loss (1)	3.4
Compressor	3.9
Controls and Fuel System	53.4
Electrical (2)	12.3
Oil-Wetted Parts (3)	19.2
Miscellaneous	7.8
Hot Parts	0.0
	100.0 (4)

(1) Includes only those events caused by stalls, damage, or deterioration of gas path elements. It excludes abnormal performance corrected by control component replacements.

(2) Key electrical control components included with controls and fuel system.

(3) Includes lube and scavenge systems sumps, seals, bearings, and sensors. Twenty-seven chip detector inspections based on cockpit chip light indications are not included, as no engine or sensor failures were involved. In most cases, manufacturing or assembly debris caused the indication. In no case, however, did the detector fail to detect a bearing failure.

(4) "All-cause" failures were included rather than engine only caused failures, the usual measure of engine reliability. For D&CM analysis purposes, detection and fault isolation of all events, regardless of cause, is of concern. For example, all FOD events were included as compressor failure events as well as all stall events (performance event), some of which may have been airframe induced.

In conjunction with OWP problems, there were 39 chip detector alarms. Of these, 12 were valid and 27 were false, caused by manufacturing or maintenance debris. The 3:1 (39/12) ratio is lower than GE T700 factory experience of 5:1 or the Army's experience of 5-6:1 on other engines; nevertheless, chip detector systems warrant improvement. Under the present T700 engine maintenance plan, the procedure in the event of a chip alarm is to first shut down the affected engine, as soon as safety permits. The next step is to remove, inspect, clean and reinstall the chip detector. If analysis is not conclusive, run the engine for 15 minutes to see if another chip alarm is generated. If another chip alarm is not generated in the 15-minute test run, it is assumed that the initial alarm was not caused by abnormal wear or failure but by manufacturing debris or normal wear fuzz, and the engine is returned to service. If another chip alarm is generated in the 15-minute run, the process is repeated until either the chips clearly indicate failure or three 15-minute runs have resulted in no chip alarm. Such failure indications will result in engine removal, teardown, and failure investigation. The above chip alarm procedure has been fully effective in discriminating between a false chip alarm and an OWP failure usually with just one 15-minute run. Every failure during flight test was detected prior to the occurrence of secondary damage, and no engine was removed due to a false chip alarm. There were no chip detector failures.

Comparison of Predicted and Actual Distribution of Field Events

Table 6 shows a close correlation of predicted field failure distribution at organizational level versus the distribution of all-cause removals that actually occurred. The predicted failure distribution was obtained directly from the current T700 Failure Mode and Effect Critical Analysis (FMECA) sheets.

GENERAL ELECTRIC MODULAR REPLACEMENT EXPERIENCE

CF6 Engine

The modular design of the CF6 family of engines facilitates quick turnaround maintenance. The engine is made up of a number of separate modules or engine maintenance units (EMU's). The engine can be disassembled into modules for sectionalized repair and for rapid engine turnaround by module replacement. Modules and their subcomponents can be changed quickly and efficiently, as illustrated by the typical replacement times shown on page 26.

TABLE 6. MATURE T700 PREDICTED FAILURE RATES VERSUS MEASURED REMOVAL RATES AT FLIGHT TEST

	Predicted Engine Caused		Measured On Flight Test All Causes	
Component	Failure Rate (10^6 hr)	Percent Engine Total	No. of Events	Percent Total
CONTROL AND FUEL SYSTEM				
Hydromechanical Unit (HMU)	41.7	7.9	37	18.3
Sequence Valve	14.0	2.6	22	10.9
Fuel Filter	16.0	3.0	2	1.0
Fuel Boost Pump	13.0	2.4	4	2.0
Fuel Manifold	10.0	1.9	1	0.5
Fuel Injectors	6.0	1.1	0	0
Anti-Icing and Starting Bleed Valve	17.0	3.2	6	3.0
Electrical Control Unit (ECU)	105.0	19.8	10	5.0
Primer Nozzles	4.0	0.7	18	8.9
Torque Sensor	8.0	1.5	5	2.5
Speed Sensor	8.0	1.5	0	0
Unknown	-	-	2	1.0
Totals	242.7	46.6	107	53.0
COMPRESSOR				
Swirl Frame	4.0	0.8	2	1.0
Front Frame	2.1	0.4	-	-
Midframe and Mainframe	12.4	2.3	-	-
Stator	11.1	2.1	8 (FOD)	4.0
Rotor	6.0	1.1	3 (Stall)	1.5
Variable Geometry Linkage	8.0	1.5	-	-
Inlet Guide Vanes	4.5	0.8	-	-
Totals	48.1	9.0	13	6.4

TABLE 6 - Continued

	Predicted Engine Caused		Measured On Flight Test All Causes	
Component	Failure Rate (10^6 hr)	Percent Engine Total	No. of Events	Percent Total
OIL-WETTED PARTS				
Chip Detector	4.0	0.75	0	-
Accessory Gearbox (AGB)	24.1	4.5	0	0
Lube and Scavenge Pump	17.0	3.2	5	2.5
Oil Cooler	2.0	0.4	6	3.0
Lube Filter and B. P. Sensor	14.0	2.6	2	1.0
No. 1 Bearing Seal	1.0	0.2	6	3.0
No. 1 Duplex Bearing	2.4	0.5	0	0
No. 2 Roller Bearing	1.0	0.2	0	0
No. 4 Roller Bearing	2.5	0.5	2	1.0
Power Takeoff Drive Assembly	1.0	0.2	-	-
No. 3 Ball Bearing	2.3	0.4	10	5.0
No. 5 Roller Bearing	1.5	0.3	0	0
No. 6 Ball Bearing	1.3	0.3	0	0
No. 5 Carbon Seal	8.0	1.5	2	1.0
Miscellaneous	-	-	6	3.0
Total	82.1	15.5	39	19.3
EXTERNAL CONFIGURATION				
Fuel Lines and Hoses	10.0	1.9	-	-
Lube Lines and Hoses	4.0	0.8	-	-
Air Lines and Brackets	4.7	0.8	-	-
Inlet Particle Separator Blower	10.0	1.9	10	5.0
Total	28.7	5.4	10	5.0

TABLE 6 - Continued

Component	Predicted Engine Caused Failure Rate (10^6 hr)	Predicted Engine Caused Percent Engine Total	Measured On Flight Test All Causes No. of Events	Measured On Flight Test All Causes Percent Total
ELECTRICAL				
History Recorder	4	0.8	9	4.5
Igniter, Plugs, and Leads	-	-	5	2.5
Ignition Exciter	20	3.8	2	1.0
Wiring Harnesses	7	1.3	4	2.0
$T_{4.5}$ Harness	19	3.6	5	2.5
Alternator	4	0.7	0	-
Total	54	10.2	25	12.4
POWER TURBINE				
Output Shaft	1.0	0.2	-	-
Power Turbine (PT) Case	2.0	0.4	2	1.0
Stage 4 Nozzle	5.0	0.9	-	-
Stage 3 Nozzle	8.0	1.5	1	0.5
Power Turbine (PT) Rotor	7.1	1.3	-	-
Exhaust Frame	2.0	0.4	4	2.0
Total	25.1	4.7	7	3.5
HOT SECTION				
Rotor Assembly (HPT)	8.9	1.7	1	.5
Combustion Liner	16.0	3.0	-	-
Stage 1 Nozzle	19.0	3.8	-	-
Stage 2 Nozzle	7.0	1.3	-	-
Total	50.9	9.6	1	.5

Engine Module or Component	Number Men	Replacement Time (Hours)
Low-Pressure Turbine	4	6:00
High-Pressure Turbine	3	3:20
Stage 1 Nozzle	2	1:00
Combustion Liner	2	1:00
Ignition Plugs	2	0:09
Fan Rotor	3	4:40
Fan Blades	3	1:25

The modular design which permits changes without compulsory pretesting of individual EMU's or assurance testing of the engine has been proven in commercial operation of CF6 engines. For example, one operator reinstalled 62 engines which had module changes without a test cell run. Of these, only three did not give satisfactory performance. A study of another operator's 46 module change-outs revealed that when 35 were again removed after considerable flight time, only four engines had problems that might have been detected earlier in test cell runs.

The CF6 modular design also allows the engine to be split and subsequently quickly reassembled into core, low-pressure turbine, and fan sections with self-contained tooling. Such capability permits shipment of the CF6 engines (with necessary tooling) in a variety of military and commercial aircraft, including wide-bodied jet transports. This feature could be a major factor in reducing aircraft on ground (AOG) time for an aircraft in an area remote from its main maintenance base.

T700 Engine

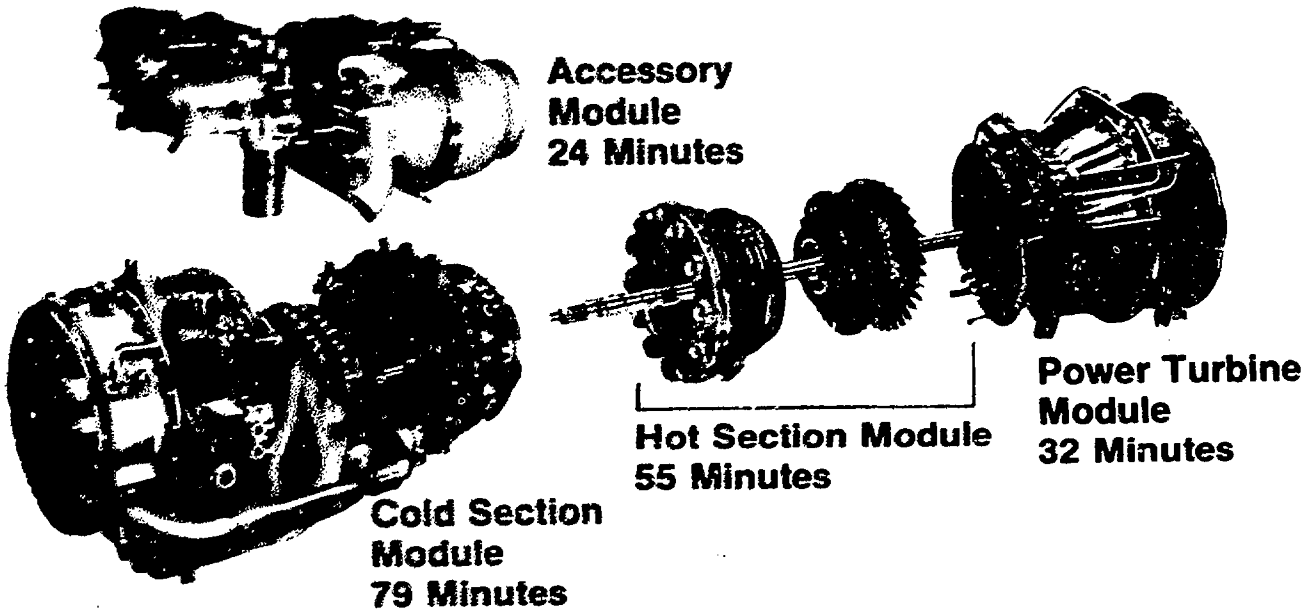
Replacing modules on this small turboshaft engine is comparatively simple. The engine is divided into four modules: the cold section module, hot section module, power turbine module, and accessory module (see Figure 1).

Cold section module removal and replacement is now done at the depot whereas the other modules are replaceable in the field.

Hot section module replacement has been difficult in the past. Now, with better control of balance and clearances, T700 production engine hot sections can be changed without match balancing.

The power turbine module has been removed and replaced frequently with no adverse effect on engine vibrations or performance.

Successful removal and replacement of the accessory module with no performance change have been demonstrated.



- Demonstrated by U.S. Army Maintenance Team
- 2 Men, Elapsed Time

Remove and Replace — Ready to Run

Figure 1. Modular Maintainability - T700.

T700-GE-700 ENGINE CONDITION MONITORING EXPERIENCE

Background

The status of Diagnostic and Condition Monitoring of the T700 engine at the completion of the UTTAS and AAH intensive flight test programs is given in Volume 8 of the T700-GE-700 Engine Design Report[4]. Volume 8 documents D&CM developments since June 1976 and offers subjective judgments and comments on the lessons learned that may apply to future turboshaft engine programs.

Engine History Recorder

The engine history recorder (EHR) is a 2-1/2-pound engine-mounted electrical analog device which is supplied on all production T700-GE-700 engines. Inaccurate counting of the number of engine starts, caused by the momentary power interruptions during preflight operations when electrical loads were being transferred from the auxiliary power unit (APU) to the aircraft alternator, was a nuisance problem during flight test. The problem has been solved by powering the EHR from the engine alternator through the engine wiring harness.

Field experience has dictated changes to the measured parameters on the original EHR to improve the utility of its output for monitoring the lives of key serialized engine components and modules. The original and improved parameter displays are compared in Table 7.

TABLE 7. MEASURED PARAMETER IMPROVEMENTS

Original Parameters	Improved Parameters
Engine Hours	Engine Hours - No Change (N/C)
Time-Temperature Index	Time-Temperature Index - N/C
Starts	Low Cycle Fatigue (LCF) Count - Full Cycles
Number of Overtemperature Events	Low Cycle Fatigue (LCF) Count - Partial Cycles
Overtemperature Flag	Eliminated

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[4] Rosen, M. M., T700-GE-700 ENGINE DESIGN REPORT, CONDITION MONITORING AND DIAGNOSTICS, General Electric Co., Lynn, MA, Aircraft Engine Group, Report R78AEG043, Volume 8, 28 June 1976.

Ideally, a more advanced unit would have two more useful output functions:

1. Computation of low cycle fatigue using a more sophisticated cycle counting method that equates all speed related cycles large and small to an equivalent number of "master cycles". This would replace two LCF cycle counts - major and minor. A program to accomplish more accurate computation of LCF has recently been initiated.

2. Computation of engine health performed in the EHR and displayed in the cockpit to relieve the pilot of some HIT check functions that divert his attention from flight operations.

Both of the above functions require computations best done by a digital computer. The advanced EHR would then have the following functions:

Engine operating hours Time - temperature LCF master cycles	Non-resettable counts
Engine health/or degradation - percent	Input to cockpit display.

Magnetic Chip Detector

One master chip detector design change has been approved recently by the Army for production engines. The secondary (nonmagnetic) gap is being eliminated in an effort to reduce the incidence of nuisance signals. This gap was located at the bottom of the detector body where nonmagnetic suspended particles would collect. Engine test confirmed that nonmagnetic metallic contaminants were not indicative of engine failures. The 5 to 1 ratio of nuisance signals to failure signals is expected to be reduced by this change. A longer range approach to the reduction of nuisance signals would be the development of a detector that could, with or without human assistance, discriminate between random metallic chips (creating nuisance signals) and debris being generated by a failure in process. A program to improve the discrimination capability of the chip detector has recently been initiated.

Oil Monitor

An Army decision has been made to defer or drop further T700 oil monitor factory evaluation on the basis that adequate bearing condition monitoring can be done with a chip detector. The oil monitor, a bench-tested device developed by GE, was more effective than spectrometric oil analysis in detecting oil contamination, but both techniques suffered because of the fine oil filtration (3 microns absolute) of the T700 lube system.

Engine Health Monitor

Preliminary factory development tests were successful in demonstrating that an engine health monitor could detect overall engine performance degradation within ±1% of an as-new baseline. The corresponding performance degradation capable of being detected in an aircraft was predicted to be ±2%. Feasibility of the engine health monitor concept has been demonstrated.

Filter Bypass Indicators

Both fuel and lube filters provide an electrical signal to the cockpit denoting actual openings of the filter bypass valve. A pop-out red button on each filter body warns the mechanic that an impending bypass condition exists. The lube pop-out button has a thermal lockout to prevent impending bypass signals due to cold oil, a temporary condition. Early problems with the thermal lockout have been resolved.

Borescope

The Army has approved a standardized rigid borescope for the T700 and two borescope ports have been relocated to facilitate insertion and removal of the borescope.

Diagnostic Connector - E4

The E4 23-pin connector on the electrical control unit is provided for ground-checking electrical control circuits. No peculiar ground support equipment (PGSE) unit has yet been authorized for this purpose. A proposal is now under consideration by AVSCOM for providing such a unit for development test use. The test unit, powered from the UTTAS or AAH APU, and simple and light enough to be carried by one man, would speed LRU fault isolation.

Rotor Unbalance Monitor

This vibration analyzer box was designed for use with a bearing-mounted accelerometer and consequently is not calibrated for use with externally mounted sensors. Internal accelerometers were found to be unreliable and were discarded. An evaluation program is under way to qualify two externally mounted accelerometers on the T700 engine, one on a special pad of the accessory gearbox (AGB) and the other on the exhaust frame flange. Three accelerometer manufacturers' sensors are being evaluated on factory development engines. Results to date have indicated a possible high temperature life problem with the exhaust frame accelerometers which are rated for temperatures up to 900°F with 20 pico coulombs/g sensitivity. Such sensors represent an advance in the current state of the art which is 10 pico coulombs/g at that temperature.

SUMMARY OF RECENT GENERAL ELECTRIC ENGINE CONDITION MONITORING (ECM) ACTIVITIES

General Electric is currently engaged in a broad range of ECM activities. They include studies to determine the appropriate ECM system for particular GE engines, the development of ECM systems to evaluate "on-line" various ECM sensors and concepts, and the production of ECM systems as part of GE engines or offered as optional equipment. While each ECM application is unique, data derived from one system can, in many cases, be applied to other systems. In the conduct of this study, General Electric utilized information gained from other ECM activities where appropriate.

Table 8 indicates the content of the various ECM activities in which GE has been involved, including comments relative to purpose, degree of success, and other pertinent information.

The data and experience gained from the work summarized in Table 8 are applicable to this FADEC study and lead to a number of general conclusions.

1. Modular performance measurement by D&CM systems has not yet been demonstrated.

   A program is underway for the CFM-56 engine to define the instrumentation and computer logic to fault isolate performance problems to the module level for this large commercial engine. If successful, an important maintenance cost & downtime saver will be achieved for the commercial engine users. No similar program is in effect for GE military engines, nor has a cost effectiveness study been done to justify the need.

2. ECM engine-mounted sensors and wiring harnesses must be specially designed to withstand the in-service engine environment.

   Experience has shown that ECM sensors and wiring unsuited to the engine environment have resulted in considerable system downtime, false signals, and loss of confidence in engine condition monitoring in general. This has been especially true in cases where false signals have caused engine shutdowns. Where ECM engine-mounted sensors and wiring harnesses have been ruggedized and designed to be insensitive to heat and vibration, failures and false signals have been reduced to an acceptable level.

3. Simplicity enhances the probability of success of ECM systems.

As ECM systems are fundamentally data acquisition, processing, and recording systems, the probability of their functioning successfully is inversely proportional to the number of sensed parameters and the number of functions provided. Complex ECM systems have experienced many problems associated with hardware and software; redesign of ECM systems invariably results in substantial simplification.

TABLE 8. GENERAL ELECTRIC ENGINE CONDITION MONITORING (ECM) ACTIVITIES

	Exceedance Monitoring	Exceedance Alarm	Life-Used Indices	LRU Fault Isolation	In-Flight Recording	Trending	Engine Trim	Parameters
<u>STUDIES</u> <u>F404 Engine ECM Study</u> The F404 ECM study has been completed. The results of the various systems considered are presented below.								
<u>System A</u> - An expensive system featuring in-flight control system monitoring, on-engine signal conditioning, and no PGSE. This system was not recommended by GE due to its weight and lack of cost effectiveness.	X	X	X	X	X	X		43
<u>System B</u> - A moderately expensive system similar in function to System A, but without on-engine signal conditioning or in-flight control monitoring. Control system data is acquired during ground runs using PGSE. This lighter and cost effective system was recommended by GE.	X	X	X	X	X	X		29

TABLE 8 - Continued

	Exceedance Monitoring	Exceedance Alarm	Life-Used Indices	LRU Fault Isolation	In-Flight Recording	Trending	Engine Trim	Parameters
<u>STUDIES</u> - Continued								
<u>Base-Line (BL) System</u> - This relatively inexpensive system was within original budgetary estimates. As compared with System A, this BL system does not have on-engine signal conditioning, in-flight control monitoring, LRU fault isolation, or PGSE,and is somewhat limited in other system features. This is the system that was adopted by the Navy.	X	X	X		X	X		13
<u>TF34 EDS I</u> - This study is still in progress. In-service failure history has been analyzed in order to determine actual versus predicted failure modes. Candidate parameters and functions have been selected and algorithms are being developed to allow the effectiveness of these parameters and functions to be evaluated. Parameters were selected in compliance with the contractural requirements that: (1) sensors be removable without engine disassembly, (2) no engine structure modification be required, and (3) only current state-of-the-art instrumentation be proposed.	X	X	X		X	X	X	*18

* These are candidate parameters. Final parameter selection has not yet been made.

TABLE 8 - Continued

	Exceedance Monitoring	Exceedance Alarm	Life-Used Indices	LRU Fault Isolation	In-Flight Recording	Trending	Engine Trim	Parameters
DEVELOPMENT SYSTEMS								
TF34 EDS II - General Electric is supporting Northrop in its demonstration program to equip three A-10 aircraft with Northrop's Engine Health Monitoring Systems (EHMS). These systems were previously utilized on Air Force T38 aircraft. In-flight data is stored in memory and transferred to PGSE postflight.	X		X		X	X	X	15
F101 CITS - This is an extensive ECM system featuring in-flight control system monitoring, on-engine signal conditioning and no PGSE. Three of these systems are functioning on B1 aircraft during the flight test program and a fourth system is being operated in the GE factory. To date most system objectives have been met and Air Force acceptance has been high.	X	X	X	X	X	X	X	44
TF39 ADEMS I - This was a joint effort by the U. S. Air Force and General Electric to design, install in a C-5A aircraft, and evaluate an Advanced Diagnostic Engine Monitoring System. Although severely damaged during its first flight, due to an emergency landing, the system operation and analysis indicated that the program objectives would have been met.	X	X		X	X	X	X	44

TABLE 8 - Continued	Exceedance Monitoring	Exceedance Alarm	Life-Used Indices	LRU Fault Isolation	In-Flight Recording	Trending	Engine Trim	Parameters
DEVELOPMENT SYSTEMS - Continued								
TF39 ADEMS II - This system is more modest in approach than ADEMS I and has 29 parameters. At this time it has undergone extensive factory checkout and is now in the process of flight checkout installed in a C-5A aircraft.	X	X		X	X	X	X	29
LM2500 I - This extensive ECM system was tested and evaluated at NAVSEC Philadelphia from November 18, 1975 to September 28, 1976. This testing allowed thorough hardware and software evaluation that led to recommendations for a follow-on system.	X	X			X	X		42
LM2500 II - This ECM system has been redesigned based on testing and evaluation of the LM2500 I system. It has been reduced from 42 to 14 parameters. $T_{5.4}$, one of the 14 ECM parameters, is determined from 11 individual $T_{5.4}$ thermocouples. The system has been completed and will be installed on board the Callahan Army Logistics Ship for one year of at-sea testing.	X	X			X	X		14

TABLE 8- Continued

	Exceedance Monitoring	Exceedance Alarm	Life-Used Indices	LRU Fault Isolation	In-Flight Recording	Trending	Engine Trim	Parameters
PRODUCTION SYSTEMS								
CF6 - Minimal ECM systems are offered to customers as options. They have had limited acceptance to date.	X		X		X	X	X	*
CFM56 - There will be qualified ECM systems offered with the engine upon certification in late 1979. The customer can purchase, as options, whatever mix of systems he desires. Flight data will be supplemented with data from specially mounted ECM sensors during ground diagnostic runs.	X				X	X	X	*

* The number of parameters available in these ECM systems will vary with airframe and customer requirements.

DIAGNOSTIC FUNCTION CATEGORIES AND EVALUATION

To meet the Army's D&CM requirements for future turboshaft engines with full authority digital electronic controls, four principal diagnostic functions must be performed. These functions (tabulated in Table 3) have the following principal purposes.

Cockpit Cautions - Warning to the pilot that an engine problem is imminent that may result in a power loss. Prompt action may prevent secondary damage.

Condition Monitoring - To support "On Condition Maintenance" by measuring and recording data indicative of the overall mechanical and thermodynamic condition of the engine and the life remaining in key engine parts.

Fault Detection - Detecting out-of-limit conditions.

Fault Isolation - The logic process utilizing engine data to isolate the cause of an undesirable engine condition to a specific module or LRU. In the case of electronic fault isolation, a simple means of communicating the finding to the maintenance person is also required.

The rankings in Table 9 result from judging today's engine needs/problems and the practicality and cost effectiveness of available techniques.

TABLE 9. DIAGNOSTIC FUNCTION CATEGORIES AND EVALUATION

	1ST PRIORITY	2ND PRIORITY	N/R* NOW	Recommend to integrate into FADEC
Cockpit Cautions Requiring Pilot Action				
- Low, high or fluctuating oil pressure	x			
- High vibration		x		
- Chip detection	x			x
- Fuel or lube filter bypass		x		x
- Combustor overpressure			x	x
- Oil temperature		x		x
- Bearing race temperature			x	

TABLE 9 - Continued

	1ST PRIORITY	2ND PRIORITY	N/R* NOW	Recommend to integrate into FADEC
Condition Monitoring for "On Condition" Maintenance				
- Performance check for engine health determination	x			x
- Count and record low cycle fatigue NG cycles	x			x
- Compute and record stress rupture life	x			x
- Measure engine operating hours		x		x
- Low cycle fatigue (LCF) - P3 cycles			x	x
- SOAP - Oil analysis			x	
- Borescope inspection	x			
Fault Detection and Recording				
- Record exceedance data sets for manual or electronic analysis		x		
- Track selected control schedules for LRU fault detection	x			x
- Track vibration as function of NP & NG to detect rotor unbalance and severe FOD		x		
- Detect sensor failures	x			x
- Detect overtemp., overspeed	x			x
- Track oil pressure and NG to detect oil system problems	x			x
- Detect stall			x	x
- Process HIT check data for performance trend analysis		x		

TABLE 9 - Continued

Fault Isolation and Annunciation	1ST PRIORITY	2ND PRIORITY	N/R* NOW	Recommend to integrate into FADEC
- Process exceedance data through logic programs for LRU fault isolation	x			
- Conduct visual inspection of engine for leaks, oil level, filter bypass, inlet FOD, loose fittings, etc.	x			
- Modular fault isolation - performance	x			x
- Modular fault isolation - oil-wetted parts (OWP)	x			x
- Modular fault isolation - vibration	x			
- Modular fault isolation - life usage	x			x

*N/R - Not recommended now.

TASK II - DIAGNOSTIC METHODS IDENTIFICATION

A comparison of the T700-GE-700 engine with the TF34-GE-2 and the TF34-GE-100 engines is given in Table 10 and shows similar trends in the distribution of D&CM events. A D&CM event is an actual or potential failure detection that would be accomplished by use of a D&CM system. In any analysis of engine field data, the number of D&CM events exceed the number of failures because many failures are detectable by more than one D&CM sensor.

TABLE 10. DISTRIBUTION OF D&CM EVENTS

	T700-GE-700 (%)	TF34-GE-2 (%)	TF34-GE-100 (%)
Vibration	4.6	7.4	-
Oil-Wetted Parts	22.2	9.6	23.3
Performance	5.9	4.4	2.5
Hot Section	9.8	22.1	15.0
Controls	32.7	37.1	18.3
Inspection Finds	18.3	14.0	12.5
Compressor and Fan	2.9	5.5	11.7
Inlet Particle Separator Blower	3.6	-	-
	100.0	100.0	100.0

The following discussion of diagnostic methods addresses each category of failure detection derived from field data analysis as summarized in Table 10. The estimates of effectiveness of diagnostic methods are based on prior GE D&CM experience cited in Task I plus other GE engine experience without D&CM.

TURBOSHAFT DIAGNOSTIC METHODS

Vibration

Vibration monitoring is potentially a valuable technique for detecting incipient mechanical failures and measuring engine mechanical degradation by trend analysis techniques. Vibration monitoring must be tailored to each engine with its peculiar characteristics. It is also one of the most difficult D&CM functions to perform reliably for the following reasons:

1. It is difficult to find locations on an engine that permit accelerometer replacement as an LRU and also produce clean signals with high ratios of signal to noise.
2. Extremely careful selection and application of accelerometer electrical connector and wiring is required to prevent electrical noise pickup and mechanical damage.
3. Skillful selection of system charge amplifiers, filters, logic, and limits is required.

GE experience has indicated that engine vibration monitoring should include measurement of broad band, and 1/rev accelerations of each rotor by use of narrow band tracking filters. Because of the specialized data processing circuit elements required, their cost and weight, possible variations in requirements of each engine application, and the special electrical shielding requirements to prevent noise pickup, the vibration data processing elements should not be included in the FADEC unit.

Oil-Wetted Parts

Oil temperature monitored by an aircraft crew member can be a useful indicator of an engine incipient failure such as loss of oil and oil cooler failure. For the oil temperature to be meaningful, a crew member must mentally integrate other data such as outside air temperature (OAT), fuel temperature, and NG. To perform the oil temperature monitoring electronically, the FADEC-D&CM system might require a fuel temperature sensor to be added to the aircraft fuel system and computer logic added to the FADEC unit. In view of the small probability of oil system events that only oil temperature measurement can detect, it is not considered a high priority parameter.

Oil pressure (PL) measured at the lube supply pump discharge and biased by bearing sump pressure is an extremely valuable and critical engine condition monitoring parameter. To be meaningful and to avoid false signals, a characteristic curve of lube pressure versus core engine speed, NG, is required together with a tolerance band to account for system and oil temperature variations. Oil system problems may be indicated by low, high, or fluctuating oil pressure. Since almost all cockpit displays include oil pressure, the primary function of oil system monitoring is to warn the pilot that he has an oil system problem so he can closely monitor his pressure gage and make intelligent decisions accordingly.

Bearing race temperature or bearing differential oil temperature measurements are not recommended for failure detection. Experience has shown that the time response of temperatures to most types of bearing failure modes is too slow to be effective in preventing secondary damage.

Oil filter bypass remote electrical signals can be used but may not be necessary. The impending bypass pop-out red button has been very useful on the T700 lube oil filter. The button is checked at least daily during preflight and/or postflight inspections by the crew chief. Because of this frequent checking, the actual bypass remote electrical signal has never been actuated except by cold oil when the sensor thermal lockout device failed. There is some question, therefore, as to the future need for a remote lube oil bypass signal. If the daily inspections are deleted, the remote signal will be very useful.

Spectrometer analysis (SOAP) is a worthwhile failure detection technique if oil system filtration is 25 microns or greater. With oil filtration down to 3 microns absolute as with the T700 engine, SOAP proved to be ineffective, as did the electro-optical oil analysis.

Magnetic chip detection has proven extremely effective on the T700 engine for early detection of bearing problems (see Task I). An improved device that can discriminate between random manufacturing chips, normal "fuzz", and debris from spalling type conditions is badly needed, however, to reduce the nuisance signals which outnumber the failure signals by over 2 to 1.

Performance

HIT (Health Indication Test) check procedures as described under Task III are ideally suited to FADEC/D&CM systems and are recommended as a means of detecting gross performance problems affecting safety of flight. HIT check accomplishment electronically is a contribution to flight safety because it requires less pilot attention.

Performance trend analysis requires consistently accurate data taken periodically over many hundreds of hours. It is done routinely by commercial airlines and has been done on military engines in the test cell environment and by MATS and SAC in an operating environment approaching that of the airlines. A study is required to determine if performance trend analysis is feasible or cost effective in the Army's operational environment as an adjunct of a future D&CM system which produces recorded data.

Modular performance fault isolation "on the wing" is a potentially valuable feature of a D&CM system that could enable the determination of which engine module is responsible for a measured loss in overall performance. The feasibility of accomplishing this on an operational Army engine has not been demonstrated and may be difficult with the limited instrumentation normally available on an installed engine. There are technical approaches that should be explored in depth to provide a basis for determining the practicality of modular performance fault isolation.

Stall detection by a D&CM system on most engines, including the T700, is not required to warn the pilot - he can hear the event. D&CM stall detection would be required in order to trigger a recording of data at the instant of its occurrence and ideally to save those snapshots of data taken before the event in order to diagnose the reason for the stall if diagnosis is desired. It is doubtful if a computer program to perform such a diagnosis would be of practical value in operational service because of the very low predicted frequency of stall events based on recent T700 engine history.

Hot Section

Low cycle fatigue (LCF) and stress rupture life of turbine components are essential measurements for the implementation of on-condition maintenance on military aircraft engines. It is well documented that many military engine problems in the past have stemmed from engine operation far different from that for which they were designed. Measurement of LCF speed cycles and time-temperature stress rupture effects on hot parts provides more accurate measures of engine life used than measurement of engine hours alone. Engine hours is also recommended as the traditional measure and the base to which LCF and stress rupture counts can be related to judge the relative severity of various aircraft missions.

Vibration monitoring and borescope inspection discussed elsewhere are also potentially valuable hot part diagnostic techniques.

Overspeed and overtemperature exceedances can be useful as measures of potential turbine damage when related to time of exposure of the exceedance. These limits can be easily stored in a digital computer in the form of curves similar to those supplied in operating and maintenance manuals.

Controls

Control system fault isolation to the LRU level currently involves four steps or functions:

1. Conduct signal validity checks to detect faulty sensors. If a failed sensor is detected, that sensor is the LRU to be replaced. If sensors are good, proceed to Step 2.
2. Detect engine exceedances such as speed, temperature, torque, and stability.
3. Track engine control schedules such as fuel schedules, VG, accel and decel, T4.5 limiting, and NG; detect out-of-limits schedules.
4. Utilize diagnostic logic programs and as many as 20 engine parameters to isolate the cause of an exceedance, instability, or schedule shift to the most likely control system LRU. In the event that the logic process identifies more than one faulty candidate, the LRU with the highest predicted failure rate is identified for replacement first.

The full potential of FADEC systems has yet to be explored. Functions 1 and 3 above are inherent in the GE FADEC concept. Further analysis and innovative design may show the way to accomplishing all of the controls D&CM functions within the FADEC unit, eliminating the need for separate D&CM equipment.

Inspection Finds

From 12.5 to 18% of the events in Table 10 are detected by visual inspection. These figures include both borescope and external visual inspections done at preflight and postflight. In most of the cases analyzed, external visual or borescope inspection was the only means of detection. A general conclusion drawn from the analyzed cases is that 10 to 15% of the failure events requiring some maintenance action will not be detected by any current state-of-the-art D&CM system or sensor. In other words, the most efficient automated D&CM system today can be expected to detect only 85 to 90% of the failure events.

External visual inspection finds include the following discrepancies:

1. Internal defects revealed by borescope.
2. FOD at engine inlet.

3. Fuel and oil leaks, loose or missing plugs and caps.

4. Cracked, bent, or damaged brackets, tubes, and links.

5. Loose fittings, electrical connectors, and accessories.

6. Fluid levels, pop-out indicators, and VG position transmitters.

7. Contaminated chip detectors.

Borescope inspection effectiveness is a function of many factors. If effectiveness is defined as the probability of finding a given mechanical defect in the compressor vanes and blades, combustor, or turbine, then effectiveness is a function of the following factors:

1. Number and location of borescope ports.

2. Percent of target part viewable from nearest port.

3. Skill and patience of operator.

4. Quality and condition of instrument.

5. Quality of instructions and illustrations to identify fault appearance.

6. Indications from other sources of where the fault is likely to be located.

7. Frequency of inspection.

8. Size of engine.

9. Failure propagation rate.

With so many variables, the effectiveness is different for each engine design, operator, and engine part. Large engines have greater potential for borescope inspection because of more space for ports, greater distance between blades and vanes for inserting borescope, and using larger instruments. D&CM can be a positive influence for improving borescope inspection effectiveness in factor 6 above through such techniques as LCF and stress rupture life measurement and vibration monitoring.

Compressor and Fan

Monitoring of compressor and fan (cold section module) involves methods already covered in the preceding discussion as follows:

Rotor Balance - Vibration
Stall - Performance
LCF - Same speed excursion counting as for hot parts
VG - Control monitoring
FOD - Vibration or pilot detection of characteristic sound

Monitoring for overpressure on T700 compressor and combustion casings is not recommended. Any predictable engine fault would not cause a damaging compressor discharge overpressure.

LCF pressure cycle counting is not recommended for T700 or similar engines. The compressor and combustion cases are not life limited and require no special monitoring.

Miscellaneous

Ultrasonics have no practical application for in-flight monitoring.

Radiography is an effective nondestructive inspection technique for large commercial modular engines. For small engines, the special restrictions on handling of radioactive pellets, special personnel training, and special equipment required make this technique very unattractive. It is easier, except in very special circumstances, to disassemble an engine than to take isotope photos and analyze them to detect mechanical abnormalities.

Transient condition monitoring is not recommended because of the large data storage capacity and large amount of complex data analysis which would be required.

Electrostatic probe exhaust analysis for detecting gas path problems is not recommended at this time. This technique utilizes a magnetic probe to detect evidence of metallic debris in the exhaust gas; the system is still in the early development phase and is showing promise.

Mechanical signal analysis is an analytical technique to detect and isolate mechanical anomalies using recorded mechanical vibration and accoustic signatures of machines. The complexity of the signatures and of the analytical techniques involved has discouraged most investigators from attempting to apply these techniques to field service problems and consequently is not recommended for an Army D&CM system.

DIAGNOSTIC METHODS CATEGORIES

Table 11 represents an initial screening of the diagnostic methods reviewed in the preceding pages and categorizes them in accordance with their monitoring requirements. The large number of recommended diagnostic methods that can be implemented using signals and sensors already available in a turboshaft FADEC control is the significant message in this tabulation.

TABLE 11. DIAGNOSTIC METHOD CATEGORIES

Method and Requirements	Diagnostic Methods
Utilizes parameters and signals common to digital engine controls.	Performance Monitoring Low Cycle Fatigue Stress Rupture (creep) Control Schedules Sensor Signal Checks LRU Fault Isolation
Requires dedicated signal conditioning.	Vibration Particle Detectors (some) Ionized Particle Detection*
Requires parameters not common to digital engine controls.	Oil System Monitoring Vibration Particle Detectors
Utilizes special (ground) equipment.	Boroscopy Radiography* Spectroscopy (SOAP)* Ultrasonics* Mechanical Signal Analysis* Electric-Optical Oil Analysis*
External inspection.	FOD - Inlet Inspection Fuel and Oil Leaks Loose, Damaged, Missing Parts Fluid Levels Magnetic Plug, Screen and Filter Inspection

*Not Recommended

TASK III - DIAGNOSTIC APPLICATION

The application of turboshaft engine diagnostic and monitoring techniques involves close coordination between the engine manufacturer, the using service, and the airframe manufacturer. Human factors engineering considerations must be applied to the choice of D&CM system displays and logic. A typical example is found in the following section which describes three Health Indication Test (HIT) monitoring systems and the trade-off choices which balance pilot attention and involvement against added D&CM system complexity. Similar trade-offs and decisions are inevitable in the design of fuel and control system fault isolation systems where human involvement in the logic process is traded off against increased system complexity. A further trade-off decision may be required in the design of the cockpit display for a discriminating type magnetic chip detector discussed in Task VII of this report.

Application of diagnostic and monitoring methods to an Army engine is a system problem with strong human factors overtones. Practical judgement to limit system complexity without overburdening the flight crews and maintenance personnel should be the design objective.

This section covers methods and techniques which permit meeting the following engine diagnostic and condition monitoring objectives:

1. Engine Health Indication Tests (HIT).
2. Fuel Control System Fault Detection and Isolation.
3. Low Cycle Fatigue and Hot Part Monitoring.
4. Storage of Flight Diagnostic Data.
5. Storage of Mission Cycle Data.

INDICATION OF ENGINE HEALTH (PERFORMANCE) WITHOUT GROUND TIEDOWN TEST OR HIT CHECK FLIGHTS

The health of a turboshaft engine can be measured by an electronic health monitor function utilizing less than half of the same digital signals required for operating a FADEC control. No added engine sensors are required based on the current FADEC functional design. On the other hand, in order to isolate the performance fault to the module level, there are a number of parametric relationships that can be used as engine health indicators. The relation of output power to power turbine inlet temperature is the most straightforward and is applicable to practically all turboshaft engines. Both functions would be corrected to standard conditions and compared with either the engine specification performance or a stored function representing each engine's "as new" performance. The actual performance could be recorded for later ground analysis or trending and some form of message would be displayed to the pilot: go/no-go or in a sophisticated system either horsepower or percent of specification power (Measured HP/Specification HP) x 100, for that operating point.

Several options exist for helicopter turboshaft engine electronic health monitoring systems, depending on the degree of automation desired. The more automation, the more complex the hardware and software required, but the less dependence on pilot procedures for getting valid data. Three systems are described in the following paragraphs as Systems A, B, and C and are of decreasing degrees of automation.

System A - Horsepower Versus Measured Turbine Inlet Temperature (see Figure 2)

Parameters
(HP vs T4.5)

P0 - Pressure Altitude
PT2 - Compressor Inlet Total Pressure
T4.5 - Gas Generator Discharge Temperature
T2 - Compressor Inlet Temperature
Q - Output Torque
NP - Low-Pressure Turbine Speed

With System A, a health check could be made either automatically when a predetermined "window" or set of aircraft and engine conditions were reached, or on pilot's command. Since all the essential parameters would be provided to the airborne computer to correct for altitude, ambient temperature, and airspeed, the pilot would not be required to conduct the health check on the ground or at a specific set of conditions. What is required, however, is a state of thermal stability. The degree to which this condition is achieved has an overriding influence on the result. The time-temperature conditions for each engine design may be quite different; however, 30 seconds is believed to be the minimum time for a health check at power levels at or near maximum continuous. For a more accurate measure, as for performance trend analysis, stabilization times of 2 minutes or more are probably required.

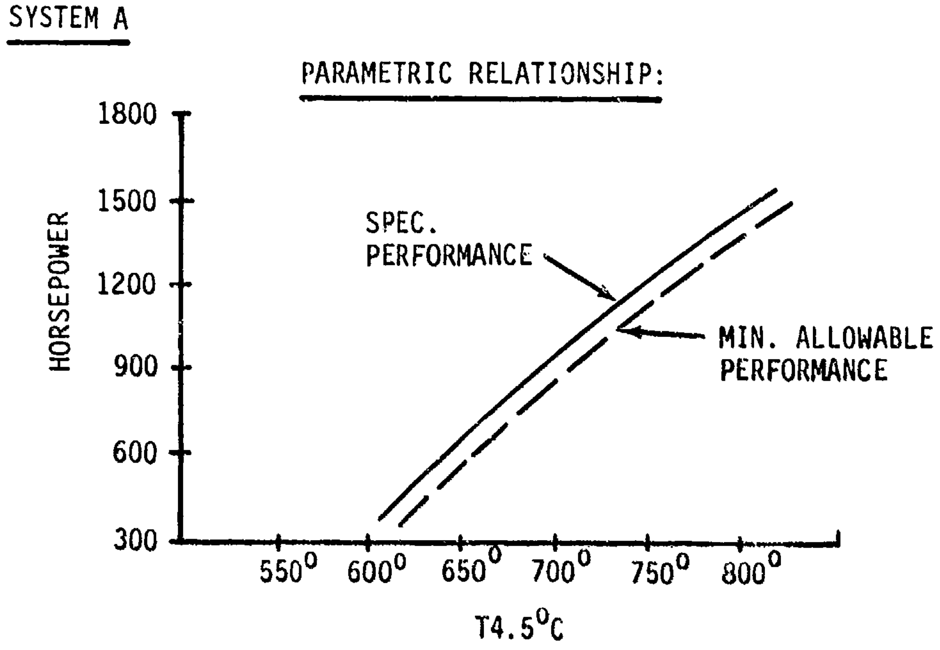


Figure 2. Horsepower versus Measured Low-Pressure Turbine Inlet Temperature - System A.

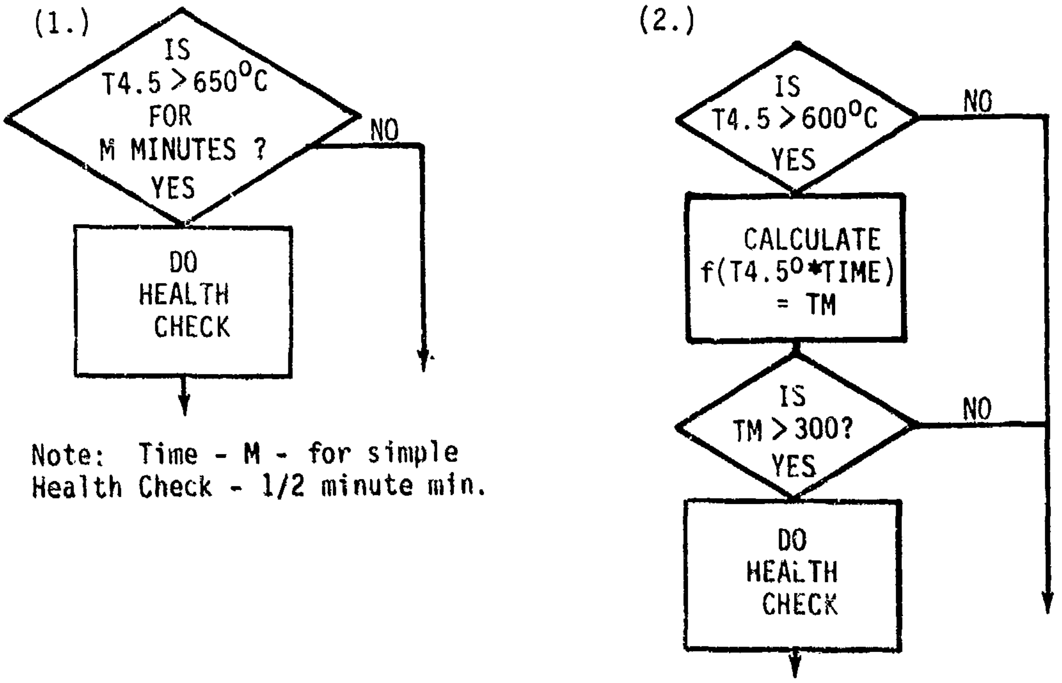
Control of Stabilization Time

The FADEC-D&CM computer diagnostic logic would require either flowchart 1 or 2 of Figure 3 preceding the health check. If the same health check were recorded and saved for long-term trend analysis, a more restrictive procedure might be required as shown in Figure 4.

In summary, System A should be able to perform HIT check without tiedown or check flights, if the mission profile provided a high enough power setting for a long enough time. Current HIT check for the T700 engine specifies that T4.5 should be at least 650°C with NP=100% for 30 seconds or more for a simple check. For trending, T4.5 would be higher and time at T4.5 would also be longer --probably 2 to 5 minutes.

The principal advantages of System A are:

1. Requires minimum attention by the pilot--a definite contribution to flight safety.



Note: Time - M - for simple Health Check - 1/2 minute min.

Figure 3. FADEC-D&CM Computer Diagnostic Logic Function.

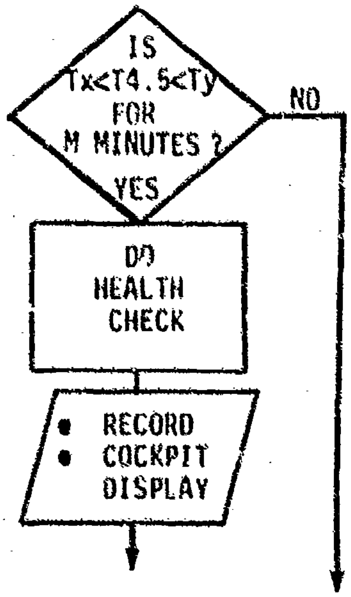


Figure 4. Long-Term Trend Analysis Logic.

2. Provides more accurate data:

   a. Eliminates human error.

   b. Prevents erroneous data caused by inadequate stabilization time.

System B - Torque Versus Turbine Inlet Temperature (See Figure 7)

Parameters
(Q vs T4.5)

P0	Q
T4.5	NP - Controlled and monitored by pilot
T2	

$f(Q/\delta\quad) \text{ vs } f(T4.5/\theta)$ and T4.5 * Time (for Thermal Stability)

System B, like System A, would provide cockpit go/no-go engine health indication and recording (if desired). Also it would not require the pilot's attention to read and record data. It does have two limitations, however:

1. The pilot would be responsible for setting NP at 100% (or some other predetermined value) and keeping it there until after the "Go" indication is received (based on steady-state time-temperature function).

2. The health check must be made on the ground or at hover since the parameter PT2 to account for flight speed is not provided.

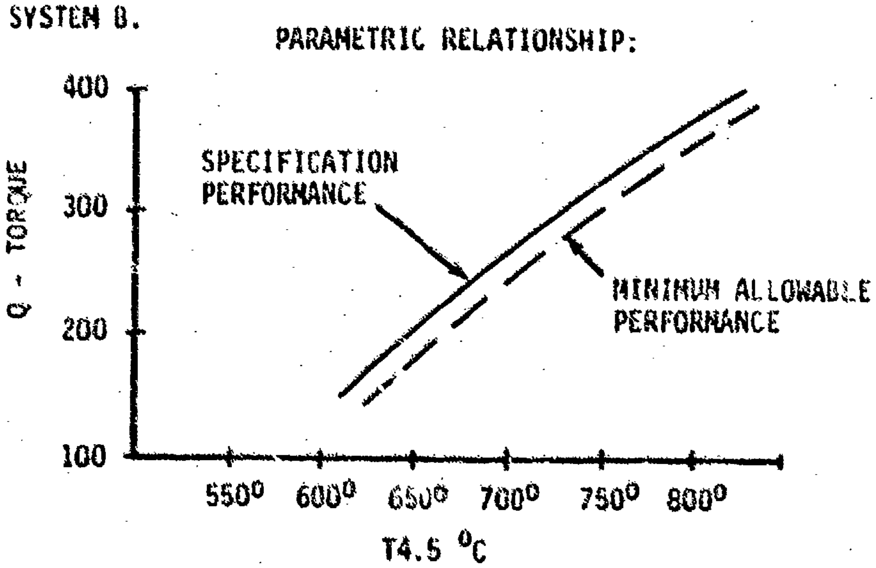


Figure 5. Torque Versus Low-Pressure Turbine Inlet Temperature - System B.

System C - Torque Versus Compressor Inlet Temperature (See Figure 8)

Parameters
(Q vs T2)

Q	NP	Controlled by pilot.
P0	T4.5	
T2		

f(Q/δ) vs f(T2) and Time * T4.5

System C would provide cockpit go/no-go engine health indication and recording. The pilot is not required to record data or refer to curves from the engine Operator's Manual to determine the engine health status. This system also requires less on-board computer capacity than A or B. It has the following limitations:

1. The pilot would be responsible for setting NP at 100% and maintaining it there (avoiding transients) until "Go" signal is received.
2. The pilot must also adjust collective pitch to maintain T4.5 at some predetermined value at or above 650°C for the required time.
3. The health check must be made on the ground or at hover.

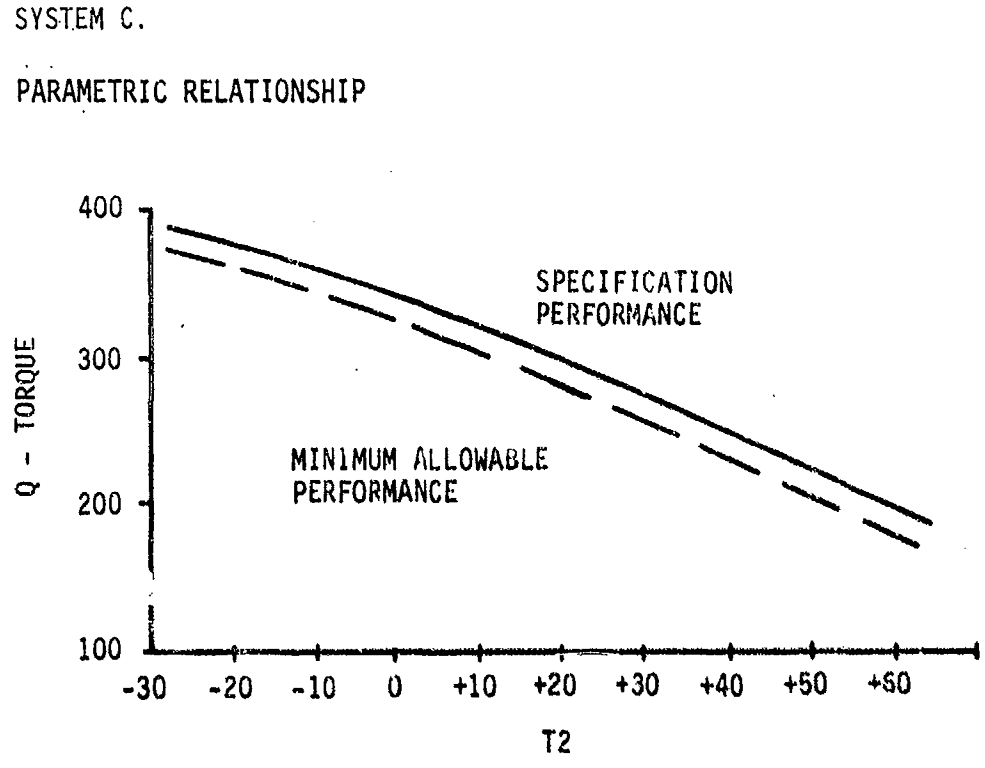


Figure 6. Torque Versus Compressor Inlet Temperature - System C.

System A computations can be performed in the FADEC unit with minor effect on its required memory capacity. HIT checks currently specified for the T700 UTTAS and AAH aircraft follow System C procedures, except that the readings are all manual.

FUEL CONTROL SYSTEM FAULT DETECTION AND ISOLATION CAPABILITY TO LINE REPLACEABLE UNIT (LRU) LEVEL

The T700 engine control system is not a module. It is a number of LRU's, some mounted on the Accessory Gearbox and consequently part of the Accessory Module, others mounted on and part of both the Cold Section and Hot Section Modules.

Control system fault detection and isolation in a current technology system can be achieved by an engine diagnostic system in the following manner:

1. Data from the engine and aircraft sensors will be recorded while the engine is in operation, either in flight or on the ground.

2. Computer-based diagnostic logic routines similar to the troubleshooting procedures presented in Chapter 1 of the T700-GE-700 Engine Maintenance Manual[3] will automatically detect and record and isolate control system faults. (See Figure 7.)

3. Messages will be generated and displayed directing maintenance personnel to the most appropriate maintenance action. These maintenance actions can include further testing or measurement, as the recorded in-flight data may have to be supplemented in order to achieve the appropriate level of LRU fault detection and isolation.

A FADEC, with its control parameters already in digital form suitable for recording, provides the best opportunity for cost effective control-fault diagnosis relative to other types of engine controls. The FADEC system by design intent will minimize the number of control system LRU's by combining functions expediting troubleshooting. Current hydromechanical systems with analog electronics require complex systems to achieve all condition monitoring functions. First-generation FADEC systems with hydromechanical backups will reduce the difficulty of fault detection and isolation by:

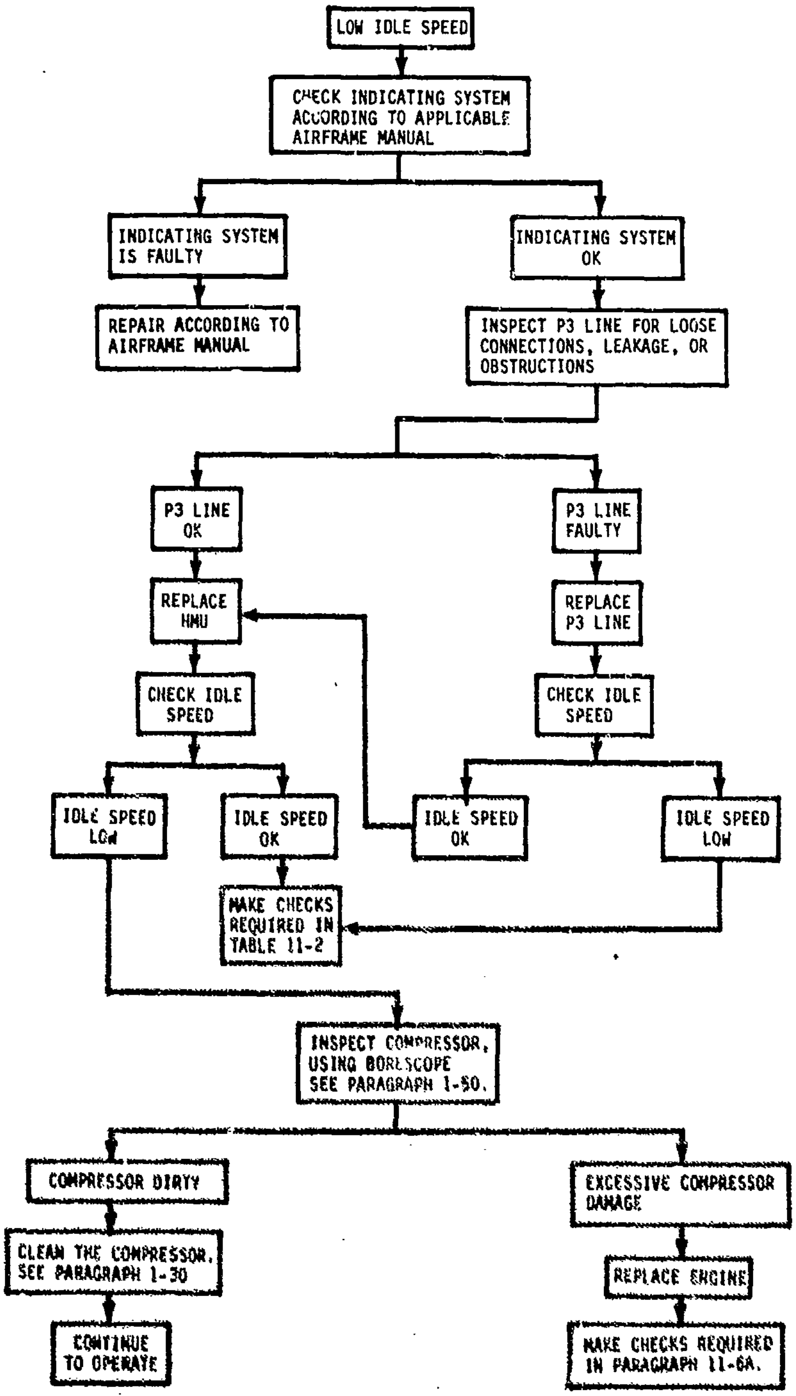


Figure 7. Troubleshooting - Steady-State, Idle.

- Providing all signals in a digital format
- Accomplishing sensor failure detection via FICA
- Accomplishing computer fault detection by self-test functions.

Additional study is required for future FADEC designs to attempt to increase the inherent fault detection. Increased fault detection will allow the control to determine corrective action so the engine can continue to operate under certain failure situations. Corrective action through redundancy and alternative control strategies will improve control system reliability. The fault detection and isolation effectiveness of a system can be assessed only through a detailed analysis of LRU failure modes and their associated failure symptoms. Analysis methods have been developed and employed with significant success in other engine diagnostic system studies, notably the F404-GE-400 Engine Condition Monitoring System (ECMS) study.[5] While this method was developed for current systems, it can be applied to future systems with slight modification. The method for identifying a practical and cost-effective system for control system fault detection and isolation will contain the following elements:

1. Fault Tree: A fault tree listing all major predicted failures will be constructed as follows (see Figure 8 for example):
   a. The failure event in the top tier is one of any primary engine failure events associated with an engine operating condition.
   b. Subsequent tier failure events identify those subordinate faults that contribute to the primary failure event.
   c. The items listed under the bottom tier are those LRU's whose failure can cause the indicated engine failure events.
2. Quantify Fault Tree: The fault tree will be quantified by assigning failure rates to each of the top tier failure events and also to low tier events. Then to each of the lower tier events must be assigned the failure rates from each of the control LRU's that could contribute to that particular engine failure event. Figure 8 is a simple example of such a fault tree with the lower tier events shown with the contributing LRU's listed under each event. The failure rate contribution of each LRU must be estimated for each event such that the total and preducted failure rate for each LRU is accounted for.

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[5] Jordan, H. J., F404 ENGINE CONDITION MONITORING SYSTEM (ECMS) STUDY, General Electric Co., Lynn, MA, R77AEG028, 15 April 1977.

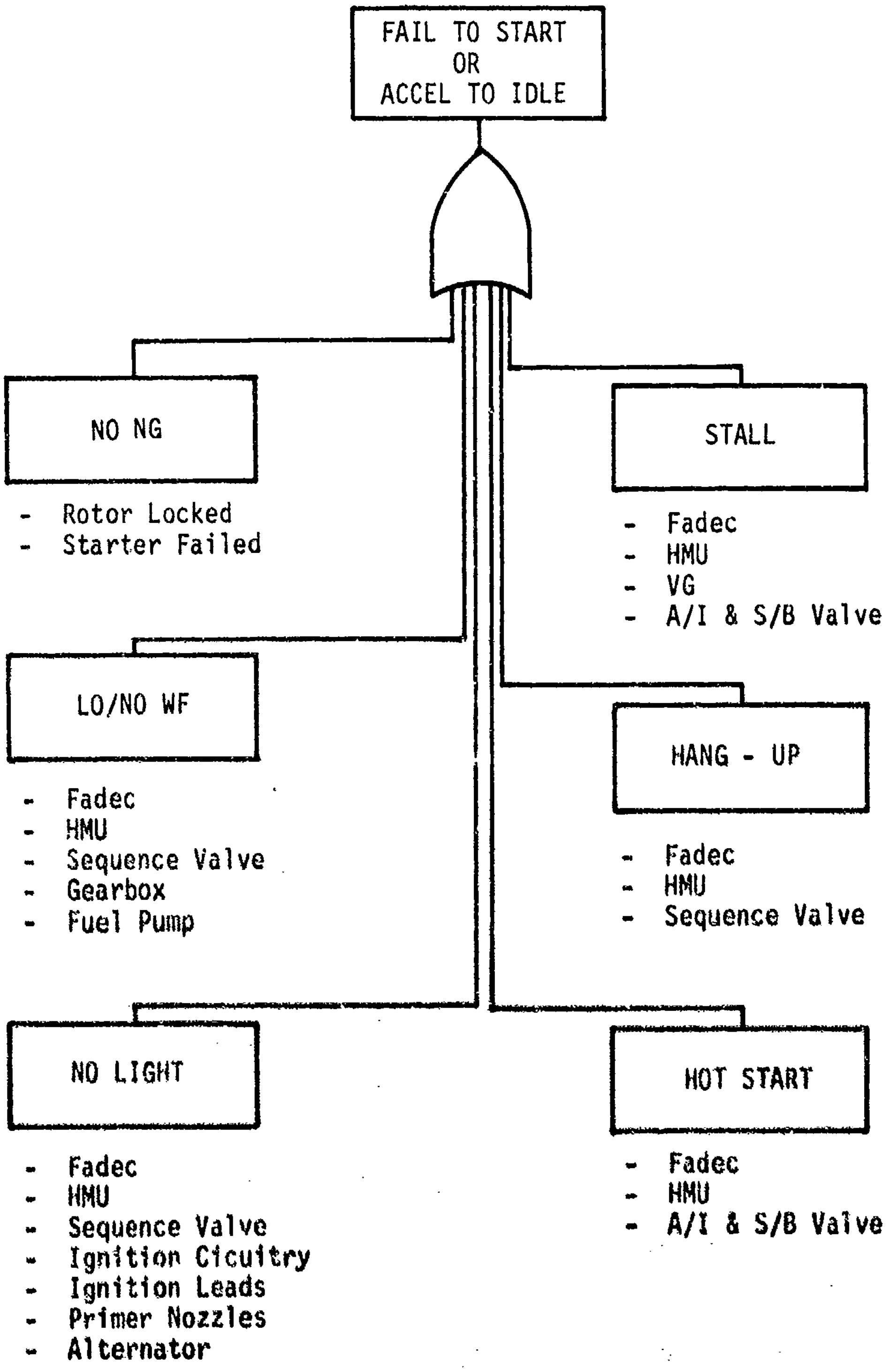

Figure 8. Example of Fault Tree With Listing of LRU's.

3. Logic Diagram: Logic diagrams are troubleshooting procedures that rely on available engine and aircraft parameters and knowledge of engine operating characteristics to isolate the malfunctioning engine components. In those cases where fault isolation is to a group of components, that component with the highest failure rate is selected as the most probable failed LRU. These logic diagrams are written as algorithms in a format suitable to conversion to computer code (see Figure 9 for example). Computer programs representative of these logic diagrams will be resident in either an airborne or ground diagnostic unit or some combination of both. This program will function as a result of the values of the condition monitoring parameters. The airborne and/or ground diagnostic units will perform fault detection and isolation automatically in a manner similar to the troubleshooting procedures presented in Chapter 1 of the T700-GE-700 Engine Maintenance Manual[4] (see Figure 7).

   The logic diagrams allow an assessment of the utility of the engine condition monitoring parameters in terms of fault detection and isolation. This assessment can lead to the identification of parameters not previously considered or the elimination of parameters with low utility (see Table 12).

4. Effectiveness: Fault detection and isolation effectiveness will be assessed for one or more proposed condition monitoring systems. Human factors considerations (man-machine interface) will be part of this assessment.

5. Life-Cycle Cost (LCC): An LCC analysis will be made for each proposed system to assess the net cost savings (or losses) attributable to a proposed system throughout the engine life cycle. In general, it compares the payoff of a condition monitoring system, in terms of net reduced maintenance costs, with investment design, engineering, and production costs.

6. Additional System Assessment Criteria: The evaluation of proposed condition monitoring systems will include an assessment of the system impact on engine weight, reliability, maintainability, and envelope.

   This methodology will provide a sound basis for decision making and avoid, to the extent possible, subjective judgements.

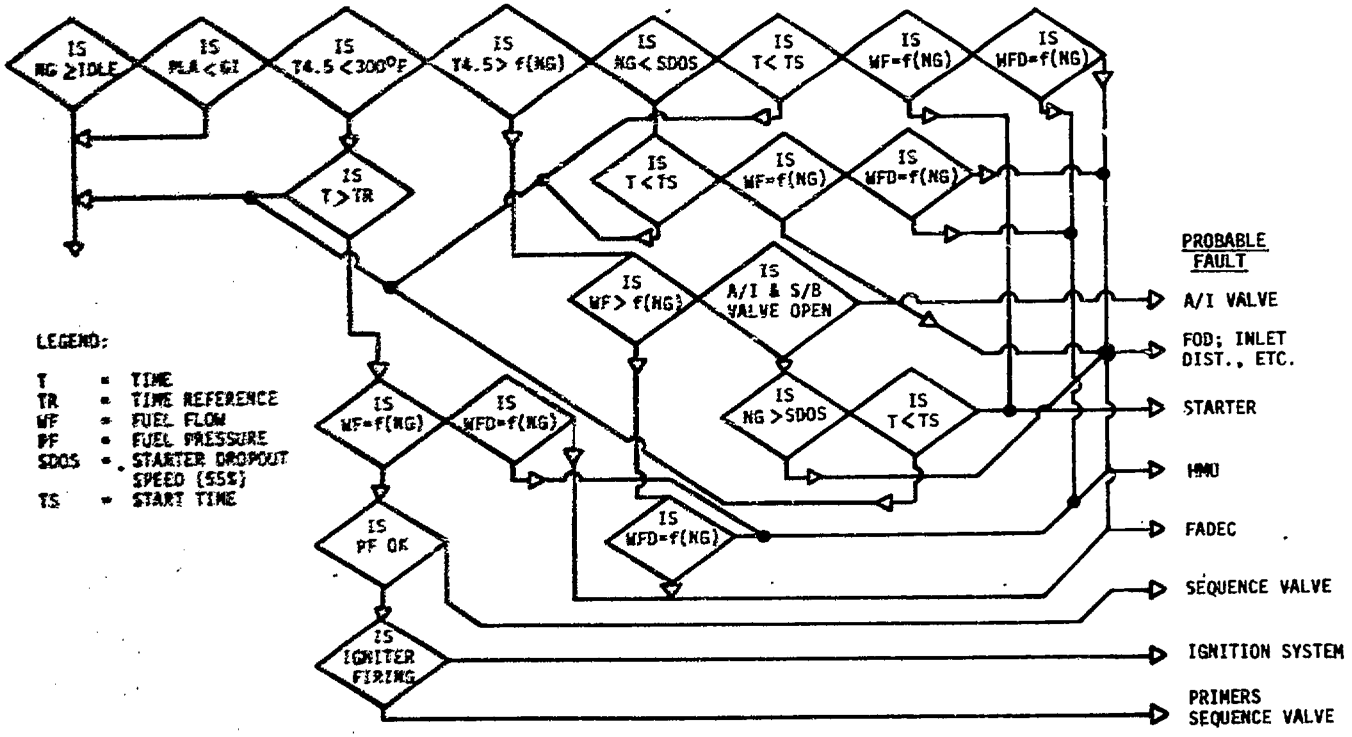

Figure 9. Example of Logic Diagram.

TABLE 12. CANDIDATE PARAMETERS FOR FUEL CONTROL SYSTEM MONITORING

Symbol	Description
NG	Gas generator speed is required to detect overspeed conditions and, in conjunction with other parameters, detect fuel control system faults.
NP	Power turbine speed is required to detect overspeed conditions and, in combination with other parameters, detect and isolate fuel control system faults. It is also used with Q_1 to compute horsepower.
T4.5	Gas generator turbine discharge temperature is required to detect overtemperature conditions. In combination with other parameters, it is used for hot parts life-used indication and fuel control fault detection and isolation (D&I).
T4.5R	Gas generator turbine discharge reference temperature provides a reference for hot parts life-used monitoring and control fault D&I.
PS3	Compressor discharge static pressure is essential to monitor modular performance fault isolation and to count pressure cycles for LCF considerations. It is also used with other parameters for fuel control fault detection and isolation.
Q1	No. 1 engine torque is required for horsepower computation and with other parameters to D&I fuel and load-share control faults and indicate engine health.
Q2	No. 2 engine torque is required in conjunction with other parameters to D&I load-share faults.
T2	Compressor inlet temperature is required to allow corrected speed to be calculated. Corrected speed is the basis for many of the control schedules and is essential in determining control schedule out-of-limit conditions. T2 is also used to correct other performance parameters used in monitoring performance deterioration.
PT2	Compressor inlet total pressure is used to correct engine power for deterioration monitoring and with other parameters to D&I fuel system faults through FICA.

TABLE 12 - Continued

Symbol	Description
AI	Anti-icing valve position is monitored to detect schedule deviation and is used by FICA to determine performance in conjunction with other parameters.
WFD	The fuel flow demand signal is used to determine the scheduled fuel demand signal.
LDS	The load demand signal is monitored to isolate "linkage" faults from schedule errors.
NPD	The power turbine speed demand is monitored to isolate "linkage" problems from schedule errors.
OS	The overspeed (OS) signal will allow ECU OS function to be checked out at a safe operating speed.
CB	The customer bleed signal is used during engine health assessment and control schedule checks.
WF FB	The fuel flow feedback signal serves the primary fuel flow indication signal and is used to detect fuel scheduling faults.
VG FB	The variable geometry feedback signal is used as an indication of VG position. It is used to detect control scheduling faults.
PAS	The power available signal is monitored to isolate input problems from schedule problems.
FWF BP	The fuel filter by-pass signal is used to detect fuel system contamination and prevent possible fuel control system failure.
VGD	Variable geometry demand is used to D&I VG control faults.

LOW CYCLE FATIGUE AND HOT PART MONITORING

Counting and recording of low cycle fatigue cycles is a simple procedure that can be accomplished using engine parameters NG (core speed) and PS3 (compressor discharge pressure). Speed cycles measure rotating part LCF life for compressor and turbine discs and blades. PS3 cycles measure combustion and compressor casing LCF life used. A computer can be programmed to cound speed and pressure excursions and store the accumulated cycle counts. Periodically, depending on airborne data storage capacity, the airborne stored data can be transferred to a ground storage unit and added to previously stored data for the appropriate serial numbered engine and/or serialized engine modules and parts. The LCF cycles counted for current GE engines, which utilize speed signals, are as follows:

LCF No. 1 NG (Start) - NG (95% IRP) - NG (Shutdown)

LCF No. 2 NG (86% IRP) - NG (95% IRP) - NG (86% IRP)

The logic to perform these functions is simple. Representative algorithms prepared for a typical modern engine are shown on Figures 10 and 11. T700 does not use PS3 cycles because the two casings are not estimated to be pressure cycle limited. The CITS system on the B-1 bomber has provisions for counting PS3 pressure cycles for the F101 engine.

The availability of on-board digital computer capacity, either within the FADEC unit or in an advanced digital Engine History Recorder, provides the opportunity to utilize a much more sophisticated LCF speed cycle counting technique. GE recommends that such a system be developed and utilized for future turboshaft engine condition monitoring. A number of similar logic systems for cycle counting have been suggested, three of which are cited below in references [6,7,8]. All methods are designed to count major cycles - start to IRP, and convert partial cycles to equivalent full cycles. A further sophistication would relate the effect of partial and full cycles to a number of rotating parts within the engine, some of

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[6] Salt, T. L., "Evaluation of Flight Mission Severity in Cumulative Damage", R & M Proceedings, Los Angeles, CA, 1971, AIAA/SAE/ASME, 10th Annual Conference.

[7] Power, E. M., "Cycle Counting Methods and the Development of Block Load Fatigue Programs", SAE paper 780102, 3/27/78.

[8] Leever, R. C., "A User's View of Fatigue Life Predictions", SAE paper 780105, 3/27/78.

which may react differently to the partial cycles than others. Major and partial cycles have been computed successfully in an on-board computer by GE. The final choice of logic program would require further study and could involve a trade-off decision between required computer capacity and cycle counting accuracy.

Hot part monitoring is normally applied to a critical turbine part, most often the Stage 1 high-pressure turbine rotor blade. The life characteristic to be measured is stress rupture life - a function of the rotating speed, blade metal temperature, time at temperature, and the blade material characteristics. FADEC calculates T3 and T4.1 (high-pressure turbine blade cooling air temperature and inlet temperature respectively) from which Stage 1 turbine blade metal temperature can be easily computed. A characteristic curve of blade metal temperature versus stress rupture life in minutes and hours can be stored in the computer and a count technique developed to accumulate numbers at a rate inversely proportional to the stress rupture life point at which the engine is operating. Through experience, a total count number at which the blades should be carefully inspected - perhaps at 75% of estimated stress rupture life - will be established. This "On-Condition Maintenance" technique is a preventive maintenance process already well proven in service that can be very cost effective in preventing in-flight turbine failure, as well as premature removals.

LCF and hot part monitoring, as stated previously, are both necessary techniques for modular fault isolation related primarily to the rotating parts and the turbine nozzle partitions. By these techniques and good computerized or other record-keeping system, specific critical serialized parts in each of the three modules - compressor, HP turbine and LP turbine - can be monitored for life used and inspected and/or replaced on a planned basis to avoid inflight failures or unscheduled maintenance.

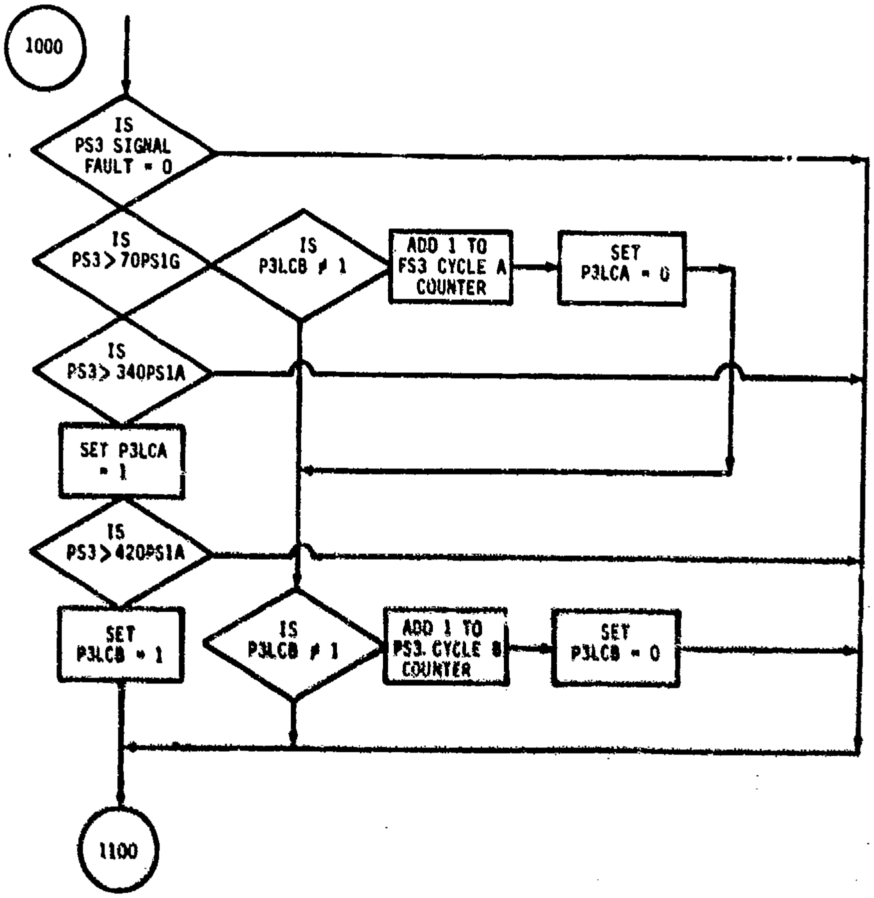


Figure 10. PS3 LCF Count.

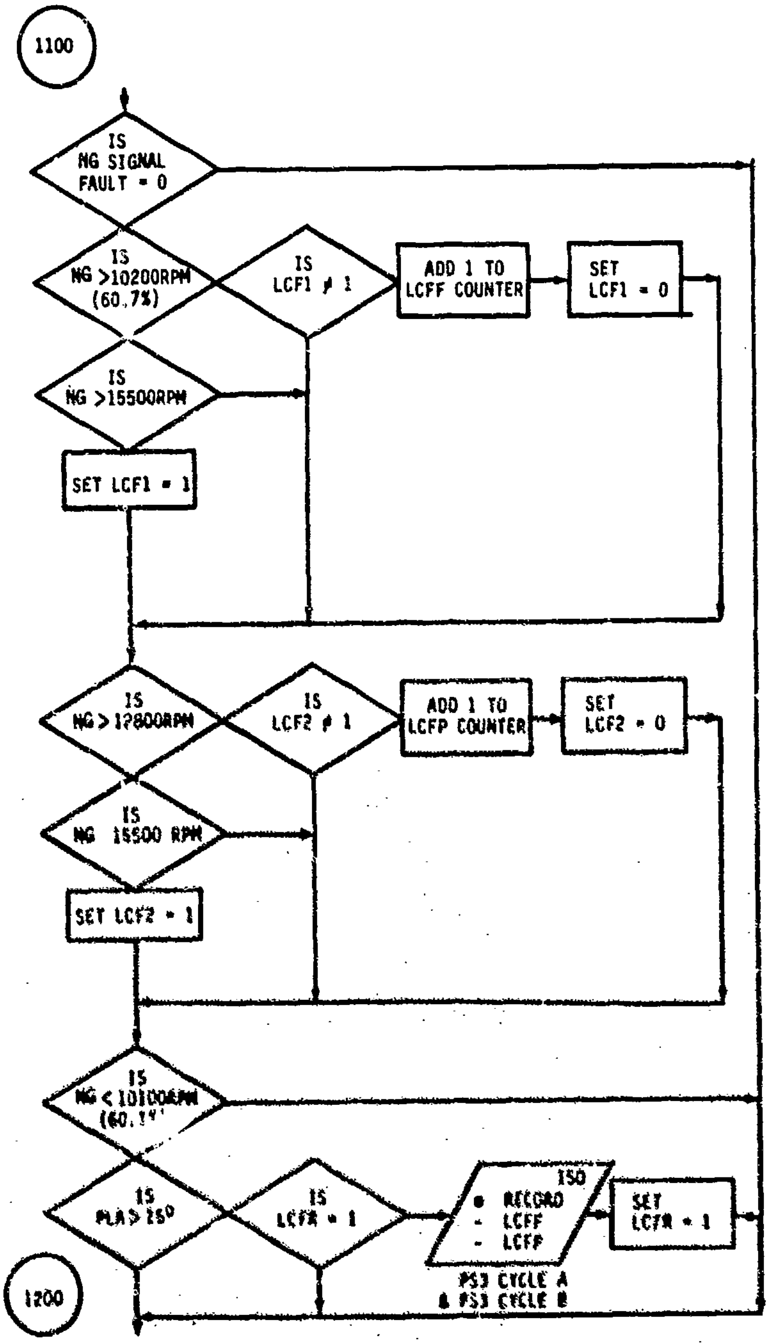


Figure 11. NG LCF Count.

STORAGE OF FLIGHT EVENTS FOR GROUND TROUBLESHOOTING ANALYSIS TO THE MODULE AND LRU LEVEL

There are three basic types of data storage for ground troubleshooting:

1. Exceedance data storage.
2. "Window" data storage.
3. Command data storage.

Exceedance Data Storage

Exceedance data storage consists of recording a complete set of data of all engine and aircraft parameters automatically whenever a single parameter such as speed or vibration or a monitored function such as a control schedule (T5 vs NG) exceeds a pre-set limit or band. It is desirable, further, to preserve several seconds of data prior to the instant of the exceedance as well as after the exceedance. If, for example, data samples are taken at 1/4-second intervals, the recorded data available for analysis could include 12 sets of data before and after the exceedance (3 seconds before, 3 seconds after). This can be accomplished if all data is put into a "scratch pad memory" unit originally and then erased if no exceedance occurs within 3 seconds. If an exceedance does occur, the stored data plus another 3 seconds worth after the exceedance is saved and transferred to a nonvolatile memory unit. Examples of useful exceedance follow:

1. Overspeed - each rotor.
2. Overtemperature (including hot starts).
3. Vibration.
4. Lube pressure.
5. Low power.
6. Control schedules.
7. Instability.
8. Oil contamination.

9. Engine stall. (Not found to be necessary on T700.)

10. Turbine-time at temperature.

"Window" Data Storage

"Window" data storage refers to data taken primarily for performance and mechanical trend analysis. The "window(s)" are a predetermined set of aircraft and engine conditions that the aircraft normally achieves on each flight at which a data set is automatically recorded for comparison on the ground with previous data. Such analysis has been extremely useful to commercial airline operators for detecting engine degradation and detecting incipient failure, as well as predicting engine removals for overhaul. Military engine users should also find this data useful, although the rate of accumulation of engine hours is much lower and presently the military services do not have systems in place to store and process such data. The type of data most useful for this purpose would be vibration, performance parameters, and possibly acceleration and deceleration times.

Command Data Storage

Command data storage is data sets taken on command of the pilot to record some condition which he suspects is abnormal or which, during a maintenance check flight, he is instructed to record for use in a particular troubleshooting procedure to confirm corrective maintenance action.

STORAGE OF MISSION CYCLE DATA FOR ANALYSIS

Mission cycle data is generally of two types:

1. Life used data as previously described in the section titled Low Cycle Fatigue and Hot Part Monitoring.

2. Typical mission and cycle data describing how the aircraft and engines are operated by the pilot to perform prescribed tactical missions.

Typical mission cycle data would consist of a time history of all the pertinent aircraft conditions such as altitude, airspeed, rotor speed, throttle position, collective pitch positions, etc., and the time duration of each condition. Concurrently, similar data would be recorded for the engine, including such things as T5, torque, NG, fuel flow, and vibration. This data would not only document the duty cycle for such types of tactical missions, but could document how individual pilots flew the same mission. This type of data would not be suitable for general use for obvious reasons: airborne data storage requirements may be excessive, the mass of data to be analyzed and saved would become unwieldy, and the data would not be useful for general maintenance and troubleshooting purposes. It would be extremely useful when taken by a few "fleet leader" aircraft in support of logistics planning, pilot training, product or life improvement programs, or special troubleshooting programs involving fleet-wide problems.

TASK IV - FULL AUTHORITY DIGITAL ELECTRONIC CONTROL (FADEC) DESIGN IDENTIFICATION

A functional baseline FADEC system is defined for the T700 engine in this portion of this study. This system maintains the same logic and functions as the current T700 system and, therefore, has twin-engine and single-engine performance the same as, or better than, the proven T700 system. A FICA system is part of the FADEC system, which increases reliability without affecting its performance. It is necessary to define the FADEC system in sufficient detail to make it part of the computer simulation used to determine FICA capabilities. The results of this simulation work are reported as part of Task V.

FADEC SYSTEM

The required functions of the advanced turboshaft engine are assumed to be the same as the T700 system requirements. Table 13 lists the functional system requirements for the T700, showing which engine-mounted components accomplish each function. Figure 12 provides a schematic of the current T700 control system.

The FADEC system must perform all computational functions of the current system. The FADEC unit is the signal processing and digital computational center for the system. Therefore, as seen in Table 13 and Figure 13, all computational functions will be handled by the FADEC unit. For this study, the T700 schedules and dynamics were used in the FADEC system. Figure 14 shows the schematic layout of the FADEC unit. Even though there were no logic changes, FADEC provides performance improvement because some nonlinearities, such as NG governor hysteresis, are eliminated through electronic processing.

The FICA concept is an integral part of the control system to provide necessary reliability to the FADEC system. FICA, through computational methods, eliminates the need for redundant sensors by utilizing the redundant information that exists when all sensors are considered as a group. The FICA calculations are accomplished within the FADEC unit, thus improving the D&CM-FADEC integration.

Table 14 is a list of candidate parameters for the D&CM system on an engine with a FADEC. This shows which parameters are expected to be required by the FADEC system, which by the D&CM system and if these signals would be available within the current T700 system. It is estimated that:

TABLE 13. CONTROL SYSTEM FUNCTIONS

T700	Advanced Turboshaft
ELECTRICAL CONTROL UNIT (ECU)	**FADEC**
NP governing - (HMU trim).	NP governing.
Load sharing during NP governing by torque matching.	Load sharing during NP governing by torque matching.
T4.5 limiting - (HMU trim).	T4.5 limiting.
NP overspeed - redundant sensor and power.	NP overspeed - redundant sensor and power. Engine history calculations.
HYDROMECHANICAL UNIT (HMU)	
NG governing - Ground Idle and Topping.	NG governing - Ground Idle and Topping.
Acceleration-Deceleration scheduling.	Acceleration-Deceleration scheduling.
VG scheduling.	VG scheduling.
Load anticipation - NG scheduling by LDS.	Load anticipation - NG scheduling by LDS.
NG overspeed - (shuts system down).	NG overspeed - redundant sensor and power (if required).
	HYDROMECHANICAL UNIT (HMU)
Fuel flow delivery.	Fuel flow delivery.
VG actuation.	VG actuation.
Backup control (manual selection by PAS).	Backup control (most transfers automatic).
SEQUENCE VALVE	
NP overspeed fuel delivery.	NP overspeed fuel delivery.
Fuel system pressurizing and draining.	Fuel system pressurizing and draining.
HISTORY RECORDER	**HISTORY RECORDER**
Engine history calculations.	
Counter storage.	Counter storage.

TABLE 14. CANDIDATE FADEC AND D&CM SIGNALS

Parameter		Used			Parameter Name	D&CM Use	Control Use	Interface Categorization				Estimated Accuracy for	
		TYPE	FADEC	D&CM				No A-D Conversion	Dedicated Conditioning	Condition For Control	Specialized	Control	D&CM
Control System Inputs													
T2	°F	M	X	X	Compressor Inlet Temperature	Correct Control and Performance Parameters for Monitoring	Schedule Parameters	-	X	X	-	±6°F	
PT2	PSIA	-	X	X	Inlet Total Pressure	Correct Performance Parameters for Monitoring	FICA	X	X	X	-		1%
PC	PSIA	-	X	X	Ambient Pressure (Altitude)	With PT2 for Flight Velocity	FICA	X	X	X	-	±5%	
NG	RPM	ME	X	X	Gas Generator Speed	Overspeed Detection, Detect Fuel System Faults	Governing and Scheduling	X	X	X	-	±0.1%	
NP	RPM	E	X	X	Power Turbine Speed	Overspeed Detection, Engine Health Detect Fuel System Faults	Governing, NP	X	X	X	-	±0.1%	
T4.5	°F	E	X	X	Gas Generator Discharge Temperature	Overtemperature Detection, Hot Part Life, Detect Control System Faults	T4.5 Limiting	-	X	X	-	±20°F	
PS3	PSIA	M	X	X	Compressor Discharge Static Pressure	LCF Pressure Cycles, Detect Fuel System Faults	Accel and Decel Scheduling	X	X	X	-	±1.5 to 2.0% of Reading	
Q1	FT-lb	E	X	X	Torque (Engine No. 1)	Engine Health, Detect Fuel System Faults	Load Sharing	X	X	X	-	±2%	
Q2	FT-lb	E	X	X	Torque (Engine No. 2)	Detect Load Share Faults	Load Sharing	X	-	X	-	±2%	
PAS	DEG	M	X	X	Power Available Signal	Detect Control System Faults	Establish Control Mode	X	-	X	-	±2%	
LDS	DEG	M	X	X	Load Demand Signal	Detect Control System Faults	Provide Anticipation	X	-	X	-	±5%	
NPD	-	E	X	X	NP Demand	Detect Control System Faults	NP Governing Reference	X	-	X	-	-	
OST	-	E	X	X	Overspeed Test	Detect Control System Faults	Reset O/S Reference	X	-	X	-	-	
CB	-	-	X	X	Customer Bleed	Engine Health	FICA	-	X	X	-	-	
AI	-	E	X	X	Engine Anti-Icing	Engine Health, Detect Control System Faults	FICA	X	-	X	-	-	
WFFB	PPH	M	X	X	Fuel Flow Feedback	Detect Fuel System Faults	Fuel Flow Scheduling	X	-	X	-	±1.5% at Calibration	
VG FB	DEG	M	X	X	Variable Geometry Feedback	Detect Control System Faults	VG Scheduling	X	-	X	-	±1.5% at Calibration	
Control Outputs													
WFD	PPH	M	X	X	Fuel Flow Demand	Detect Control System Faults	WF Requested of HMU	X	-	X	-	-	
VGD	DEG	M	X	X	Variable Geometry Demand	Detect Control System Faults	VG's Requested of HMU	X	-	X	-	-	
OSD	-	E	X	X	Overspeed Demand	Detect Control System Faults	O/S Actuation to Sequence Valve	X	-	X	-	-	
FC	-	-	X	X	Failure Code	Indicate Control System Faults	FICA Output	X	-	X	-	-	
Exclusive D&CM													
PL	PSIA	-	-	X	Lube Oil Pressure	Monitor Lube System	-	X	X	-	-		±2% Full Scale
TL	°F	E	-	X	Lube Oil Temperature	Monitor Lube System, Cockpit Display	-	-	X	-	-		±20°F
TWF	°F	-	-	X	Fuel Temperature	Monitor Lube System	-	-	X	-	-		±20°F
FL B/P	-	E	-	X	Lube Oil Filter By-Pass	Monitor Lube Filter Contamination	-	X	-	-	-		-
FWF B/P	-	E	-	X	Fuel Filter By-Pass	Monitor Fuel Filter Contamination	-	X	-	-	-		-
MCD	-	E	-	X	Master Chip Detector	Monitor Lube System Debris	-	X	-	-	-		-
V1 & V2	-	-	-	X	Vibrations	Monitor Mechanical Integrity	-	-	-	-	X		±5%
FP	PSIA	-	-	X	Fuel Boost Pump Pressure	Monitor Boost Pump	-	X	X	-	-	-	±2% Full Scale
IPSP	°F or PSIA	-	-	X	Blower Delta Pressure or Temperature	Monitor Inlet Particle Separator Blower	-	-	X	-	-	-	±2% or ±5°
IGN	Volts	-	-	X	Ignition Exciter Output	Monitor Exciter	-	-	X	-	-		±5%
T3D	°F	-	-	X	Compressor Discharge Temperature	Probably Required for Modular Fault Isolation.	-	-	X	-	-	To be Defined	

NOTES 1) In Used column: M - signal in mechanical form, E - signal in electrical form
2) Additional study is required to determine the necessity for measuring.

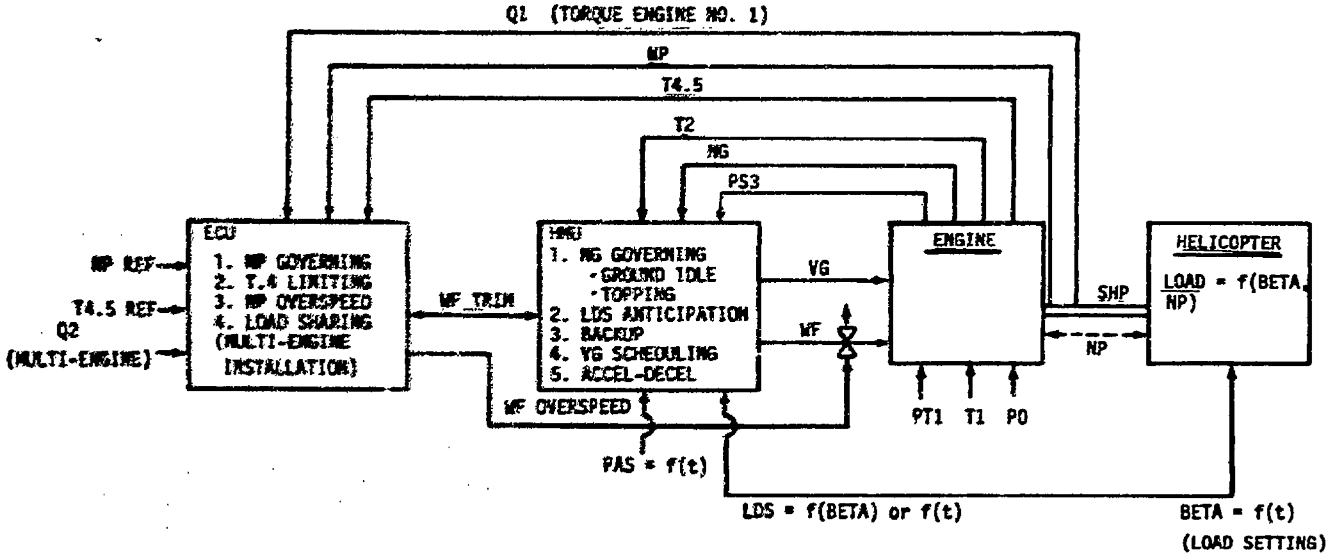


Figure 12. T700 Control System.

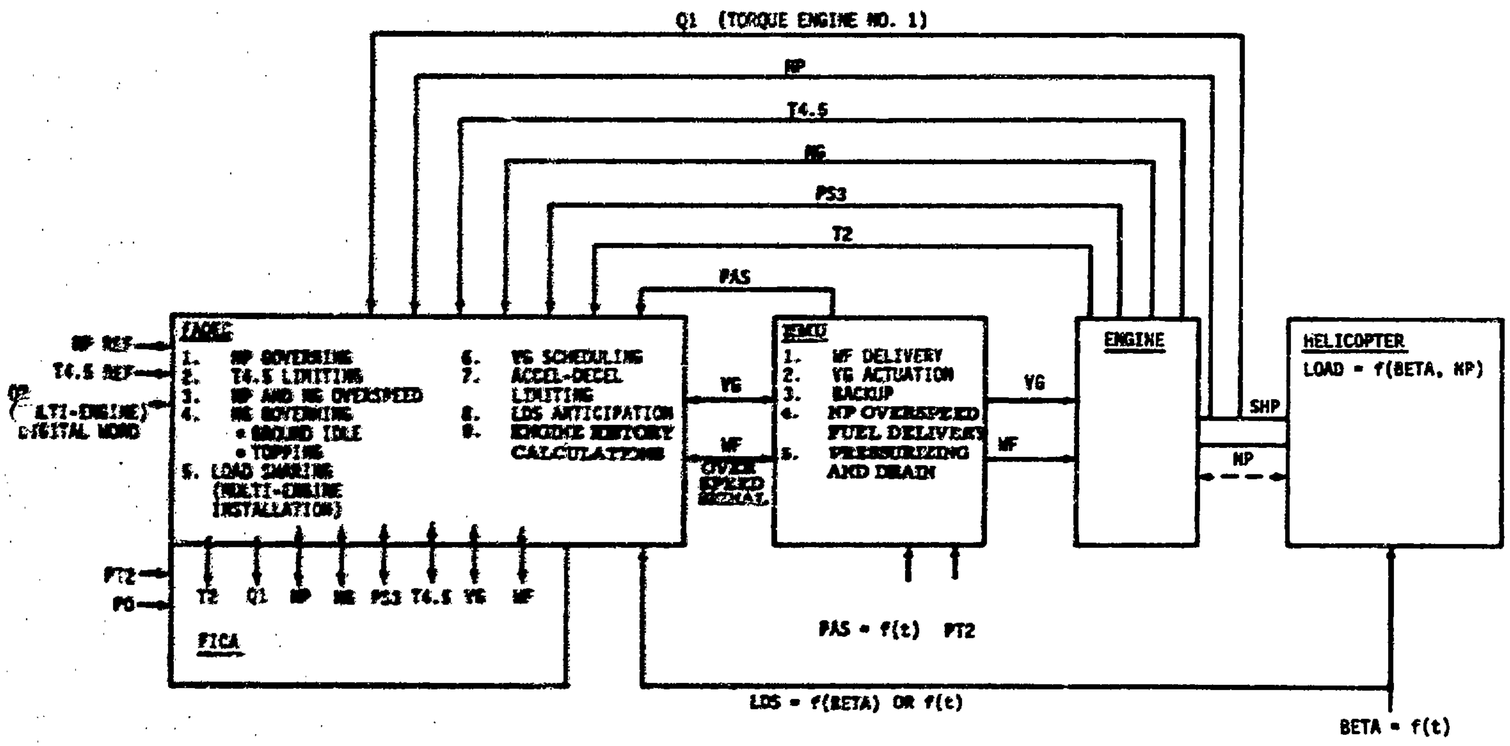


Figure 13. T700 FADEC Control System.

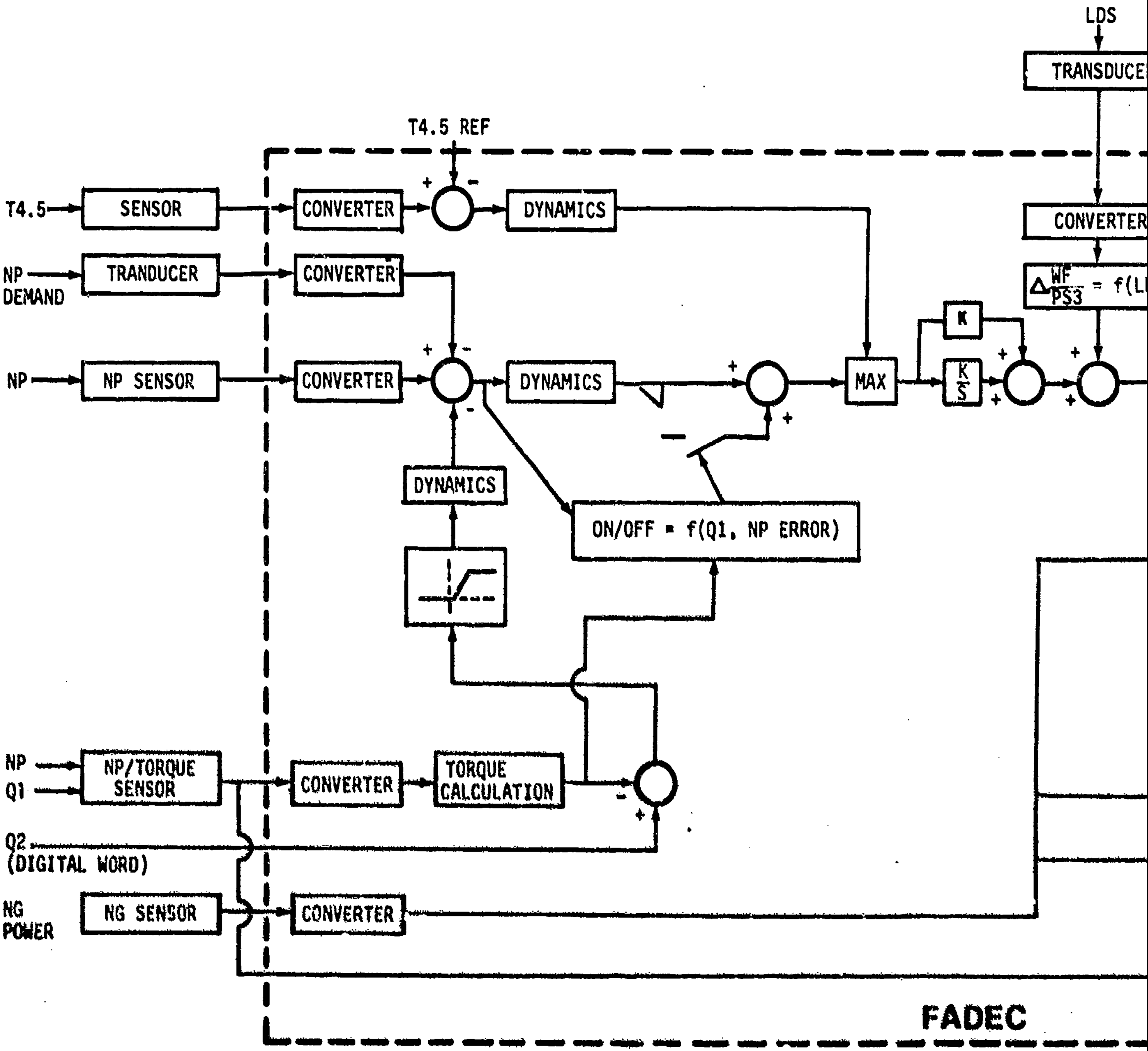
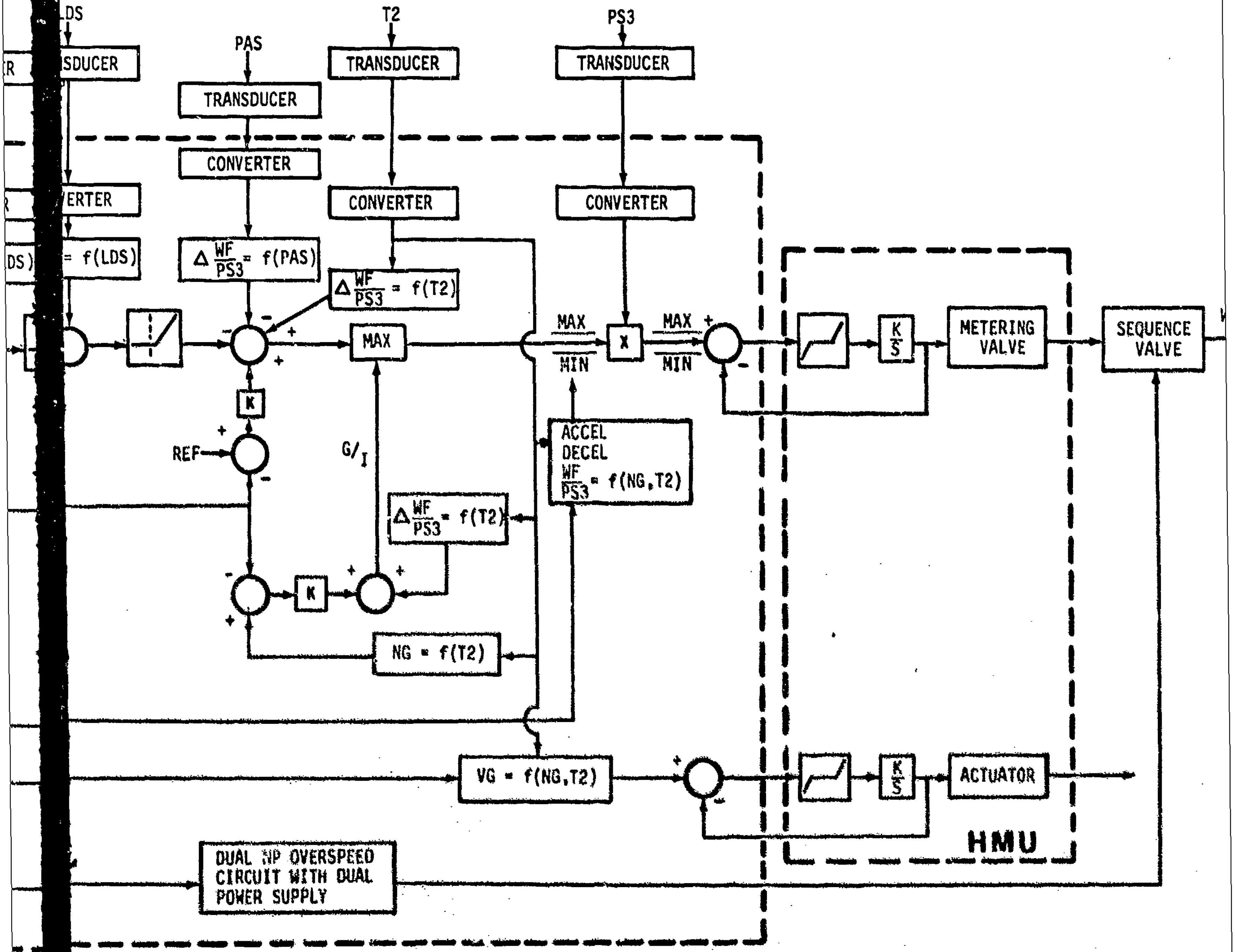


Figure 14. FADEC Logic Diagram


LDS
SDUCER
VERTER
= f(LDS)
PAS
TRANSDUCER
CONVERTER
Δ WF/PS3 = f(PAS)
T2
TRANSDUCER
CONVERTER
Δ WF/PS3 = f(T2)
PS3
TRANSDUCER
CONVERTER
MAX
MAX/MIN
X
MAX/MIN
K
REF
G/I
ACCEL
DECEL
WF/PS3 = f(NG,T2)
Δ WF/PS3 = f(T2)
K
NG = f(T2)
VG = f(NG,T2)
K/S
METERING VALVE
SEQUENCE VALVE
K/S
ACTUATOR
HMU
DUAL NP OVERSPEED CIRCUIT WITH DUAL POWER SUPPLY

2

1. Thirty-three signals are required for D&CM tasks.
2. Twenty-one (~64%) signals will be available in FADEC.
3. Eight signals would be available electrically in the current T700 electrical control; however, most of these would require additional buffering.

Currently, it is anticipated that all D&CM signals, except vibration, would be processed in the FADEC unit. Grouping of signal processing and computations within FADEC will minimize cabling, as signals can be multiplexed to the airframe as required.

It is noted that FICA uses four signals, also required for D&CM, which are not T700 control system signals. The anti-icing (AI) signal is available as a simple on-off switch and requires no new sensor. The customer bleed (CB) sensor or signal is not defined, as CB effects on FICA were not considered in this contract. PT2 and PO are assumed as additional sensors; however, equivalent signals could probably be obtained from the airframe. FICA studies, discussed in the next section, indicate a potential for eliminating the PO from the control system.

The hydromechanical fuel interface and metering valve function are shown schematically in Figure 14. T700 dynamics were used for these components in our system study. No other hydromechanical details were developed, as they have minimum impact on this study.

SIMULATION

In order to determine the capabilities of the FICA system, it was necessary to model the FADEC system and analyze its effect on an engine. At the start of this program the best transient T700 simulation was a nonlinear, partial derivative, digital simulation. The FADEC and FICA designs were programmed and added to this engine simulation. The total system simulation with a dynamometer load was then capable of a variety of standard engine transients. This simulation provided much valuable information, the results of which are discussed in the section on FICA. This simulation does have some limitations, since it does not account for customer bleed effects, off-design VG migration, and anti-icing.

[redacted]

During this study a more complex transient digital model became available which used a complete cycle calculation to simulate the engine. Even though not scheduled in the contract, the FADEC system was added to this new simulation which more accurately matches the engine cycle, including anti-icing and customer bleed. The more complex model was used to study the need to measure ambient pressure and the system performance at other flight conditions. The model is being updated to include off-design VG effects. When the updated model is available, it will be available for use in detailed FICA design studies.

FADEC HARDWARE

Based on T700 FADEC and GE18 development proposals, FADEC preliminary system hardware designs can be used to estimate the system performance and computer size. The following estimates are provided as guidelines in determining the D&CM impact on the FADEC system. The processor, which will be similar to the schematic shown in Figure 15, will use a 4,000 16 bit word memory. This is estimated to provide a loop update time of .005 to .007 second. Current design will have a constant loop update time regardless of path taken. D&CM calculations in general require less frequent update than do control functions. Therefore, if D&CM calculations were added to the FADEC computer they would not have to be made in each cycle. This provides a means of adding lengthy calculations with a minimum cycle time impact by spreading the calculations over several cycles. The estimates of D&CM impact on FADEC made during Task VI are based on preliminary algorithms. They were used only to provide guidelines in considering the D&CM impact on FADEC.

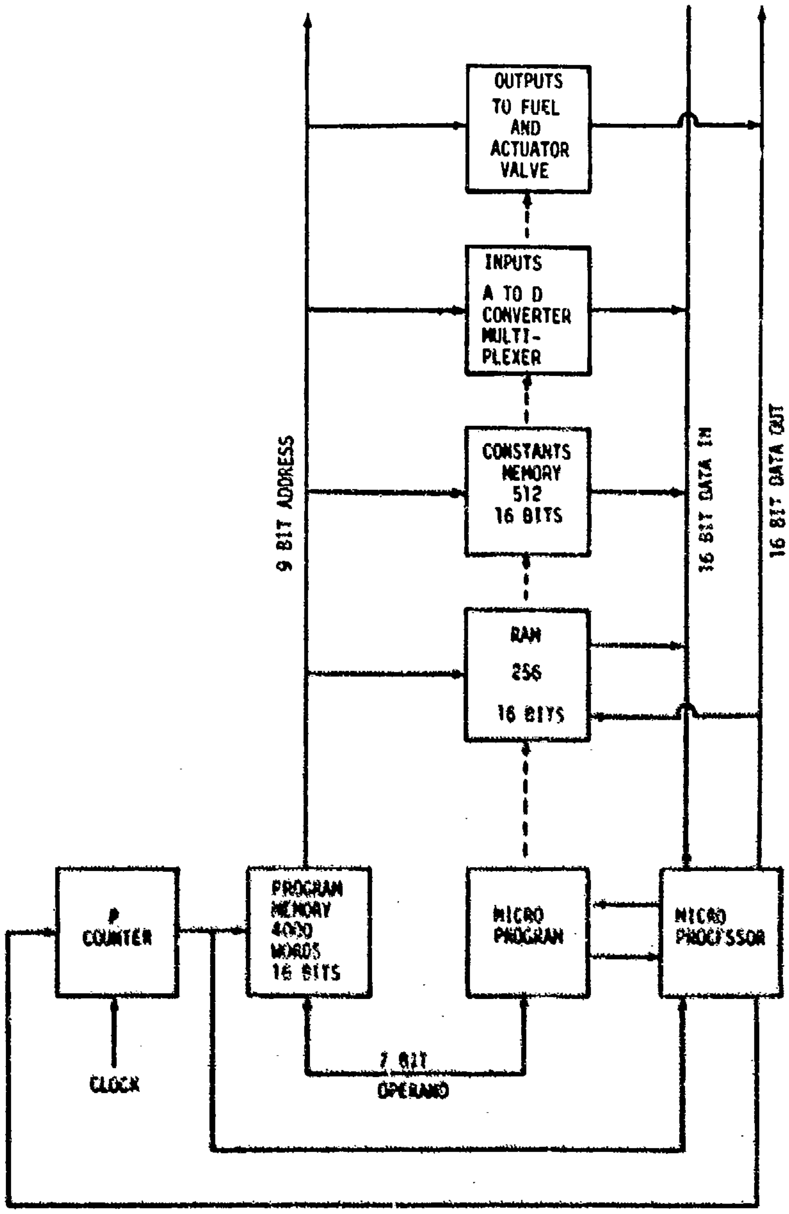


Figure 15. Microprocessor Schematic

TASK V - FAILURE INDICATION AND CORRECTIVE ACTION (FICA)

OVERVIEW

In order to prevent loss of power modulation in the event of a failed sensor, an automatic failure indication and corrective action (FICA) strategy developed by General Electric Co. was implemented to work as part of the FADEC control. FICA, as designed, provides for both the detection of a failed sensor and the generation of the best estimate of the failed signal which is then used by FADEC to provide for continuity of stable engine control. The technical basis for FICA is a modification of Kalman-Bucy filter theory[9], a technique for optimal estimation. To apply the technique, FICA uses a complex mathematical model which represents the static and dynamic behavior of the engine. This model uses the same inputs and outputs as the real engine. The outputs of FICA are simulated sensor signals which are compared with the actual engine sensors and the resulting error is computed. These errors are weighted by a set of gains which are used to force the mathematical model to track the engine. Under normal operation the magnitudes of these errors are small. However, if a sensor fails, the error for that sensor will exceed a threshold. FICA senses this and reacts by providing an indication of the failed sensor and "switches-out" the failed sensor from the engine control and "switches-in" the mathematical best estimate of the signal. This provides for continuity of control.

FICA proved to be extremely successful in being able to detect and correct for single and many combinations of multiple control sensor failures. In addition, FICA was shown to have additional impact on D&CM by making available, with reasonable accuracy, engine parameters which are not normally measured.

The technical details of the design of FICA which formed a major work effort under this contract begin with the section of this report titled Technical Considerations. It will be assumed in that section that the reader is familiar with elementary Kalman filter theory. (For the design of a FICA for turbofan application, the reader is referred to the report by Spang and Corley[10].)

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[9] Kalman, R., "A New Approach to Linear Filtering and Prediction Problems", Transactions ASME J. Basic Engineering, Vol. 82, pp 34-35, March 1960.

[10] Spang, H. A., and Corley, R. C., "Failure Detection and Correction for Turbofan Engine", General Electric Co., Lynn, MA, TIS Report No. 77CRD159, June 1977.

The excellent results obtained by FICA are shown in a set of computer plots which are discussed in the section titled Nonlinear Simulation and Results. This section illustrates the capability of FICA to provide for continuity of control in the presence of many combinations of failed sensors and it illustrates, by actual comparisons, the accuracy of the FICA estimates.

TECHNICAL CONSIDERATIONS

FICA is based on the well-known Kalman-Bucy theory with several significant modifications. In its basic form a Kalman filter is a minimum variance unbiased state estimator for a linear system described by the following equations:

$$\begin{aligned} \dot{X}(t) &= F(t)\,X(t) + G(t)\,U(t) + W(t) & \qquad W(t) &\sim N\,(O,\ Q(t)) \\ Y(t) &= H(t)\,X(t) + V(t) & \qquad V(t) &\sim N\,(O,\ R(t)) \end{aligned} \tag{1}$$

where X(t) is the state vector
U(t) is the input vector
W(t) is the process noise vector which is Gaussian distributed with zero mean and covariance Q(t)
Y(t) is the output vector
V(t) is the measurement noise vector which is Gaussian distributed with zero mean and covariance R(t).

The best estimate of state X is $\hat{X}$, given by

$$\dot{\hat{X}} = F(t)\,\hat{X}(t) + K(t)\,[Y(t) - H(t)\,\hat{X}(t)]$$

where K(t) is known as the Kalman gain matrix.

For a more detailed discussion of the basic Kalman filter and its discrete-time counterpart, see Gelb[11].

The general solution requires K(t) to be a function of time. However, in the case where the system and measurement dynamics are linear, constant coefficient equations, and the driving noise statistics are stationary, the Kalman gain matrix may reach a constant steady-state value. The Kalman gain matrix is determined by specifying the linear dynamics of the process and the two driving noise

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[11] Gelb et al, APPLIED OPTIMAL ESTIMATION, the MIT Press, 1974.

covariance matrices R and Q. The solution for K is obtained by solving a matrix Riccati equation. For the case where the process dynamics are nonlinear, it is necessary to formulate the extended Kalman filter. The extended Kalman filter algorithms are the same as for the basic Kalman filter with the exception that at each instant of time the process dynamics must be linearized about the current state estimate. This requires a new evaluation of the Kalman gain matrix at each instant of time. This, unfortunately, presents a major computational burden and one which cannot be done on an engine-mounted computer within the current state of the art.

To eliminate this computational complexity in the Kalman filtering algorithm, it is necessary to formulate a major simplification since the turboshaft engine dynamic equations are highly nonlinear. This simplification technique was originally proposed by Spang and Corley in the design of a FICA for a turbofan engine. In their approach the nonlinear model equations are used in the generation of the residuals (errors between the state estimates and the actual state measurements), but the Kalman gain matrix is assumed to be a <u>constant</u>, independent of either time or state estimate. This allows the Kalman gains to be precomputed using a linear model of the engine. The use of a constant Kalman gain matrix produces a suboptimal filter but one which is adequate for the task. Of more importance is the stability of the structure. Safonov and Athans[12] of MIT call this structure a constant gain extended Kalman filter CGEKF. Their results indicate that for many applications, satisfactory performance can be obtained from a CGEKF designed to be optimal for a constant stochastic linear model approximating the actual nonlinear system. They have been able to prove that the CGEKF is intrinsically robust against the effects of approximations introduced in the design of the constant Kalman gain matrix. These results provide the theory of why FICA performs as well as it does. Their results indicate that the emphasis on performance should be placed on a good nonlinear representation of the process.

The structure of FICA consists of two parts: a nonlinear model of the turboshaft engine and update logic utilizing the residuals weighted by the Kalman gain matrix to force the model to "track" the actual engine. The design of both elements will be described in detail later.

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[12] Safanov, M.G., and Athans, M., "Robustness and Computational Aspects of Nonlinear and Stochastic Estimators and Regulators," MIT technical report No. ESL-P-741. April 1977.

Further theoretical points which will be discussed are the conditions necessary and sufficient for a solution to exist to the Kalman filtering problem. The question may be asked: Under what conditions can a FICA reconstruct a failed sensor signal? The answer to this question involves the concept of observability[9]. In order for a Kalman filter to exist for the system described by equation (Eq 1), it is necessary that (F,H) be observable; i.e., the well-known observability matrix be full rank. When a sensor fails, a row of the H matrix is reduced to zero. If the system with the reduced matrix H remains observable, then a FICA exists which will reconstruct the failed signal. This places a limitation on the subset of sensors whose failures can be corrected. For the turboshaft application considered here, the requirement for observability necessitates that either NP or Q1 must always be a measured signal and that a single FICA cannot detect failures in both.

For purposes of this study, Q1 will not be reconstructed. However, a FICA structure which will detect a failure of Q1 will be discussed later. In elementary terms, the observability requirement means that there must be redundant information in the remaining (unfailed) sensors which is extracted by FICA to estimate the failed sensors.

Nonlinear Model of a Turboshaft Engine

An accurate nonlinear model of a turboshaft engine forms a key component of FICA. An obvious trade-off must be made in terms of accuracy and complexity since the model must be run in the on-engine digital computer. The model must represent both the steady-state and transient performance of the engine. The actual functional equations which represent the mass flows, pressures, and temperatures form the basis for the model. The model has the same inputs and outputs as the actual engine. A station diagram of the engine is shown on Figure 16.

The compressor discharge total pressure is a function of the static pressure

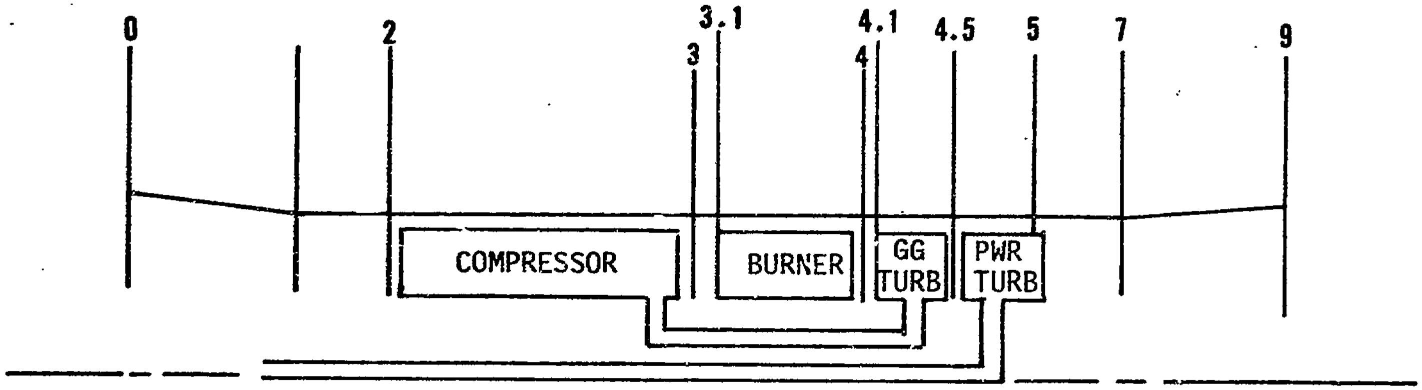
$$P3 = f(PS3) \tag{3}$$

For the compressor the airflow is of the form

$$W2 = P2/\sqrt{T2} * f(NG/\sqrt{T2}, PS3/P2) \tag{4}$$

The compressor discharge temperature is given by

$$T3 = T2 * f(NG/\sqrt{T2}, P3/P2) \tag{5}$$



0. FREE STREAM AIR CONDITIONS
1. INDUCTION SYSTEM OUTLET/ENGINE INLET INTERFACE
2. COMPRESSOR INLET
3. COMPRESSOR OUTLET
3.1 BURNER INLET
4. BURNER OUTLET/FIRST TURBINE STAGE INLET INTERFACE
4.1 FIRST TURBINE ROTOR STAGE INLET
4.5 GAS GENERATOR TURBINE OUTLET/POWER TURBINE INLET INTERFACE (INLET TO POWER TURBINE NOZZLE)
5. LAST TURBINE STAGE OUTLET
7. ENGINE OUTLET/EXHAUST DUCT INLET INTERFACE
9. EXHAUST DUCT OUTLET

Figure 16. Station Identification

The compressor discharge airflow is given by

$$W3 = C * W2 \tag{6}$$

where C is a constant

The temperature rise in the combustor depends on fuel-air ratio.

$$T4.1 - T3 = f(WF/W3) \tag{7}$$

where WF is the fuel flow

The airflow leaving the combustor is of the form

$$W4.1 = C * W3 + WF \tag{8}$$

The gas generator turbine inlet pressure is based on a fixed area nozzle

$$P4.1 = C * W4.1 \sqrt{T4.1} \tag{9}$$

The compressor discharge static pressure is related to the turbine inlet pressure

$$PS3 = C * P4.1 \tag{10}$$

The turbine discharge airflow is given by

$$W5 = C * W2 + WF \tag{11}$$

The static pressure in the exhaust duct inlet is given by

$$PS7 = PO - C * T5 * W5^2/PO \tag{12}$$

The power turbine static discharge pressure is given by

$$PS5 = PS7 - C * T5 * W5^2/PS7 \tag{13}$$

The power turbine discharge total pressure is given by

$$P5 = PS5 + C * T5 * W5^2/PS5 \tag{14}$$

The interturbine total pressure and temperature are given by

$$P4.5 = P5 * f(P4.1/P5) \tag{15}$$

$$T4.5G = C * T4.1 \tag{16}$$

The power turbine exit temperature is given by

$$T5 = T4.5G * f(P5/P4.5) \tag{17}$$

The power extracted by the compressor is a function of airflow and temperature rise

$$PW2 = C * W2 * (T3 - T2) \tag{18}$$

The gas generator turbine power is given by

$$PW4 = f(T4.1,\ P4.5/P4.1,\ W3,\ WF) \tag{19}$$

The power turbine power is given by

$$PW5 = f(T4.5,\ P5/P4.5,\ W3,\ WF) \tag{20}$$

The power extracted by accessories is given by

$$PXC = P2\ \sqrt{T2} * f\left(NG/\sqrt{T2}\right) \tag{21}$$

The power turbine torque is a function of power turbine power and speed

$$Q5 = f(PW5,\ NP) \tag{22}$$

The above equations express the thermodynamic relationships which exist within the engine. The dynamics of the engine are determined by the rotor accelerations produced by unbalanced torque. The rate of change in the rotor speed is given by

$$\frac{d\,NG}{dt} = C * (PW4 - PW2 - PXC)/JG * NG \tag{23}$$

$$\frac{d\,NP}{dt} = C * (Q5 - Q1)/JP \tag{24}$$

where: JG = moment of inertia of gas generator rotor
JP = moment of inertia of power turbine rotor
Q1 = power turbine shaft torque

The only significant sensor dynamics is that of T4.5. Denoting the sensor measurement of T4.5G as T4.5, the dynamics is modeled as

$$\frac{d\,T4.5}{dt} = C * (T4.5G - T4.5) \qquad (25)$$

Fuel flow is essentially an integration of torque motor current

$$\frac{dWF}{dt} = \begin{cases} C * (TMI - H) & TMI > H \\ O & H \geq TMI \;\; \geq H \\ C * (TMI + H) & TMI < H \end{cases} \qquad (26)$$

Since the actual hardware displays significant deadband in the relationship between torque motor current and fuel flow, deadband (H) was added to the model. The effect of the amount of this deadband is discussed later.

The last four equations represent the dynamic behavior of a turboshaft engine. They form the state vector of a fourth-order system. A brief explanation of the method of solution for these equations will now be given.

The resulting system consists of 4 first-order differential equations and 20 simultaneous algebraic equations. In order to solve them, one needs the input values of PO, T2, P2, TMI and Q1. Inputs TMI and Q1 are inputs to the engine and PO, T2, P2 determine the external operating environment and must be known. In its current formulation FICA is unable to reconstruct them. An alternative formulation for reconstruction of Q1 will be discussed later. Knowing these inputs will yield a solution to the system of equations. Unfortunately, the algebraic equations which determine the thermodynamic behavior of the engine are iterative in nature and one must determine a converged solution at each loop update time of the computer. This could pose a computational burden for an on-engine computer. Consequently, an iteration scheme which allowed only one pass through these equations was implemented. The two iteration variables chosen were T5 and PS3. These variables are updated at the beginning of each time step by means of a weighted error matrix from the last iteration using a modified Newton-Raphson approach with constant weights determined from calculating the Jacobian matrix at NG = 95%. This technique produced excellent results with a one-pass iteration over the engine operating range.

The accuracy of the simplified nonlinear model was judged to be adequate by running it in parallel with a complex transient cycle model of the T700 engine which was known to agree with actual engine behavior. Each of the simplified equations was fit to actual cycle data for the range 85% corrected NG to 102% corrected NG. Most of these fits were either linear or quadratic and were accurate to within 2 or 3%.

As was previously mentioned, the nonlinear partial derivative engine simulation does not account for off-design VG migration, customer bleed effects, and anti-icing. Consequently these effects were not considered in the FICA model. If sufficient data had been available, the VG actuation system would have been modeled in a similar fashion to the fuel flow actuator. This would produce both an additional state variable and measured output variable VG FB. This would increase the number of elements in the Kalman gain matrix from 20 to 30 to allow FICA to detect and correct for a failure of the VG feedback signal. The FICA designed by Spang and Corley[10] for a turbofan engine satisfactorily included the effects of off-design VG.

State and Output Vectors

The state vector X and the output vector Y are defined to have the following components:

$$X = \begin{bmatrix} NG \\ NP \\ T4.5 \\ WFFB \end{bmatrix} \qquad Y = \begin{bmatrix} NG \\ NP \\ T4.5 \\ WFFB \\ PS3 \end{bmatrix} \qquad (27)$$

This establishes the number of elements in the Kalman matrix equal to 4 x 5 = 20.

Kalman Gain Matrix

FICA is implemented as a CGEKF which requires a linear system model for evaluation of the Kalman gain matrix. Consequently the nonlinear dynamics were linearized at a nominal NG = 95%. This linearization was accomplished by perturbing each state, one at a time, while keeping the other states and inputs fixed. The matrices F, H in (Eq 1) are computed as follows:

$$[Fij] = \frac{\Delta \dot{X}i}{\Delta Xj} \Bigg| (\Delta Xi = 0 \quad i \neq j) \qquad j = 1, 2, \ldots N \qquad (28)$$

$$[Hij] = \frac{\Delta Yi}{\Delta Xj} \Bigg| (\Delta Xi = 0 \quad i \neq j) \qquad j = 1, 2, \ldots N \qquad (29)$$

where [Fij] and [Hij] are the elements in the i'th row and j'th column of the respective matrices.

The linearized matrices are given by

$$F = \begin{bmatrix} -3.14 & 0 & 0 & .071 \\ 9.98 & -1.74 & 0 & .261 \\ -8.77 & 0 & -.5 & .787 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 6.02 & 0 & 0 & .0774 \end{bmatrix} \tag{30}$$

In order to calculate the Kalman gain matrix, it is necessary to specify the driving noise covariance matrices. The Q matrix (process driving noise matrix) is a measure of modeling errors; i.e., it reflects how well the simplified model matches the actual engine. For this study Q was assumed to be diagonal. From an analysis of transients run on both the full nonlinear simulation and the simplified nonlinear model, it appeared that bias errors were dominant and that a standard covariance calculation might be misleading. Therefore, it was decided to select the diagonal elements of Q such that the standard deviation of each state was 1% of its maximum value. This is consistent with model accuracy.

The R matrix (measurement noise driving matrix) is a measure of sensor accuracy. In a similar fashion its diagonal elements were selected as a percentage of full-scale readings. The resulting R matrix was multiplied by a scalar $\underline{z}$ whose value alters the determinant of R. As $\underline{z}$ is reduced to zero the Kalman filter weights the residuals more heavily. Therefore, one can control the Kalman gains and the corresponding closed loop eigenvalues by a variation of $\underline{z}$. Four iterations were required to produce a set of Kalman gains which yielded a stable set of closed loop eigenvalues under any one sensor failure. This was assessed by checking the closed loop eigenvalues of the filter, setting each row, in turn, of H to zero.

The filter eigenvalues are displayed below:

Closed Loop No Failures	NG Failure	NP Failure	T4.5 Failure	WFFB Failure	PS3 Failure
-63.5	-57.6	-63.6	-63.5	-63.5	-20.0 ±j 0.12
-20.2 ±j 0.28	-20.1 ±j 0.17	-20.0 ±j 0.11	-20.2 ±j 0.27	-20.4	-19.7
-20.1	-20.2	-1.74	- 0.5	-20.0	- 9.7
				- 0.12	

Failure Detection Logic

In order to detect sensor failures, it was necessary to implement a threshold logic system such that when the error between the actual and estimated signals exceeds this threshold the sensor will be assumed to have failed. This threshold logic makes use of the estimated covariance of the error obtained from solution of the Riccati equation. This covariance is given by

$$Ry = R + H\ Pn\ H^t \tag{31}$$

where Pn is the expected covariance matrix of the error in the state estimate.

The detector for the failure is given by[13]

$$\begin{aligned} \left| yi - \hat{yi} \right| &\leq Ki \sqrt{Ryii} \quad \text{No failure} \\ \left| yi - \hat{yi} \right| &> Ki \sqrt{Ryii} \quad \text{Failure} \end{aligned} \tag{32}$$

where Ki is the threshold constant. Since the sensor errors displayed a steady-state bias, the threshold constant was chosen to insure that the normal biases would not produce an erroneous failure. The resulting thresholds for each sensor are listed below. These values proved quite satisfactory in all transient cases studied.

NG	3%
NP	3%
T4.5	12°F
WFFB	9 PPH
PS3	5 PSIA

The actual flowchart of the detection logic will be discussed later. The detection system does not "lock up" on a sensor failure. That is, should the error at some later time come within the bounds, FICA will switch to the actual sensor measurement.

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[13] Anderson, T.W., An Introduction to MULTIVARIABLE STATISTICAL ANALYSIS, J. Wiley and Sons, N.Y., 1958.

SUMMARY OF FICA OPERATION

Figure 17 is a flowchart of the operation of FICA as it was implemented in the computer simulation program. The dynamic equations were discretized using well-known techniques[14] to be compatible with a computer update time of 0.005 sec. It is necessary to delay the arming of the sensor replacement feature until initial transients die out when the FICA model is initialized. This was effected by delaying the "arming" of FICA for 0.5 sec. In the actual engine it would be more appropriate to wait until a predetermining NG level is reached before arming for that operational period.

With reference to Figure 17 the operation of FICA can be explained as follows: At each time step the state equations are integrated one step ahead in time. The two iteration variables (T5, PS3) are predicted ahead to the new time step. The cycle equations are computed (one pass only). The outputs of this last step are the best sensor estimates. These estimates are compared with the actual sensor signals and errors are generated for each sensor. Each error is compared with a threshold. If the error is within bounds, the actual sensor measurement is fed into the control. If the error is outside of bounds, the following events happen. First, FICA declares that the sensor has failed. Second, the failed sensor signal is replaced by the sensor estimate. Third, the failed sensor error only is set to zero to prevent a failed sensor from modifying the state equations. Only good sensors are used in the Kalman filter tracking logic. The estimate of the sensor is used in the control. All errors are weighted by multiplying them by the Kalman gain matrix. The state derivatives are then calculated. These are modified by the weighted errors to force the model to track the engine. Time is then advanced and the entire process is repeated. As implemented, the detection logic does not lock out a sensor once it has failed. If the error at some later time comes within bounds, FICA will no longer declare the sensor failed and will use the actual sensor in the control and filter update logic.

Intermediate Parameter Tracking

In its standard form the Kalman filter is a state estimator; i.e., it forces its output of the model to track the output of the engine, adding correction terms to the state derivatives. However, it was decided for D&CM purposes to exploit the fact that FICA had a cycle model, and in the process of calculating the necessary outputs it has had to calculate many intermediate quantities, such as pressures and temperatures which are not normally measured. The standard Kalman

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[14] Fossard, A., MULTIVARIABLE SYSTEM CONTROL, North-Holland, 1977.

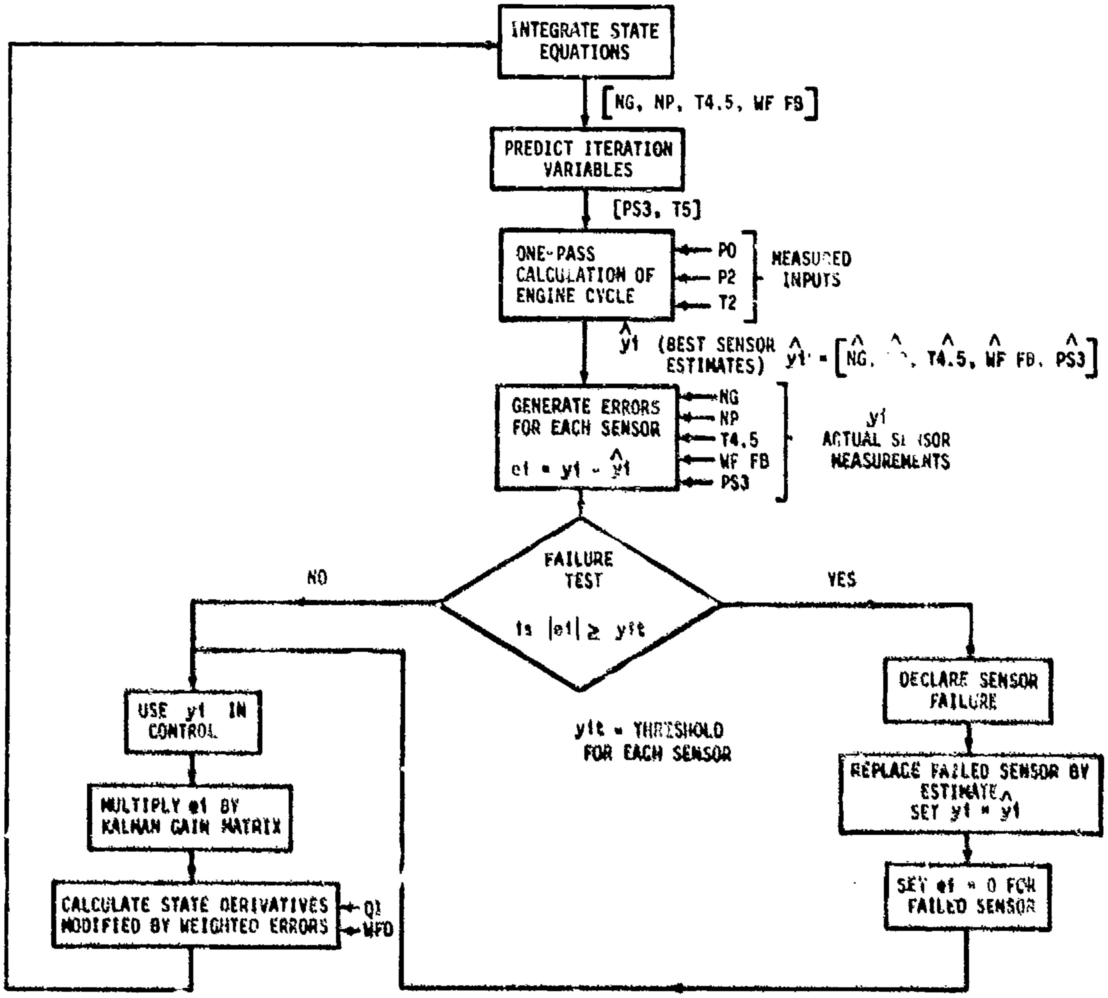


Figure 17. FICA Flowchart.

filter logic does not specifically address itself to the accuracy of these intermediate parameters. A method was developed to use the Kalman gains to correct specific intermediate parameters. The most significant improvement is in the accuracy of T4.1. The method is based on calculating an accurate T4.5G.

The dynamic equation for T4.5 is given by

$$\frac{d\,T4.5}{dt} = \frac{1}{TC}\,(T4.5G - T4.5) \tag{33}$$

The best estimate of $\widehat{T4.5}$ is given by

$$\frac{d\,\widehat{T4.5}}{dt} = \frac{1}{TC}\,(T4.5G - \widehat{T4.5}) + K\,(y - \hat{y}) \tag{34}$$

which is the standard Kalman filter equation.

Rearranging (Eq 34) yields

$$\frac{d\,\widehat{T4.5}}{dt} = \frac{1}{TC}\left(\left\{T4.5G + TC*K(y - \hat{y})\right\} - \widehat{T4.5}\right) \tag{35}$$

The best estimate for T4.5 is identified as

$$\widehat{T4.5G} = T4.5 + TC * K\,(y - \hat{y}) \tag{36}$$

which is the best estimate of the actual interturbine gas temperature (not subject to thermocouple lags). Given T4.5G, T4.1 can be calculated as follows:

$$\widehat{T4.1} = f(\widehat{T4.5G},\ NG,\ dNG/dt) \tag{37}$$

where the dependence on d NG/dt is needed to account for transient heat sink. These corrections were applied to all simulations shown in the next section.

NONLINEAR SIMULATION AND RESULTS

To assess its stability and capabilities, FICA was programmed into two accurate nonlinear transient simulations of the T700 engine. The characteristics of these simulation programs were discussed previously.

The following results were obtained using the original nonlinear partial derivative simulation. A list of computer runs is shown in Table 15. The reader is referred to the glossary as an aid to interpreting the computer plots. All variables which are calculated by FICA start with the letter Y. For each parameter plotted, both the actual value and the value calculated by FICA are shown. All scales have been adjusted so that two large divisions are equivalent to about 10%. Variable YSFAIL is the base 10 equivalent of a binary indication of failed sensors.

$$\text{YSFAIL} = \left\{ \begin{array}{c}\text{PS3}\\ \text{failed}\end{array} = 1,\ \begin{array}{c}\text{WFFB}\\ \text{failed}\end{array} = 1,\ \begin{array}{c}\text{T4.5}\\ \text{failed}\end{array} = 1,\ \begin{array}{c}\text{NP}\\ \text{failed}\end{array} = 1,\ \begin{array}{c}\text{NG}\\ \text{failed}\end{array} = 1 \right\} \qquad \text{(Eq 38)}$$

For example, if both the T4.5 and NG sensors are failed, YSFAIL in binary would be (00101), which is equal to 5 in decimal representation.

Computer run 100.00 (Figures 18, 19 and 20) is an open loop comparison in which the Kalman gains were set to zero and the FICA detection logic was disabled. Also, it was necessary to set both the actuator and model deadbands equal to zero to prevent an ever-increasing offset in fuel flow. The transient is a 5-second load burst with a change in collective pitch from 0 to 68 degrees. This produces a change in NG of approximately 85% to 95%. As seen in the plots, large errors exist between the actual sensor signals and the open loop FICA estimates. The exception is in fuel flow, which has no offset since the same signal drives both the engine and FICA. The most significant error is in NP, which is caused by the difficulty in calculating power turbine power. Additional effort in modeling the power turbine did not improve this problem.

Computer run 100.01 (Figures 21, 22, 23) shows the same transient with the closed loop FICA system enabled. Comparing these plots to 100.00 shows that the errors between the actual sensors and the FICA estimates have been greatly reduced. Notice particularly how well YT45 tracks T45E1 and YTEMP tracks TEMP. This was produced by using the Kalman gains to correct intermediate cycle variables, which was discussed previously. Also notice that it takes approximately 0.2 sec for FICA to initialize. In these computer runs the failure detection and replacement feature of FICA is disabled during this period. The FICA estimate of shaft torque YQ5 has an offset with actual shaft torque. This is produced by the previously mentioned inaccuracy of calculation of power turbine power. FICA produces this offset so that YPNP1 will track actual PCNP1. All subsequent computer runs are with the FICA system enabled.

Computer run 100.02 (Figures 24, 25, 26) shows the response to a more severe transient. The transient involves the same change in collective pitch from 0 to 68 deg but in 2 sec as opposed to 5 sec. While both transients are normal in T700 operation, the faster transient is more difficult for the FICA model to track. Even with this more severe transient, all estimated variables track their actual counterparts exceptionally well. One additional comment concerning the behavior

TABLE 15. COMPUTER RUN INDEX

Run No.	Transient	Sensors Failed	Figure No.
100.00	5 sec., NG 85% 95%; Standard Engine	Open Loop	18, 19, 20
.01		None	21, 22, 23
.02	2 sec., NG 85% 95%; Standard Engine	None	24, 25, 26
.03		NG	27
.04		NP	28
.05		T4.5	29, 30
.06		WFFB	31
.07		PS3	32
.08		NG, PS3	33
.09		NG, WFFB & PS3	34
200.00	NG 85% 95%; Sea Level; Ram Pressure Ratio = 1.2	None	35, 36, 37
.01	NG 85% 95%; 20,000 Ft.; Ram Pressure Ratio = 1.2	None	38, 39, 40
.02		NP	41

of the control is in order. During the load change, LDS is connected to the load input. This means that LDS is also moved 0 to 68 deg in 2 sec. As the control system is designed, LDS produces an increase in WF in order to anticipate the load change. For this transient the amount of anticipation is greater than that required, and this produces a transient <u>increase</u> in PCNP1.

Computer run 100.03 (Figure 27) shows the response with the NG sensor failed at 2.0 sec. In accord with the FICA logic, after 2 sec, YPNG1 is used by the control instead of PCNG1. The transient is almost identical to the no-failed sensor transient.

Computer run 100.04 (Figure 28) shows the response with the NP sensor failed at 2.0 sec. This response is less stable than the previous case but is still satisfactory. However, there is a 5% offset between YPNP1 and PCNP1. This offset is caused by the difficulty in calculating the shaft torque in the simplified model. Since the NP sensor has failed, the Kalman gain on that state has been set to zero and cannot help in reducing the error. However, since the other Kalman gains are nonzero, the magnitude of the offset is less than in the open loop case (run 100.00). In order to provide adequate overspeed protection, there are currently redundant NP sensors. For this transient, a switchover to the redundant sensor is possible, as will be discussed later.

Computer run 100.05 (Figure 29, 30) shows the effect of a failure of the T4.5 sensor at 2.0 sec. This transient is almost identical to the no-failure case. After the sensor fails, FICA sets T45EL1 equal to YT458. The only consequence of the sensor failure for this case is the discrepancy between T45E1 and YT45^{S} and between TEMP and YTEMP. With the sensor failed it is not possible to improve the estimate of these intermediate parameters.

Computer runs 100.06 (Figure 31) and 100.07 (Figure 32) show the effects of a failure of the WFFB sensor and the PS3 sensor respectively. In both cases, the transients are perfectly satisfactory. One conclusion is that the engine will run stably with FICA for any single sensor failure.

Several combinations of double sensor failures were examined, of which computer run 100.08 (Figure 33) is typical. In this run, both NG and PS3 sensors are failed at 2.0 sec, producing minimal effect on transient response. All possible combinations of two sensor failures have not been examined. However, one combination was unstable. This combination consisted of a failure of both the NP sensor and the WFFB sensor at 2.0 sec. Since a single failure of either the WFFB sensor or the NP sensor is stable, a switchover to a redundant NP sensor would solve this dual failure problem.

It is to be noted in the above cases that when a sensor fails it is common that an offset will develop between the FICA estimated value and the actual engine value. While this offset does not affect the stability of NP governing, its presence may dictate modification to the control upon indication of a failure. When the PS3 sensor fails, the offset in the PS3 signal can create a problem with the acceleration and deceleration schedules being wrong by the amount of the offset. A similar problem occurs when the WFFB sensor fails. The control system is aware of the failure mode, but the degree and direction of the offset are not known.

If system studies indicate a stall problem because of the offset, the control could reduce the acceleration schedule when it was notified of a PS3 or WFFB failure.

Computer run 100.09 (Figure 34) shows the system response to a failure of three sensors (NG, WFFB, PS3), all occurring at 2.0 sec. While there are more oscillations than in the no-failure case, the transient is perfectly satisfactory, demonstrating the capability of FICA in a multiple failure environment.

One area of concern initially was the problem of actuator nonlinearities. In the current control this is modeled as a significant amount of deadband in the torque motor (see Figure 14). As mentioned previously, a different amount of deadband was added to the dynamic equation for WFFB. All previous cases had a deadband of 8 MV in the torque motor and a deadband of 10 MV in the FICA model. The amounts of deadband are not significant in the no-failure cases. However, several cases were studied, all of which had a failed WFFB sensor, to examine the effect of deadband on fuel flow offsets. The best transient response was observed when both deadbands were equal. When the FICA model deadband was increased to 12 MV the fuel flow oscillations increased slightly in magnitude but were still acceptable. When the FICA model deadband was reduced to 6 MV, the offset between YZW1 and WFM1 became significantly worse. Therefore, it is concluded that the FICA model deadband must be greater than that of the actual actuator.

All previous runs were made with the nonlinear partial-derivative simulation. About halfway through this study a more complex transient digital model became available. This simulation uses a complete cycle calculation to represent the engine. Even though not scheduled in the contract, the FADEC system was added to the new simulation. This new simulation provided the capability to study performance at other flight conditions and was used to assess the need to measure PO (ambient pressure). All 200 series computer runs were made with this new simulation.

Computer run 200.00 (Figures 35, 36, 37) shows the response to the 2 sec base transient initialized at the same power level for sea level altitude with a ram pressure ratio of 1.2. Computer run 200.01 (Figures 38, 39, 40) shows the response for the same transient at an altitude of 20,000 ft and a ram pressure ratio of 1.2. In both cases excellent tracking is observed, demonstrating that FICA will track well throughout the flight envelope.

Computer run 200.02 (Figure 41) shows the failure of the NP sensor at altitude for the same transient 200.01. For this transient, NG reaches the topping limit. This transient demonstrates satisfactory FICA performance at altitude.

An analysis was made using this second simulation to assess the necessity of measuring both P0 and P2. It was found that if either was eliminated by using P2 for P0 and vice versa, tracking errors significantly increased. In the failure of the NP sensor, offsets became unsatisfactorily large, which resulted in unacceptable transient response. Consequently, it was concluded that both P0 and P2 must be measured. Two transients were run failing the NG sensor with P0 set equal to P2. These cases were acceptable, so with only a limited amount of data it may be possible to eliminate the need to measure P0 if it is not required to reconstruct a failed NP sensor. However, a significant amount of additional analysis over the entire flight envelope would be needed to justify this conclusion.

AREAS OF ADDITIONAL STUDY

As seen in the previous section, FICA as designed works extremely well. However, it was felt necessary to further address certain areas which arose in the study and to comment on possible improvements.

The first area of concern is the inability of FICA as designed to reconstruct the shaft torque sensor Q1. This was referred to previously as being an observability problem and therefore it is theoretically impossible to reconstruct simultaneously both NP and Q1. However, if one of these is measured, the other one can be reconstructed. For the purpose of this study it was assumed that Q1 would be the known input and FICA was designed to reconstruct NP and therefore detect NP failures. FICA could have been designed to use NP as an input and reconstruct Q1. One obvious possible solution is to duplicate the power turbine equations in FICA producing in essence a dual FICA system, one of which is capable of reconstructing NP and the other capable of reconstructing Q1. This dual system would be capable of reconstructing either an NP or Q1 failure but not a dual failure of both.

A second area of concern is the magnitude of the offset between YPNP1 and PCNP1 when the NP sensor fails. The following scheme makes use of the fact that there are dual NP sensors on each engine. The first NP sensor will be denoted NPS. The second NP sensor is part of the torque measuring system and will be denoted NPQ. This second sensor will fail when the torque sensor fails. The logic is as follows. It will be assumed that Q1 will be an input to FICA as in the current design. FICA will therefore calculate a best estimate of NP which will be denoted NPC. The logic is to compare all three NP signals. If they all agree within the designed threshold, assume that no failure has occurred and continue to use NPS in the control. If NPS fails, FICA will detect the failure and NPC will be a good estimate which is then compared to NPQ. If the error between NPQ and NPC is within bounds, NPQ will be switched into the control which will eliminate the NP offset. If the torque sensor fails, FICA will incorrectly declare NPS to have failed. NPC will be greatly different from both NPS and NPQ. Therefore, excluding dual failures, it can be concluded that the Q1 sensor failed and NPS can be used for control.

A third area requiring further investigation is the behavior of FICA when the engine enters a region where the compressor stalls. In this stall region, the cycle equations which make up the FICA model are no longer valid, which provides the potential for FICA making an incorrect decision on sensor failures. It may be necessary to disable FICA upon stall detection or modify its equations to represent behavior in stall.

The fourth area is that of a control system malfunction caused by a FICA system failure itself. A digital system which is structured for maximum reliability by the inclusion of computer self-tests and/or the most appropriate utilization of component redundancy will minimize the probability that a FICA failure will go undetected. For a twin-engine installation, an additional check of whether or not a sensor is functioning could be to compare each sensor to its counterpart on the second engine. Since the engines are normally run in a load sharing mode, parameters on both engines are relatively close in magnitude.

An associated problem is that of control failure caused by an actuator failure. In its present form, FICA is not capable of detecting actuator failures. An alternative approach to this problem is indicated, since one would like not only the notification of an actuator failure but would demand no loss of power modulation ability. A satisfactory solution may require either the use of hardware redundancy or the structuring of the control system architecture to provide a control which is stable but may provide for less performance capabilities in the presence of one or more actuator failures. With current FADEC technology, computer and actuator interface failures are handled by having a hydromechanical backup system. It is possible that this backup can be eliminated by utilizing a digital architecture for FADEC which is both intrinsically reliable and is structured to provide for continued control.

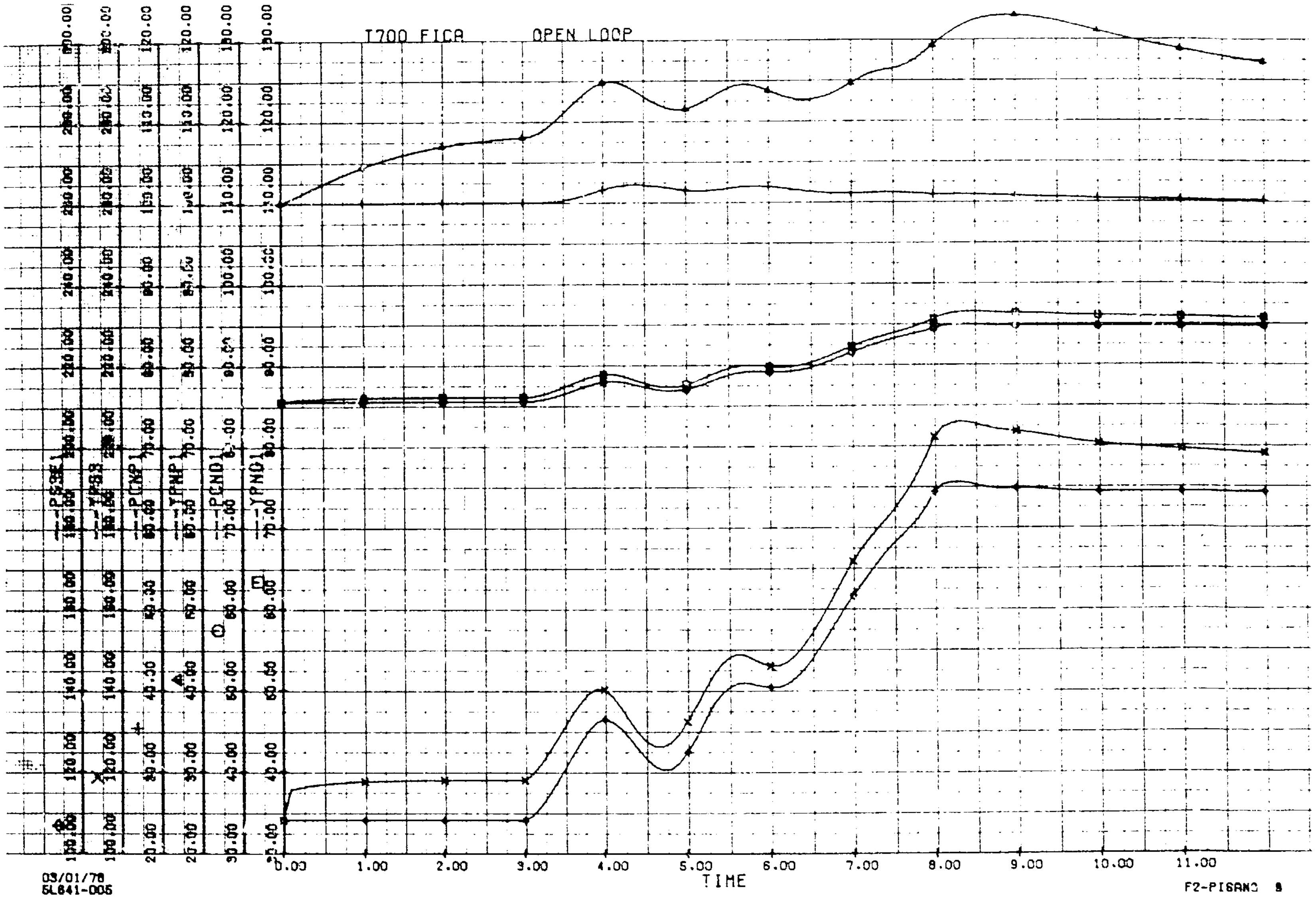


Figure 18. Run 100.00 - FICA Open Loop (Sheet 1 of 3).

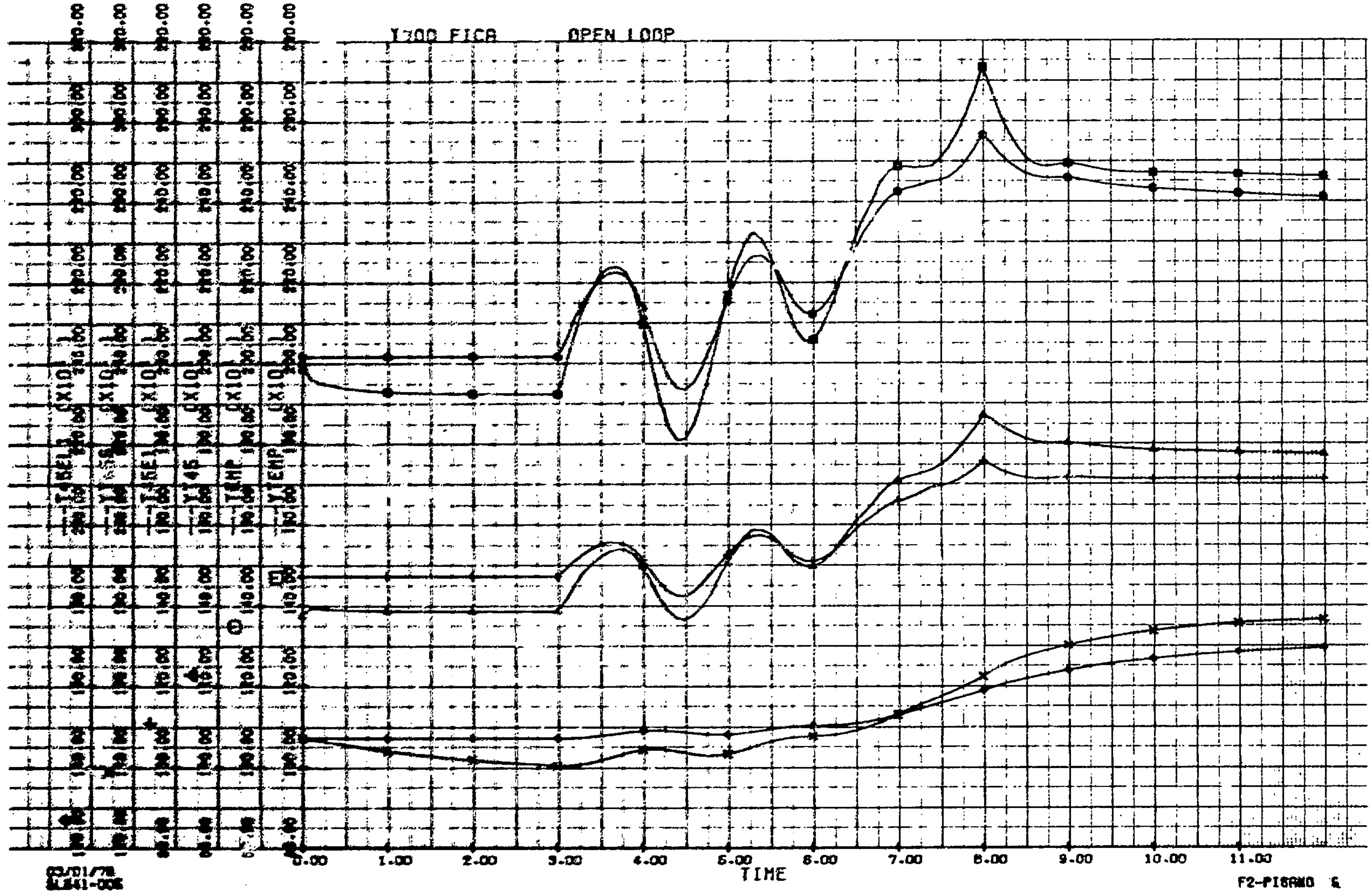


Figure 19. Run 100.00 - FICA Open Loop (Sheet 2 of 3).

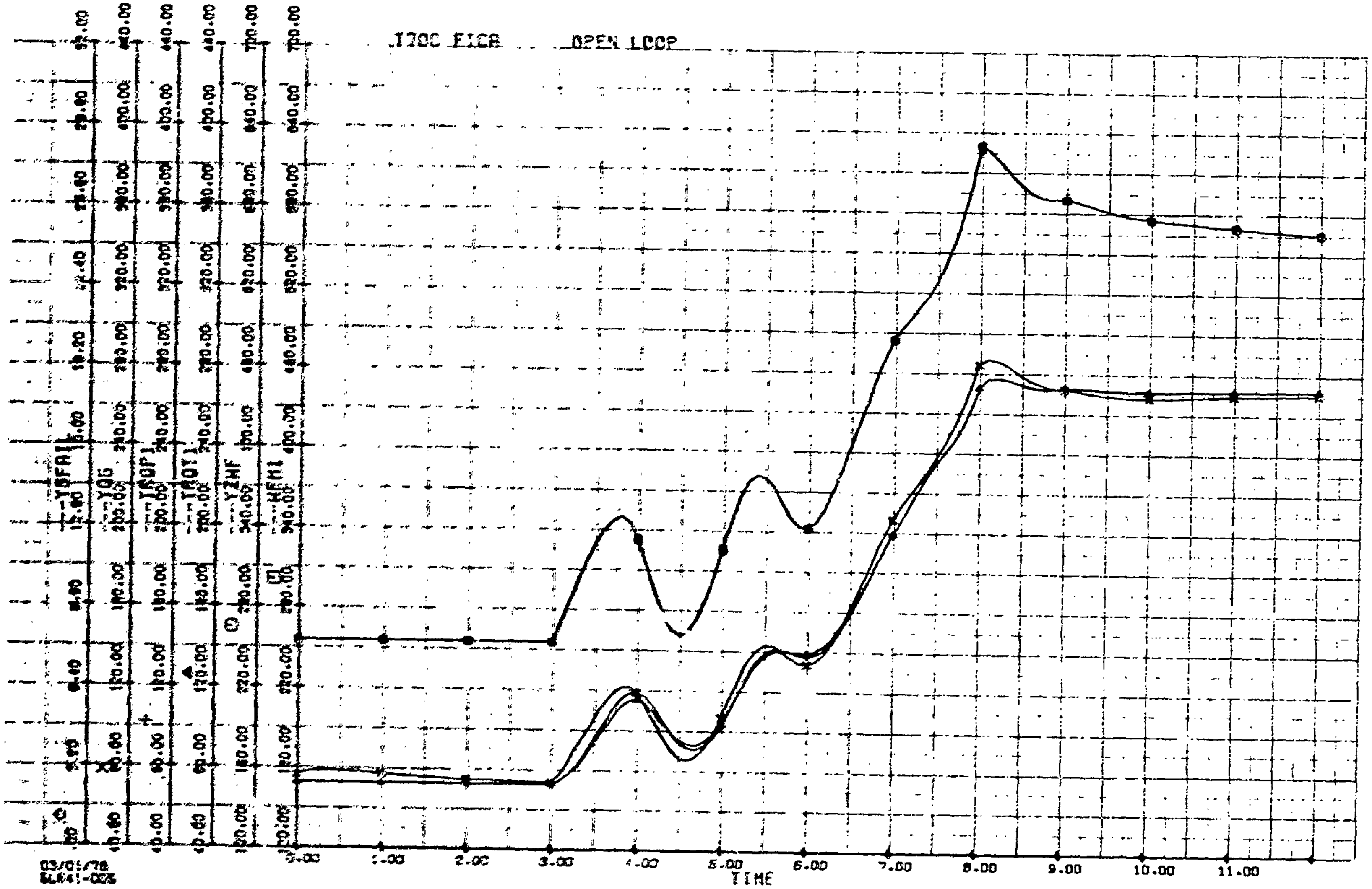


Figure 20. Run 100.00 - FICA Open Loop (Sheet 3 of 3).

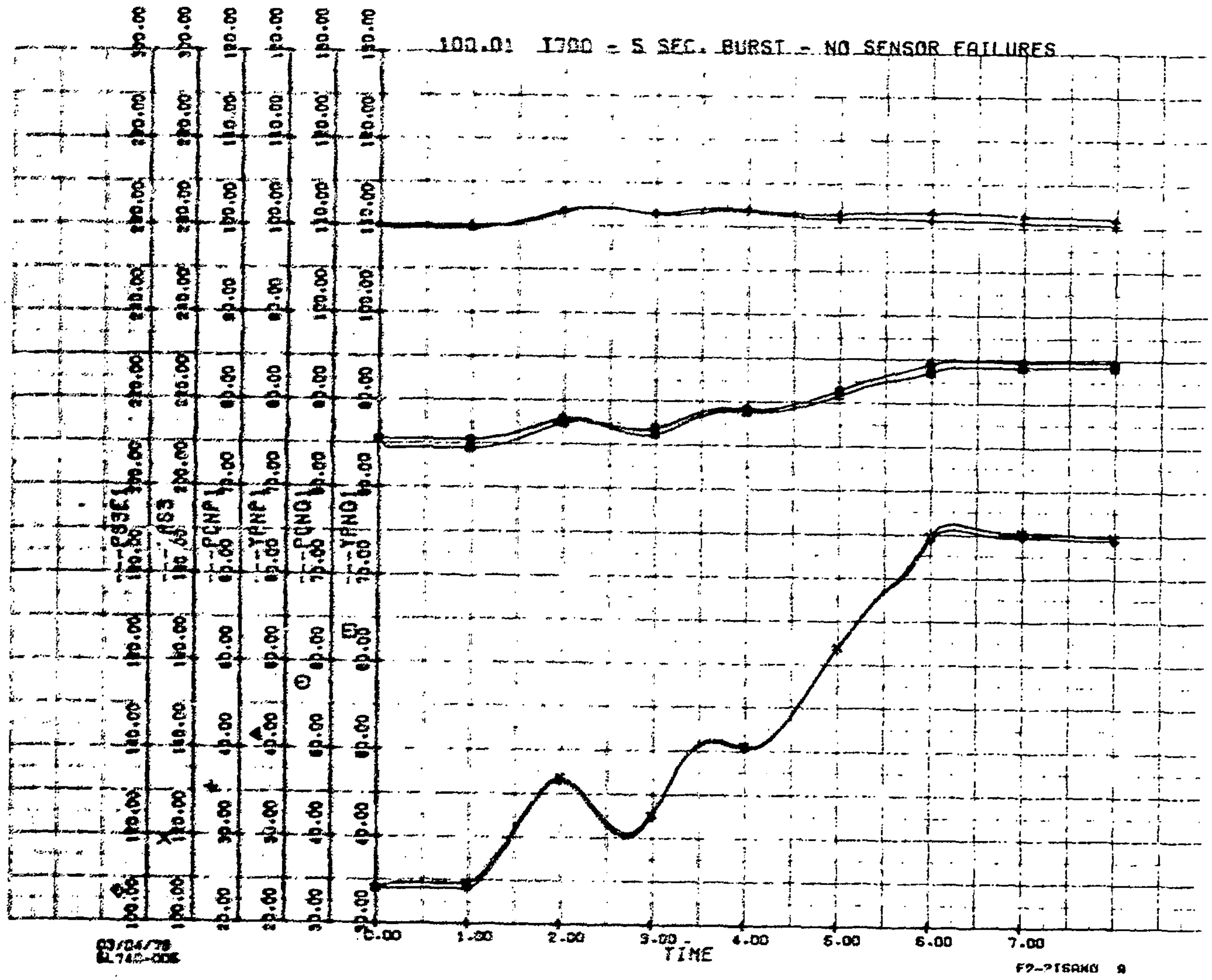


Figure 21. Run 100.01 - 5-Second Burst - No Sensor Failures (Sheet 1 of 3).

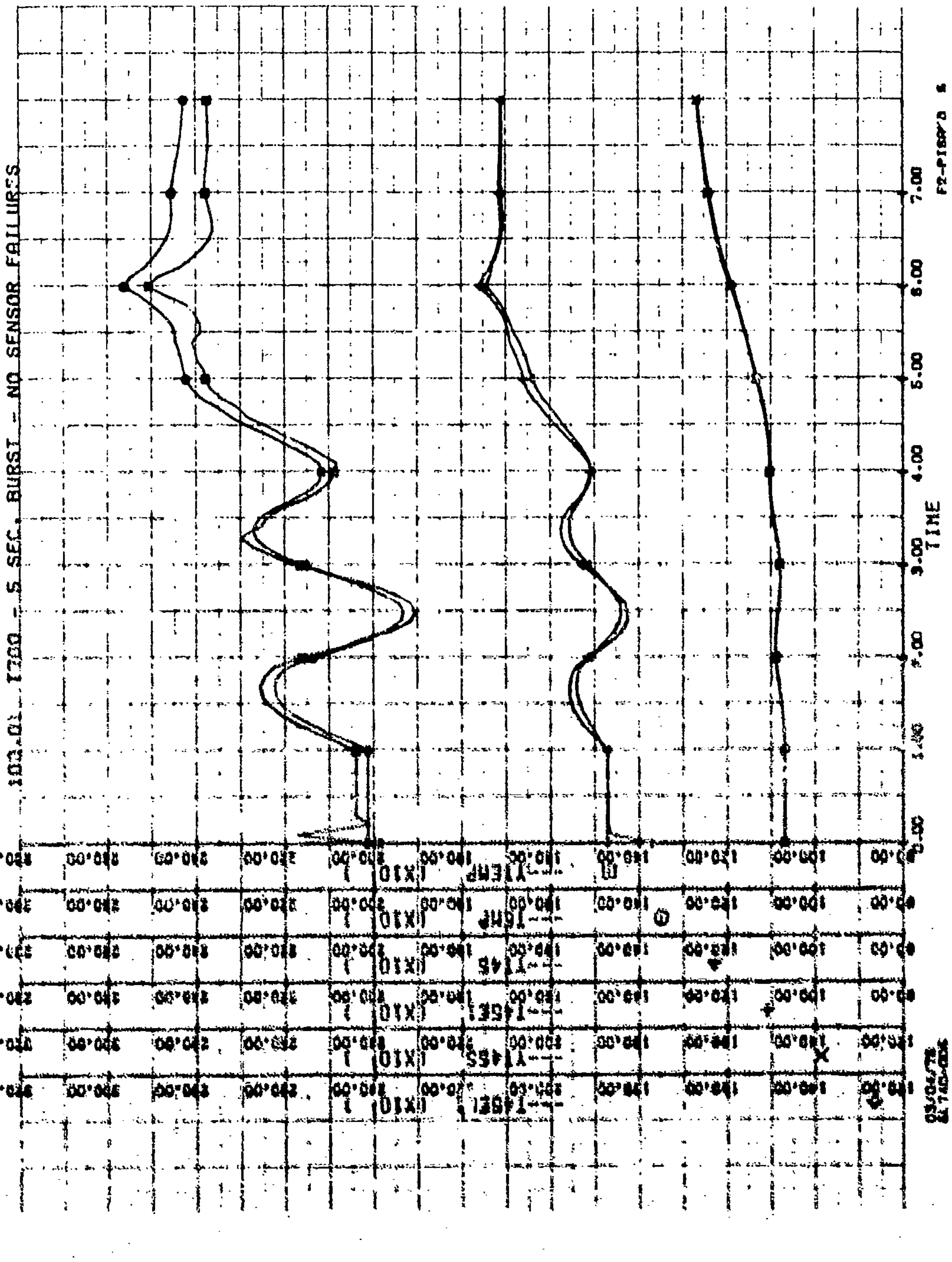


Figure 22. Run 100.01 - 5-Second Burst - No Sensor Failures (Sheet 2 of 3).

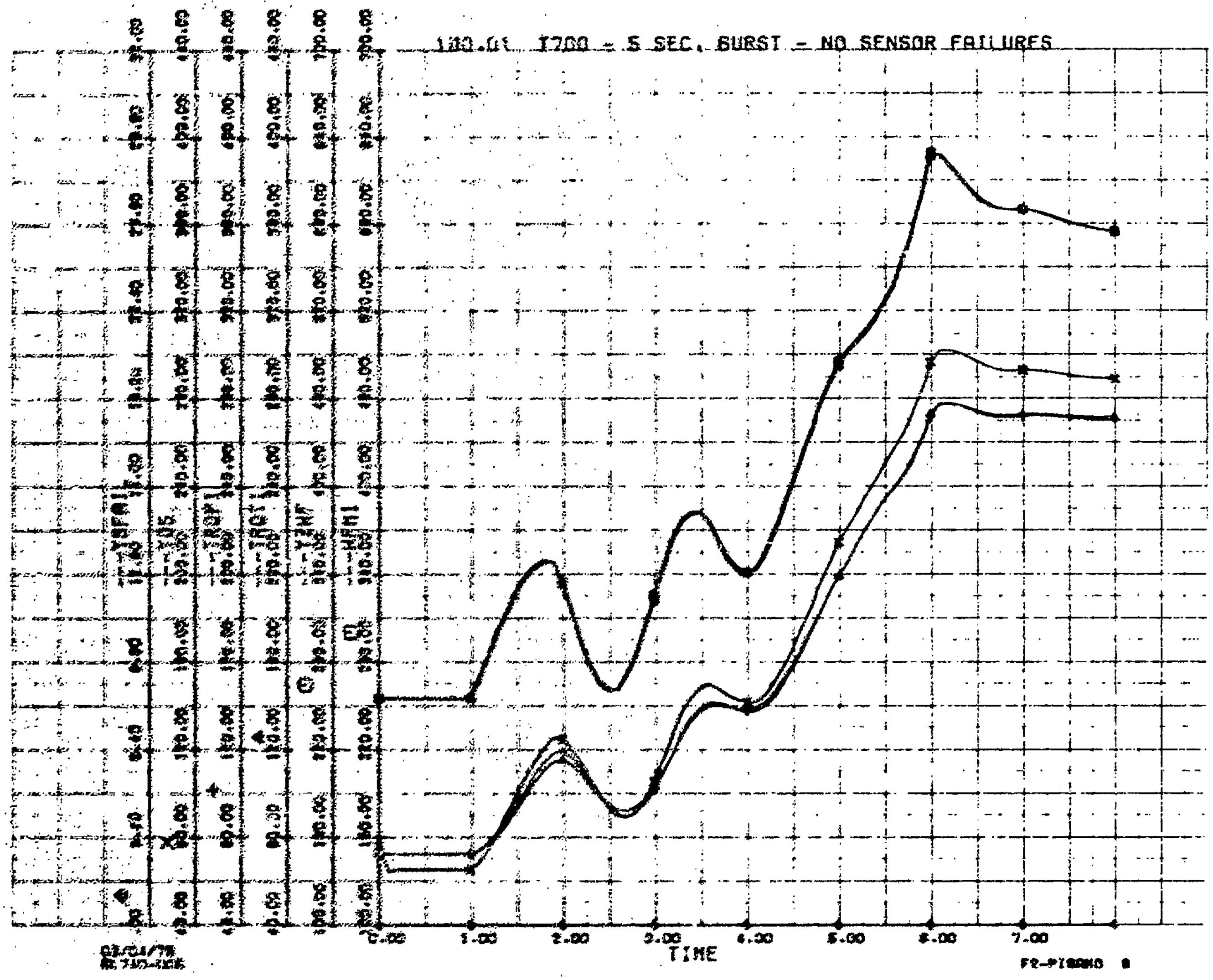


Figure 23. Run 100.01 - 5-Second Burst - No Sensor Failures (Sheet 3 of 3).

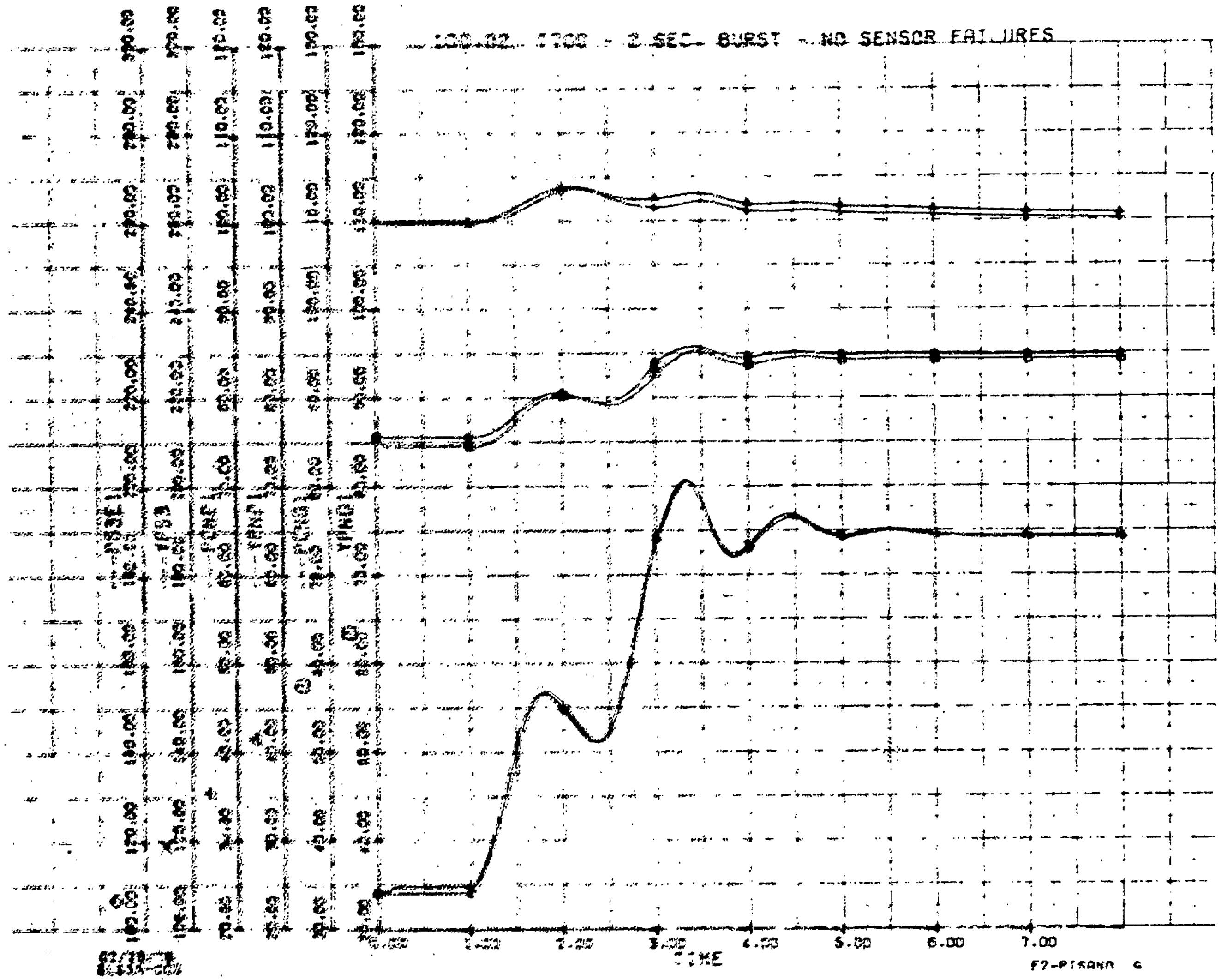


Figure 24. Run 100. 02 - 2-Second Burst - No Sensor Failures (Sheet 1 of 3).

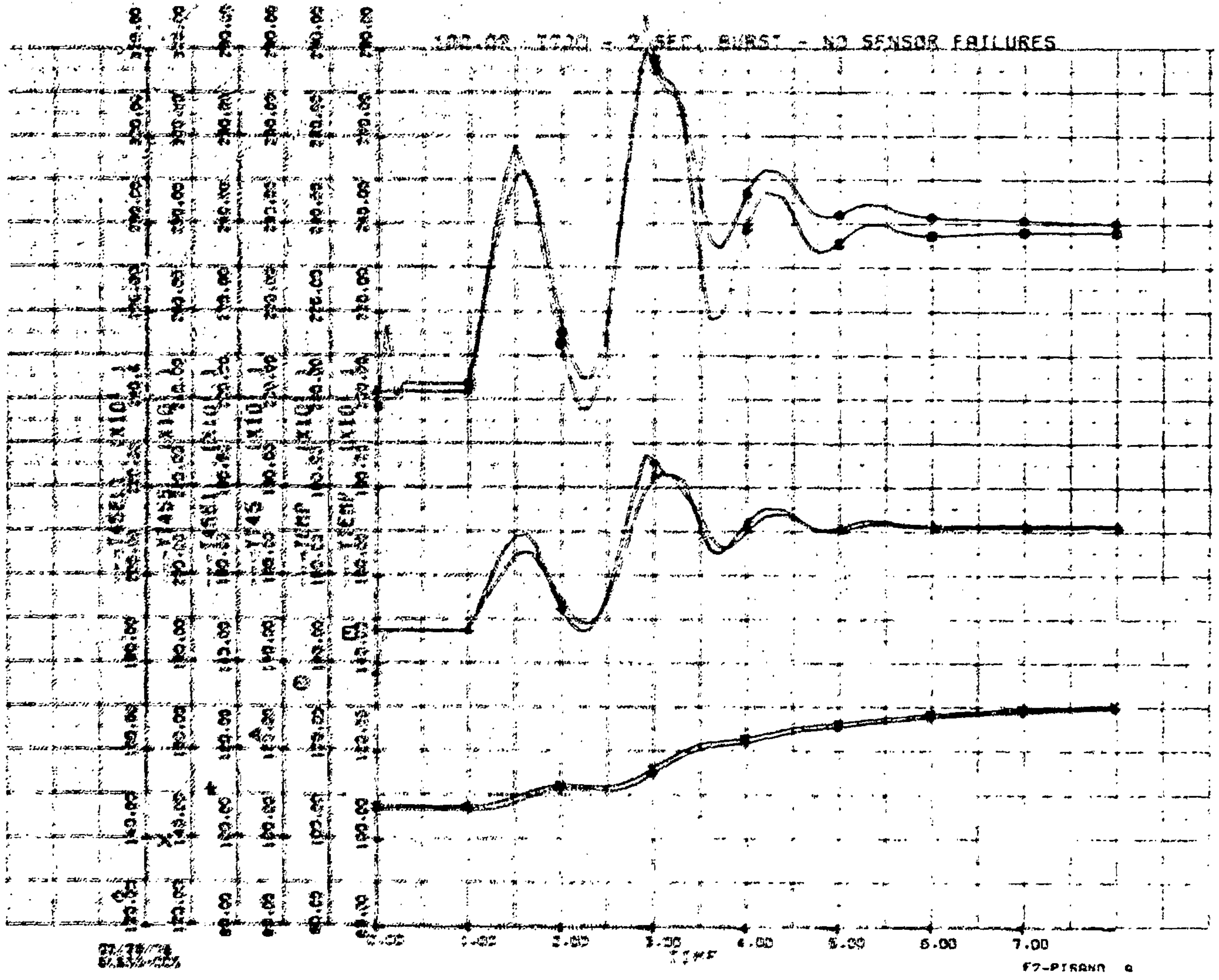


Figure 25. Run 100.02 - 2-Second Burst - No Sensor Failures (Sheet 2 of 3).

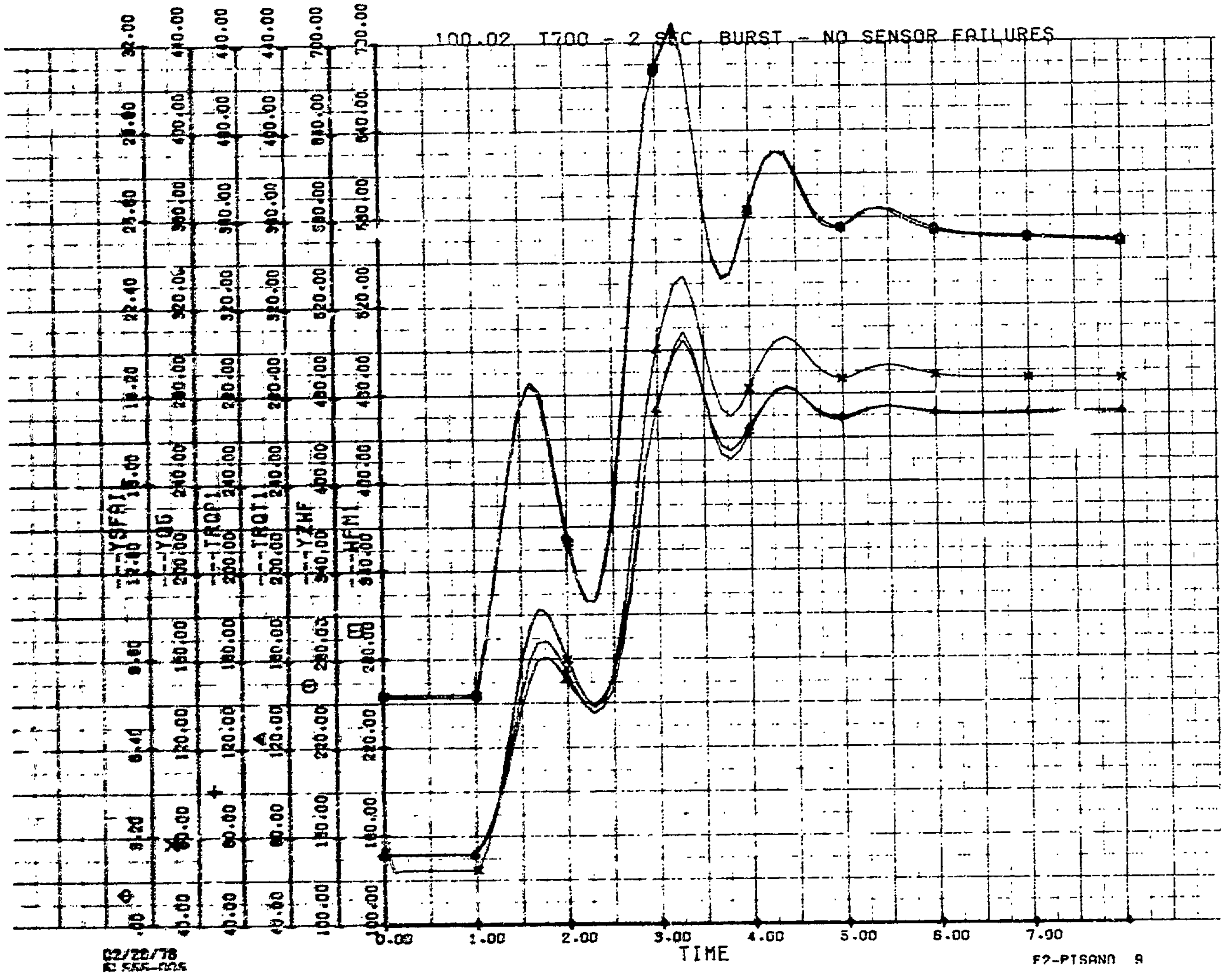


Figure 26. Run 100.02 - 2-Second Burst - No Sensor Failures (Sheet 3 of 3).

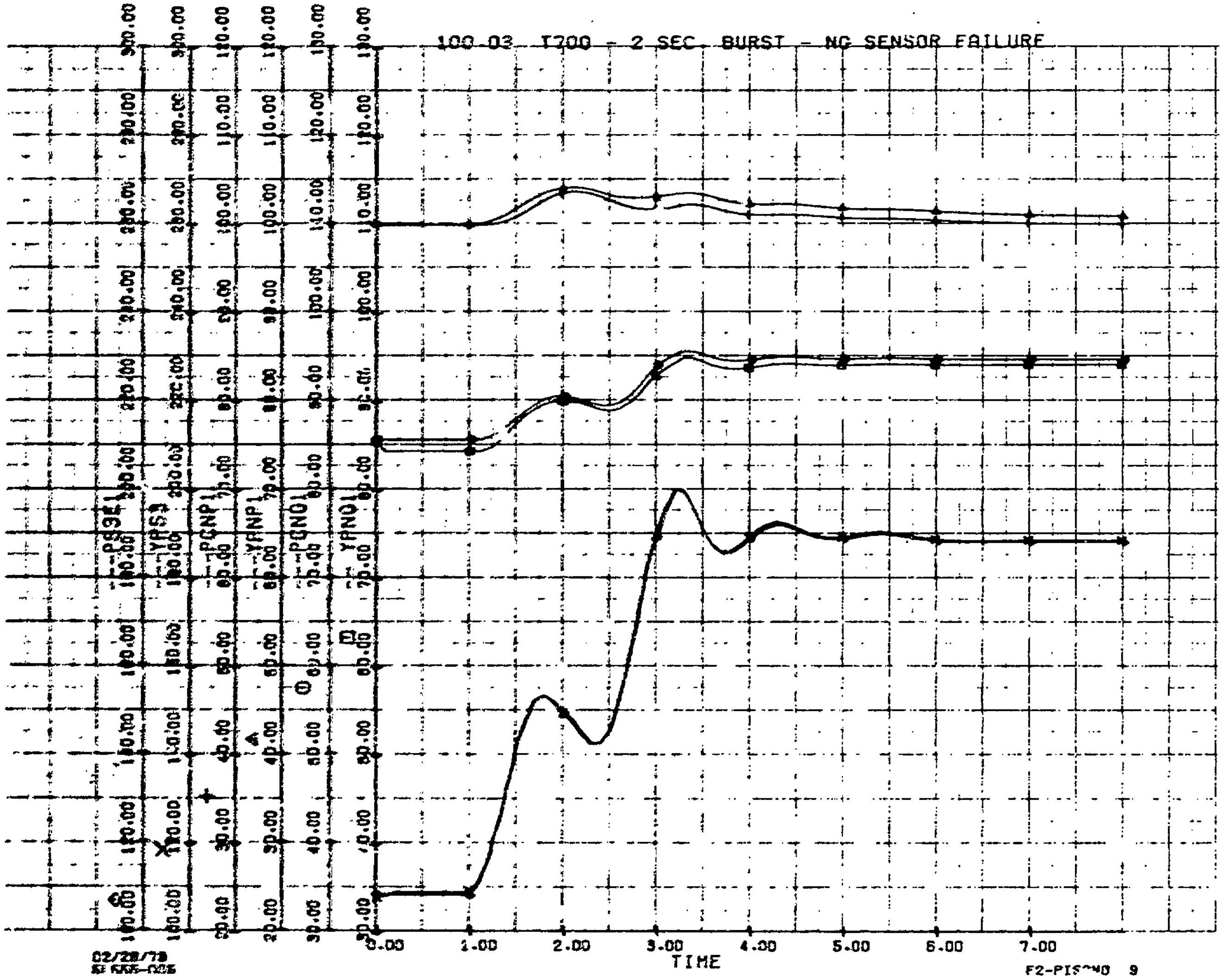


Figure 27. Run 100.03 - 2-Second Burst - NG Sensor Failure

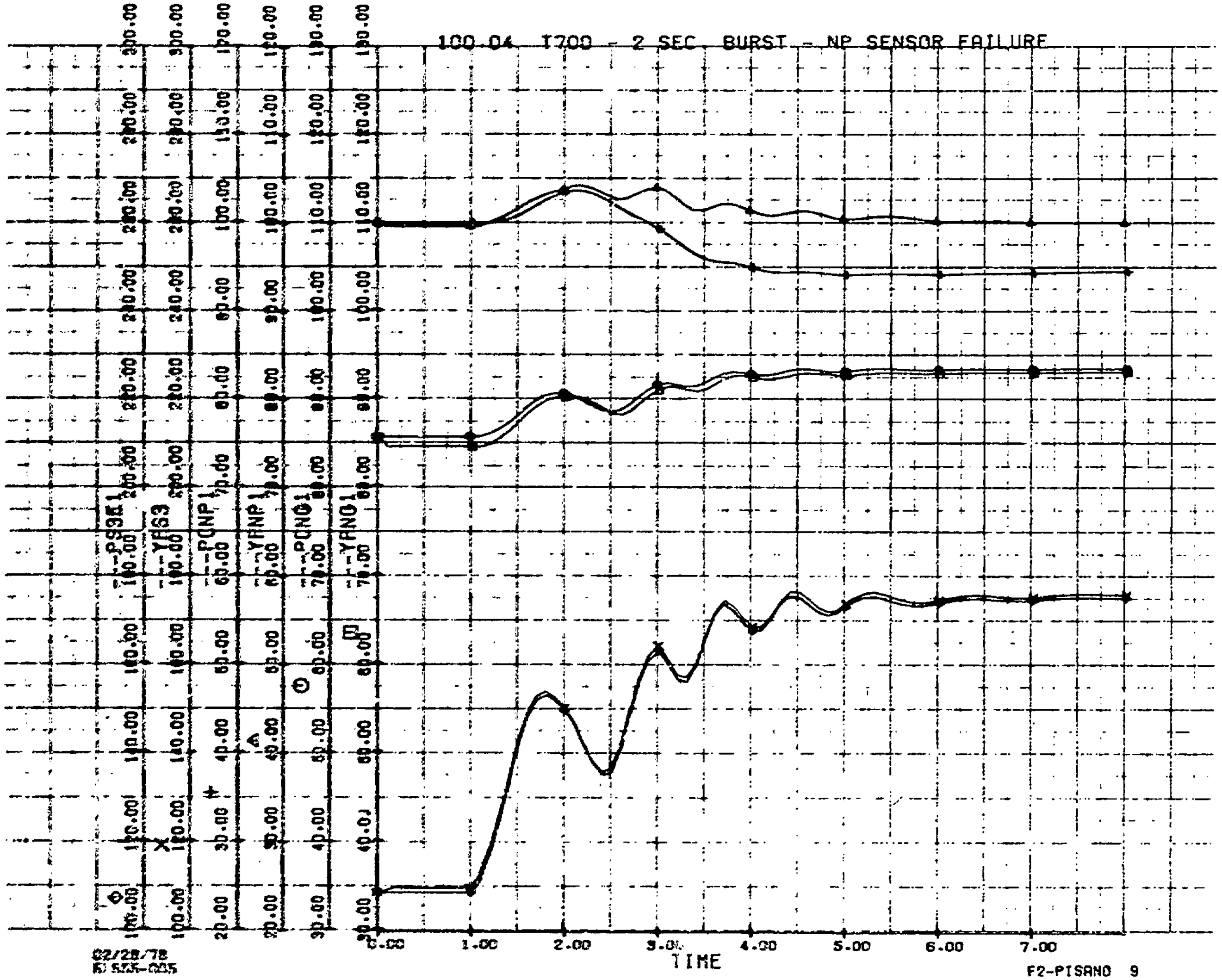


Figure 28. Run 100.04 - 2-Second Burst - NP Sensor Failure.

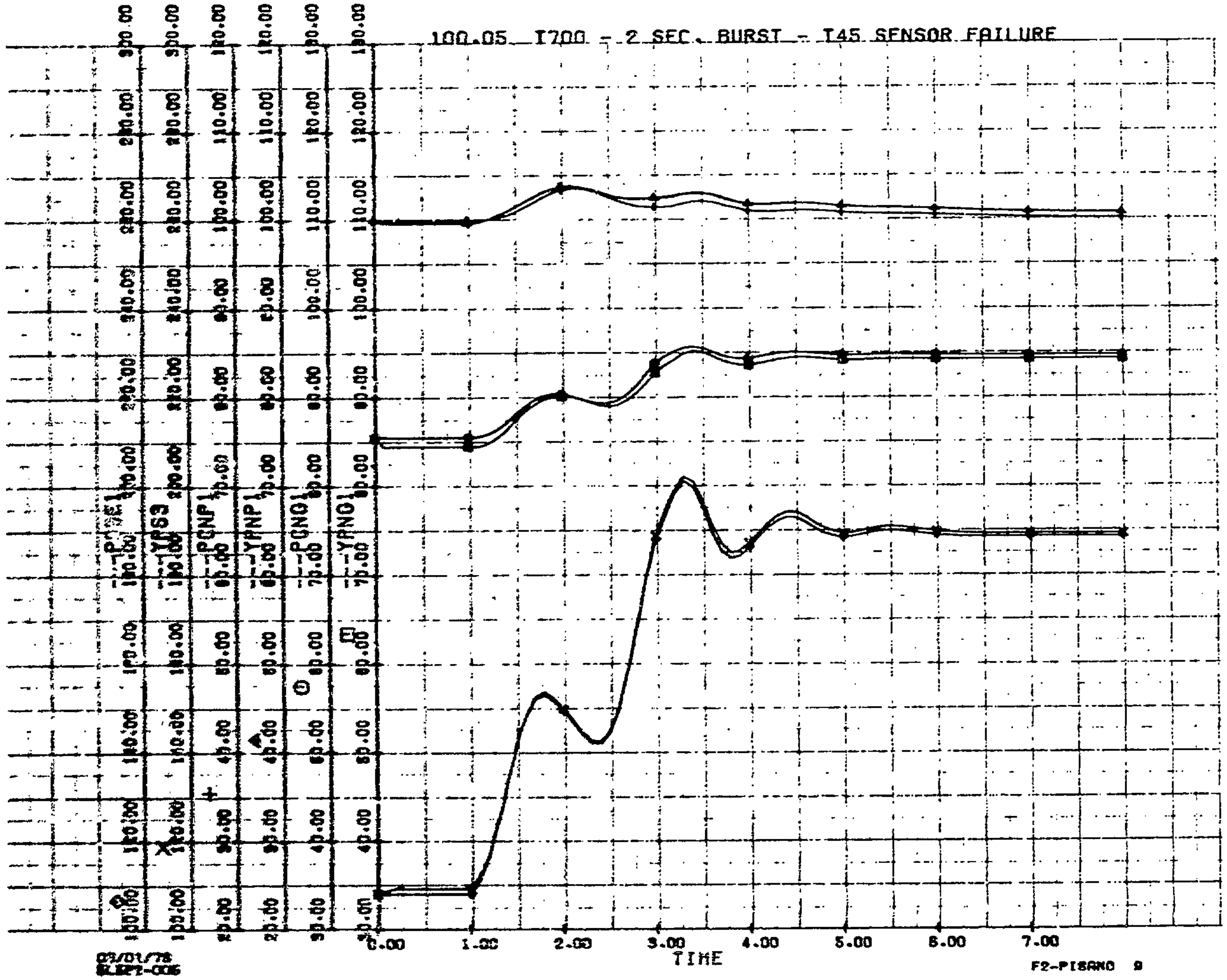


Figure 29. Run 100.05 - 2-Second Burst - T4.5 Sensor Failure (Sheet 1 of 2).

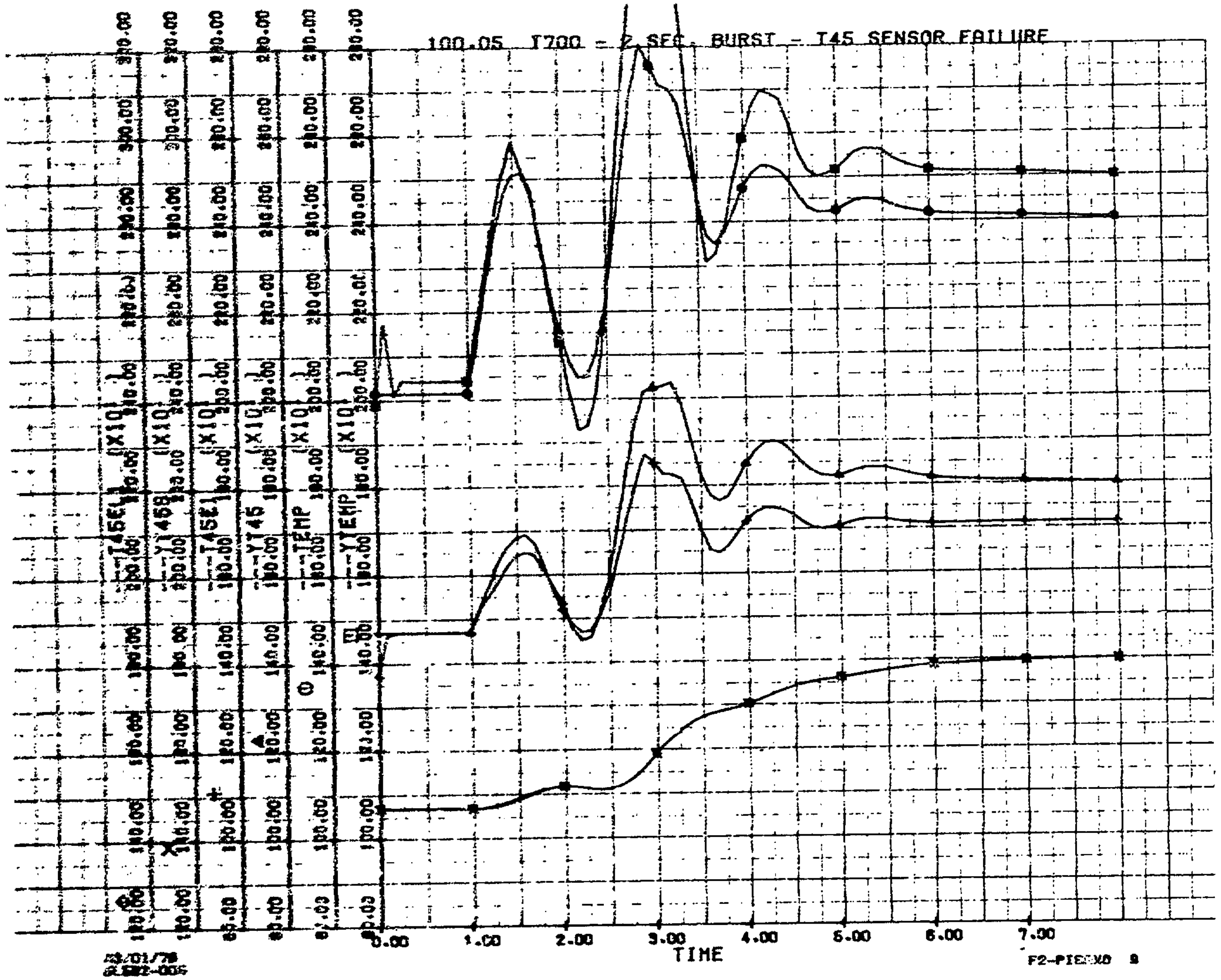


Figure 30. Run 100.05 - 2 Second Burst - T4.5 Sensor Failure (Sheet 2 of 2).

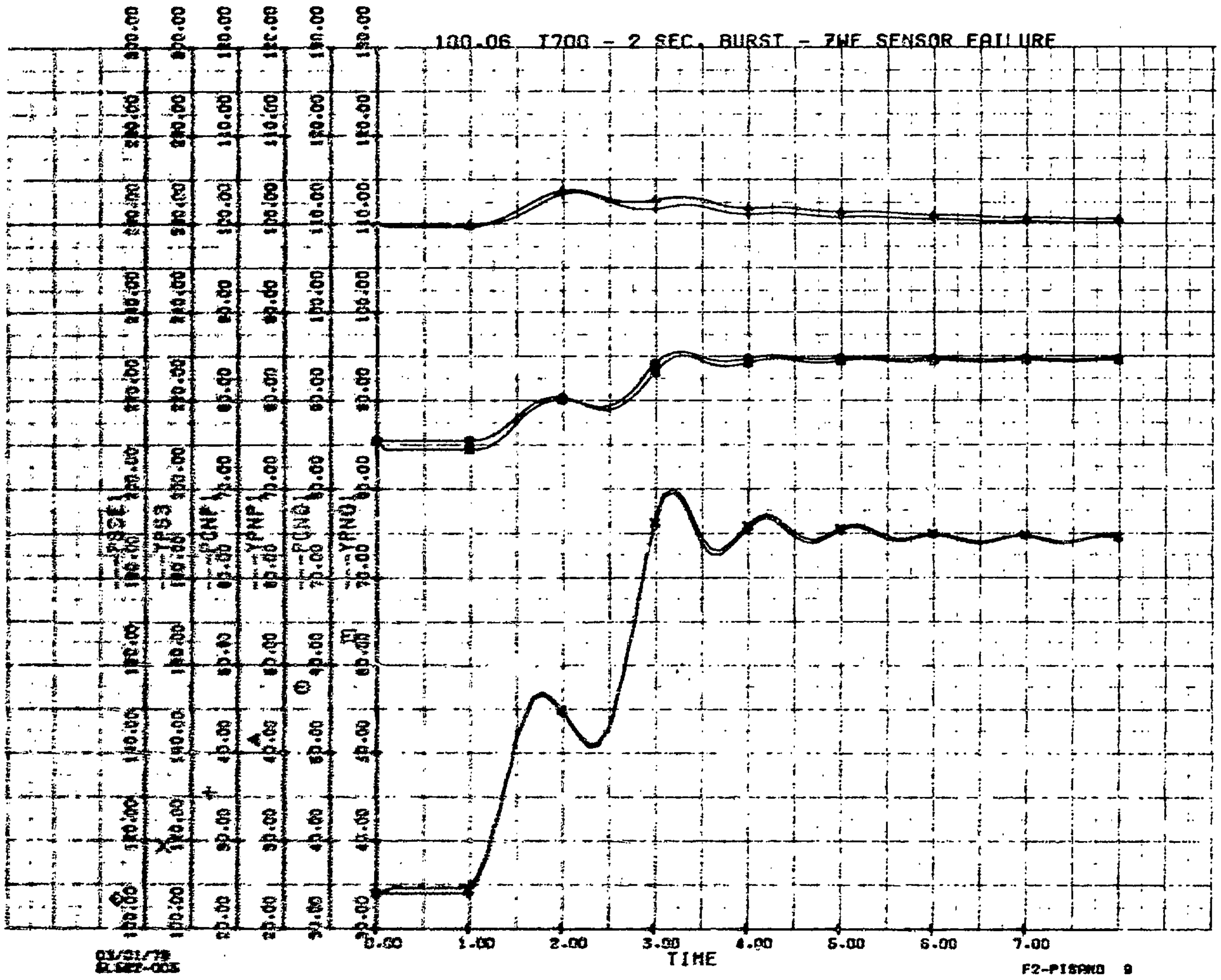


Figure 31. Run 169.06 - 2-Second Burst - ZWF Sensor Failure.

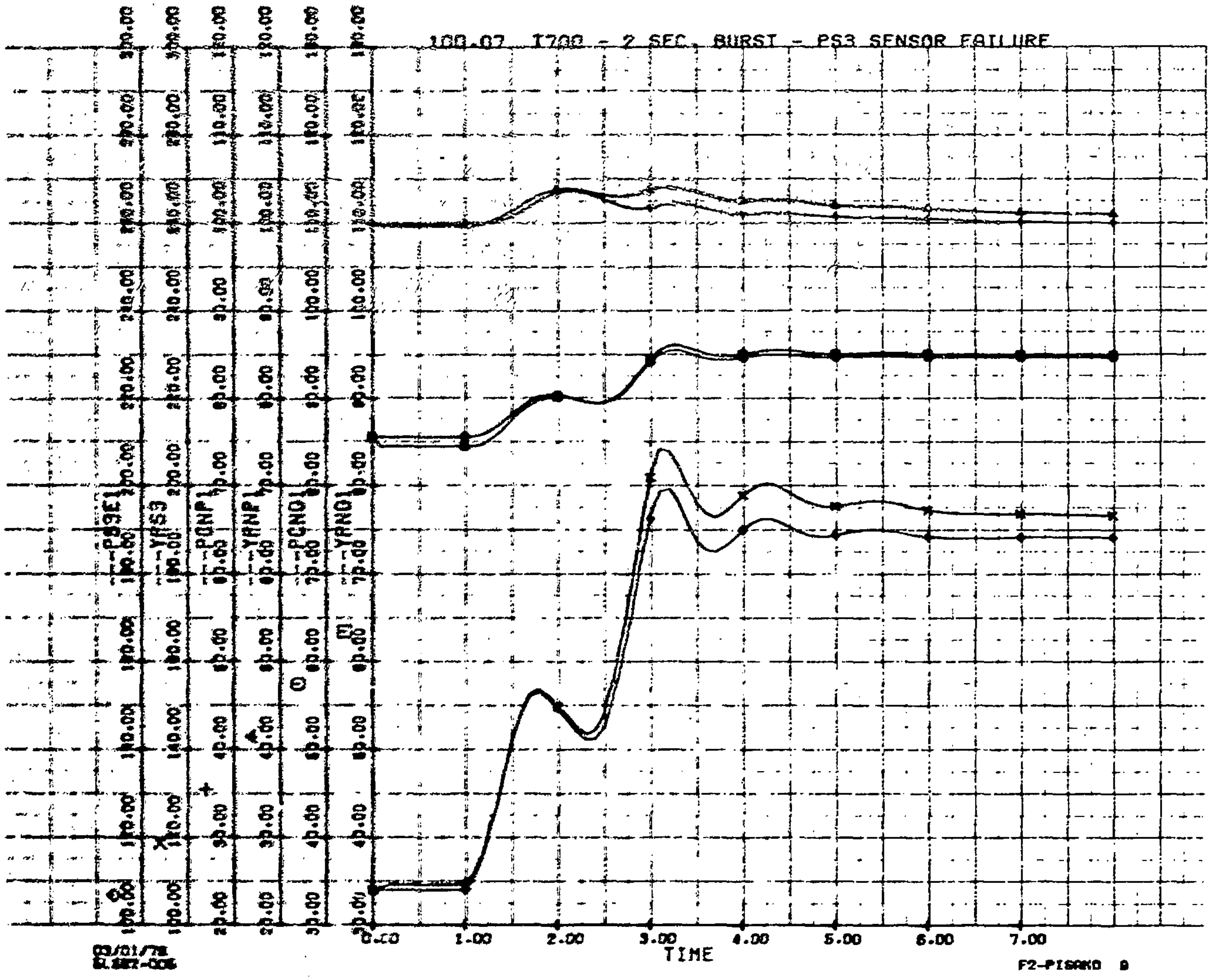


Figure 32. Run 100.07 - 2-Second Burst - PS3 Sensor Failure.

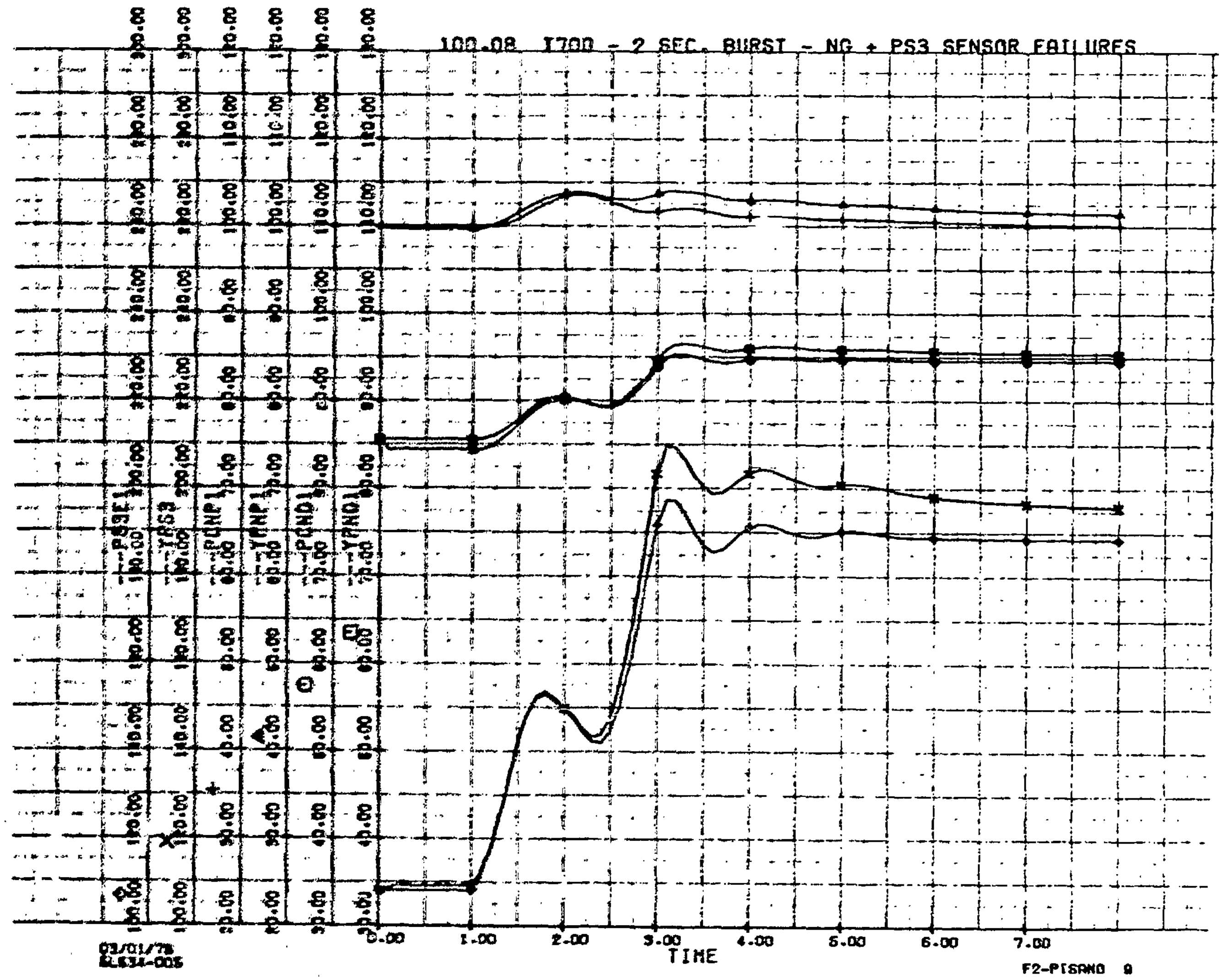


Figure 33. Run 100.08 - 2-Second Burst - NG and PS3 Sensor Failure.

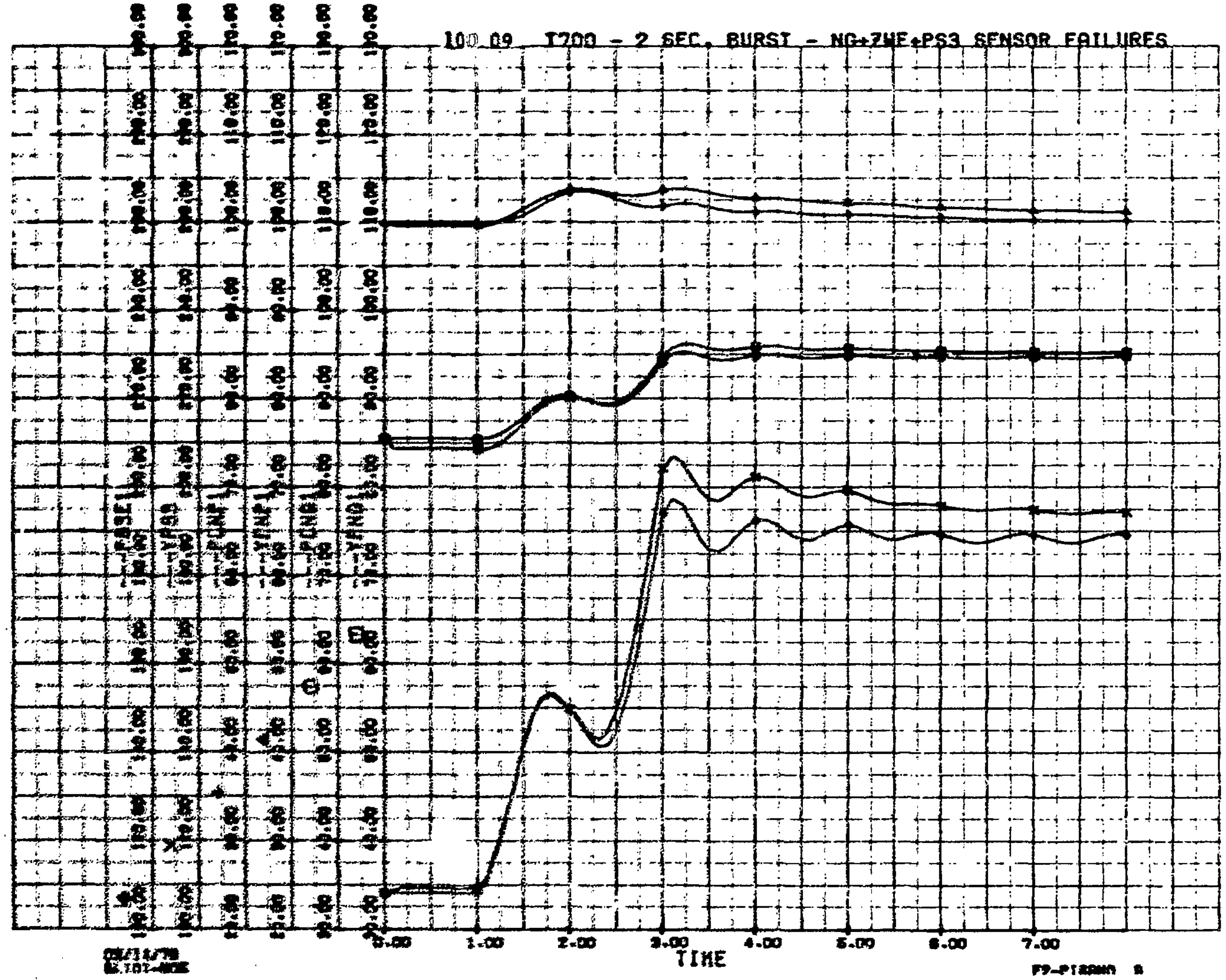


Figure 34. Run 100.09 - 2-Second Burst - NG, ZWF and PS3 Sensor Failures.

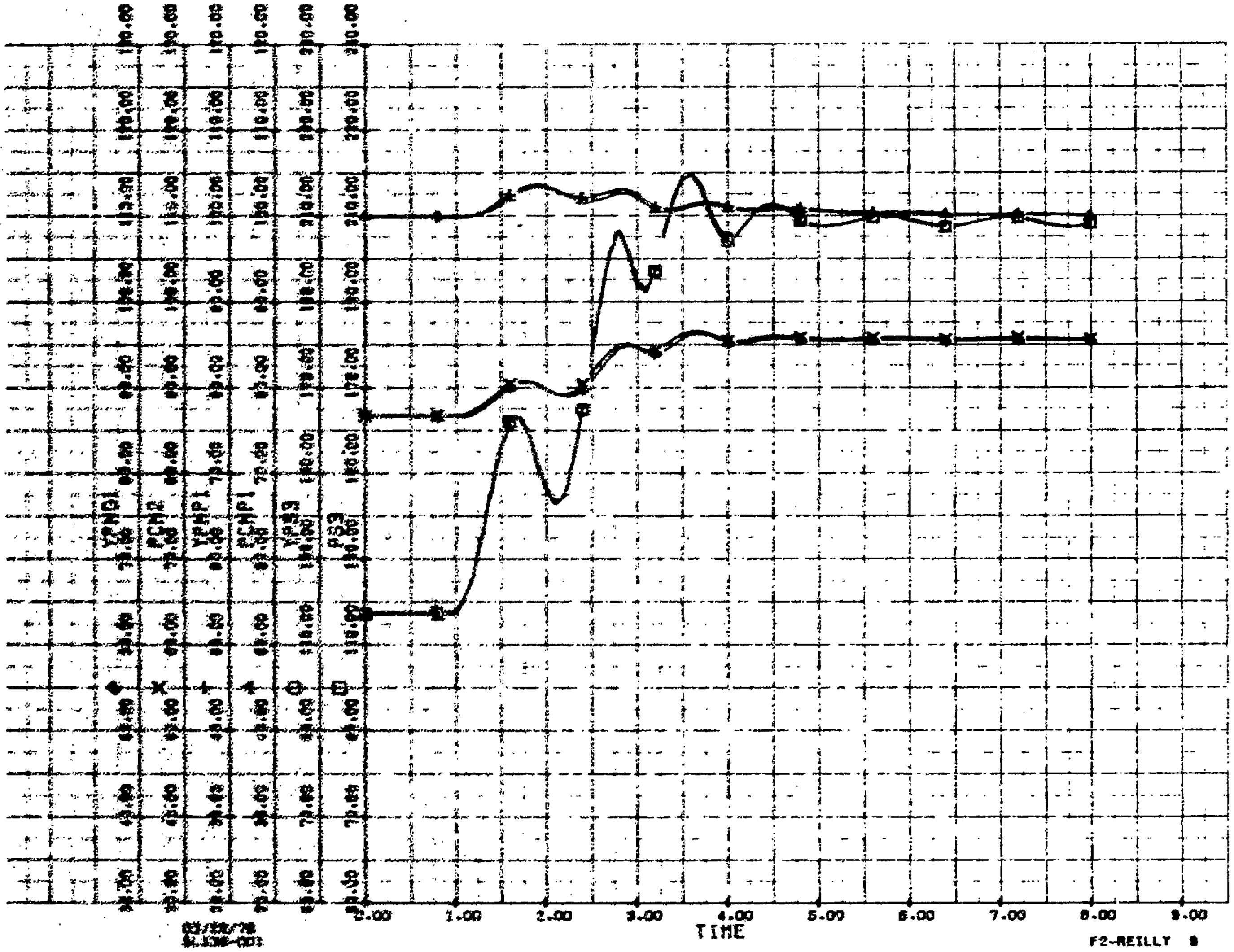


Figure 35. Run 209.09 - 2-Second Burst - SL RPR = 1.2 - No Failures (Sheet 1 of 3).

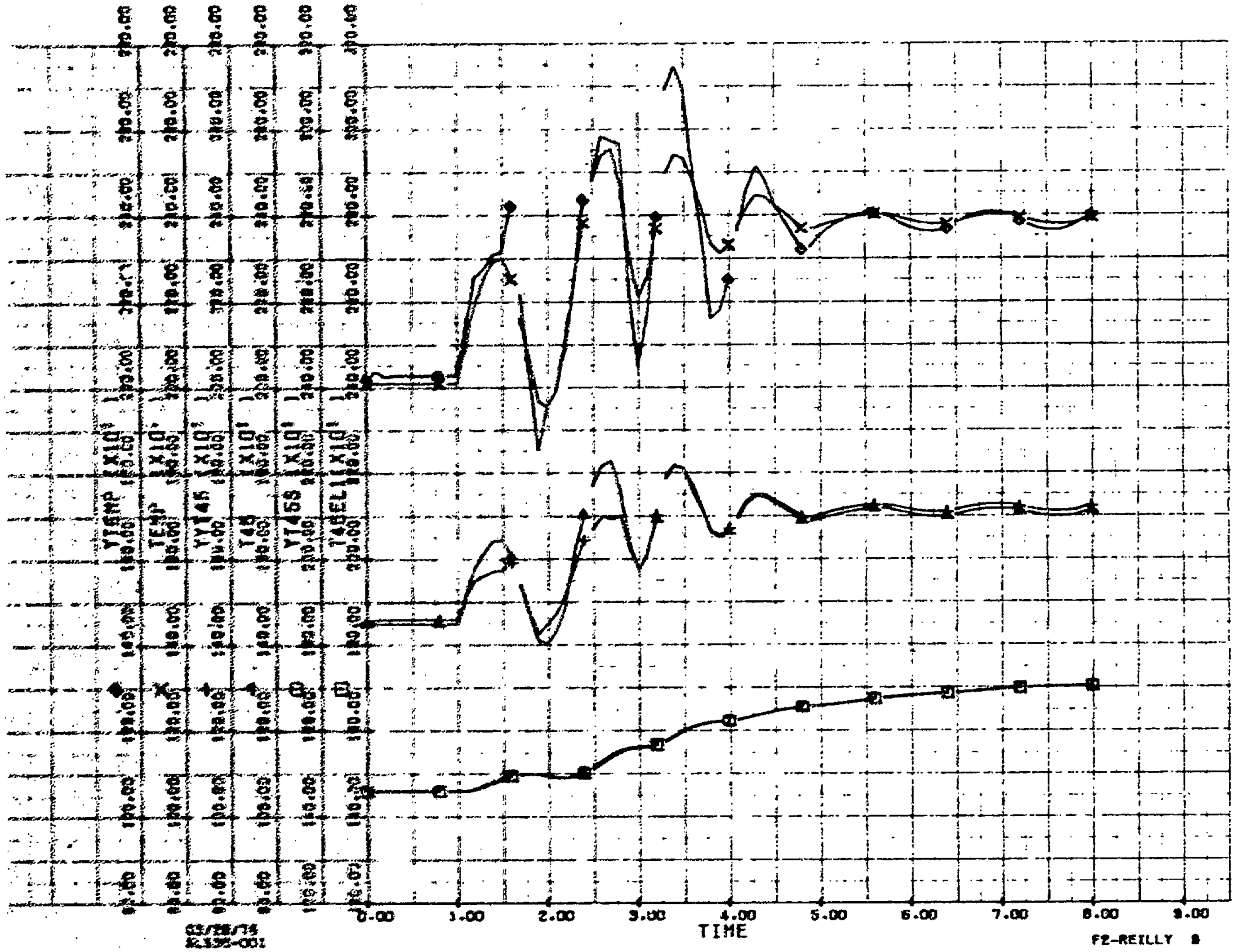


Figure 36. Run 200.00 - 2-Second Burst - SL RPR = 1.2 - No Failures (Sheet 2 of 3).

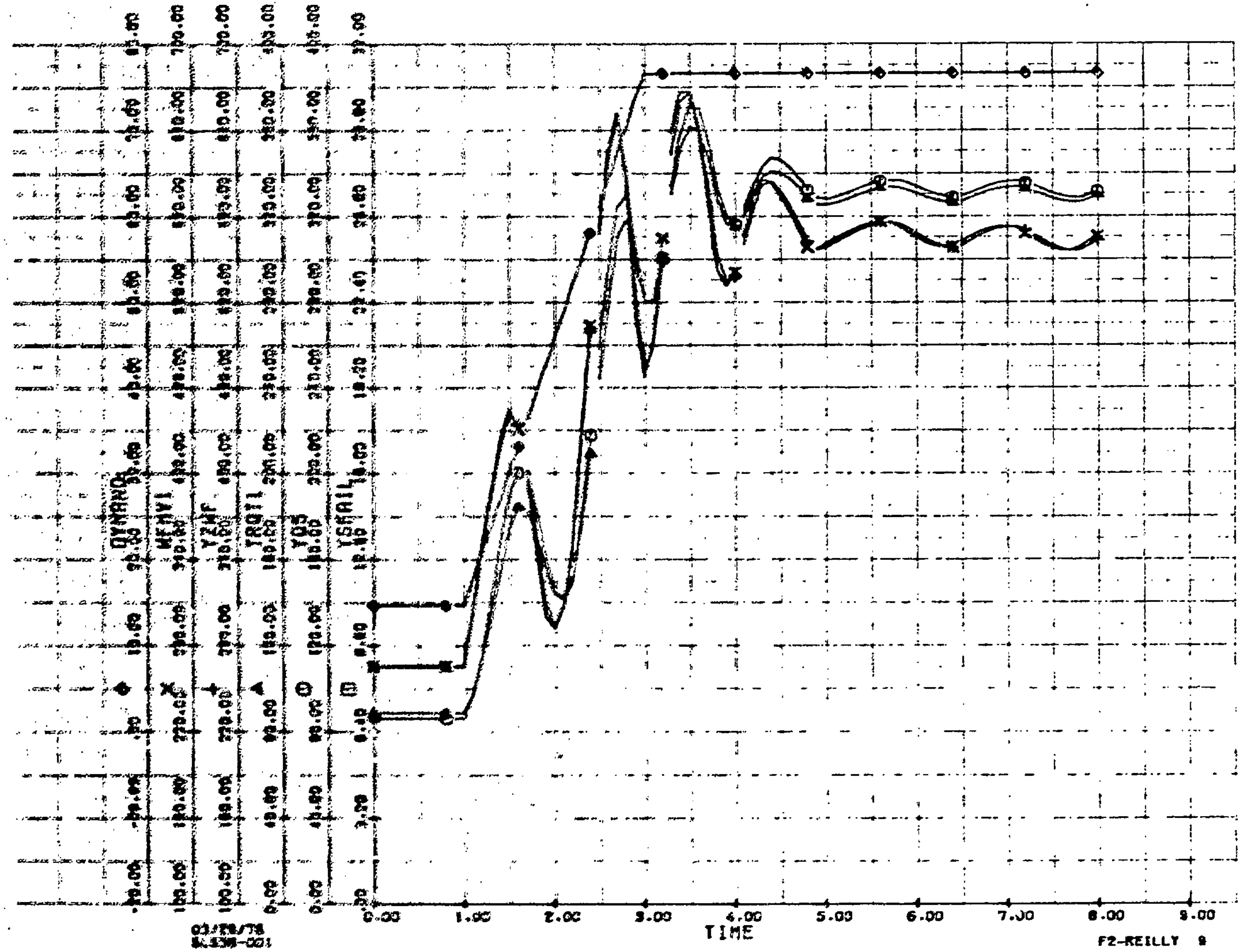


Figure 37. Run 200.00 - 2-Second Burst - SL RPR = 1.2 - No Failures (Sheet 3 of 3).

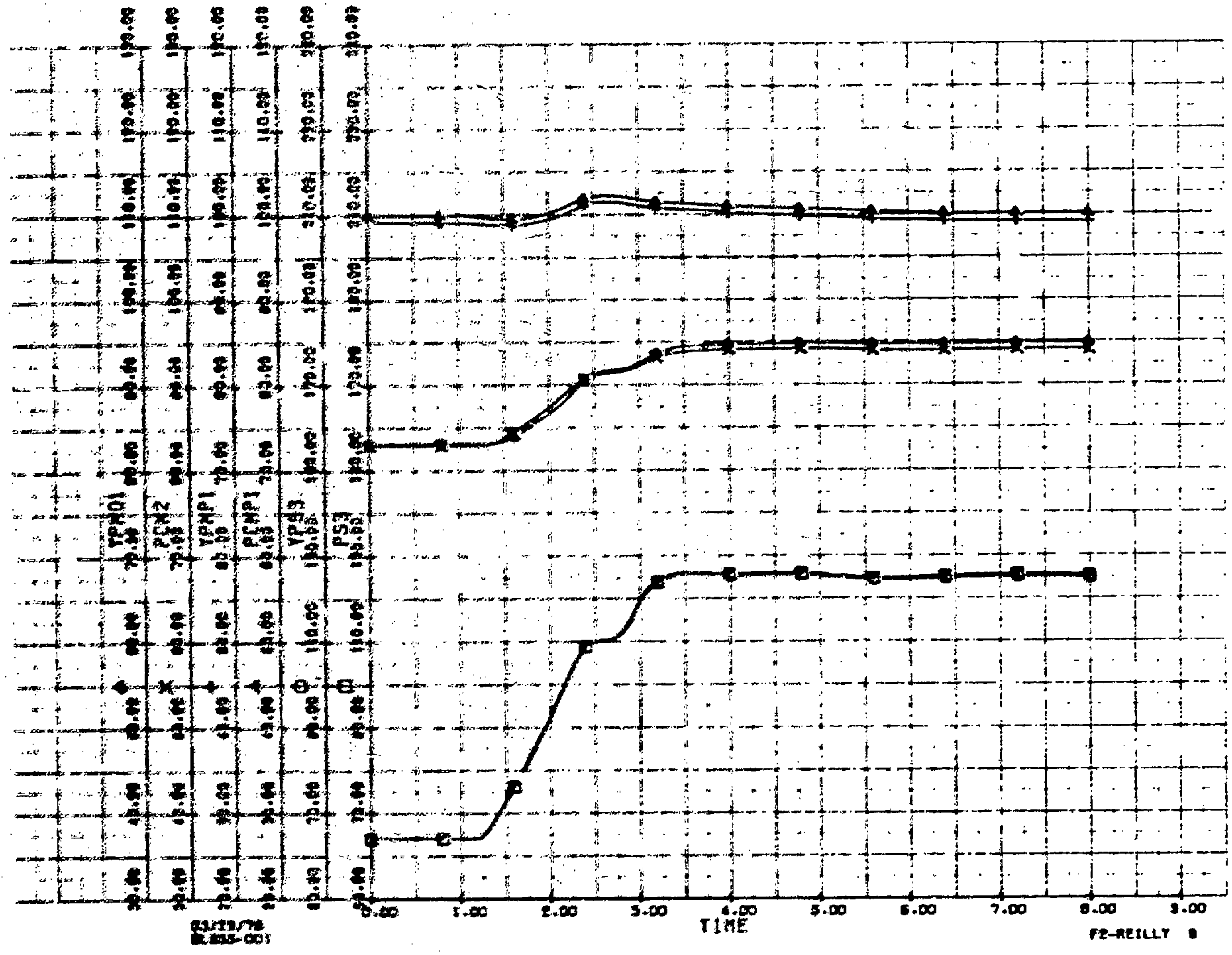


Figure 38. Run 200.01 - 2-Second Burst - 20,000 Feet RPR = 1.2 - No Failures (Sheet 1 of 3).

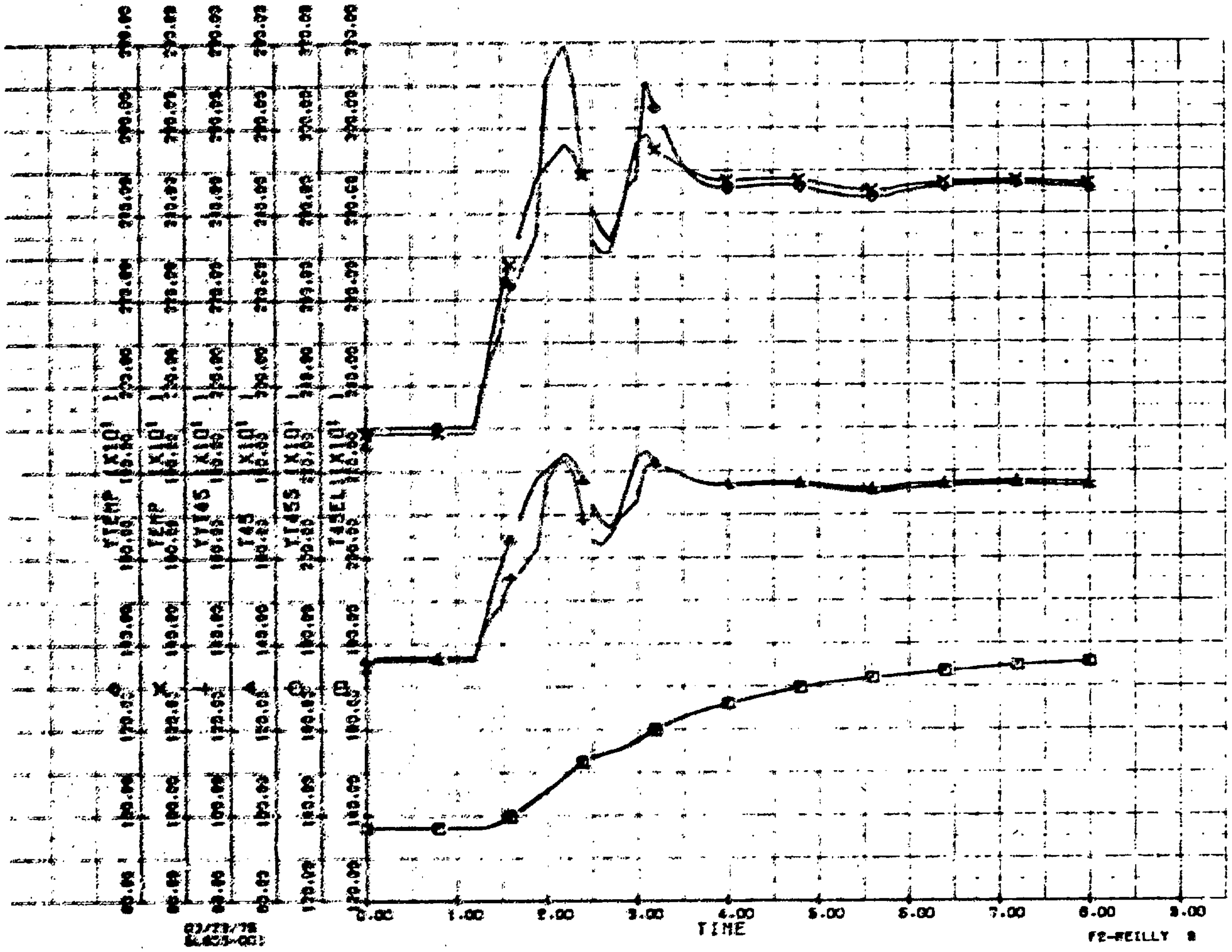


Figure 39. Run 200.01 - 2-Second Burst - 20,000 Feet RPR = 1.2 - No Failures (Sheet 2 of 3).

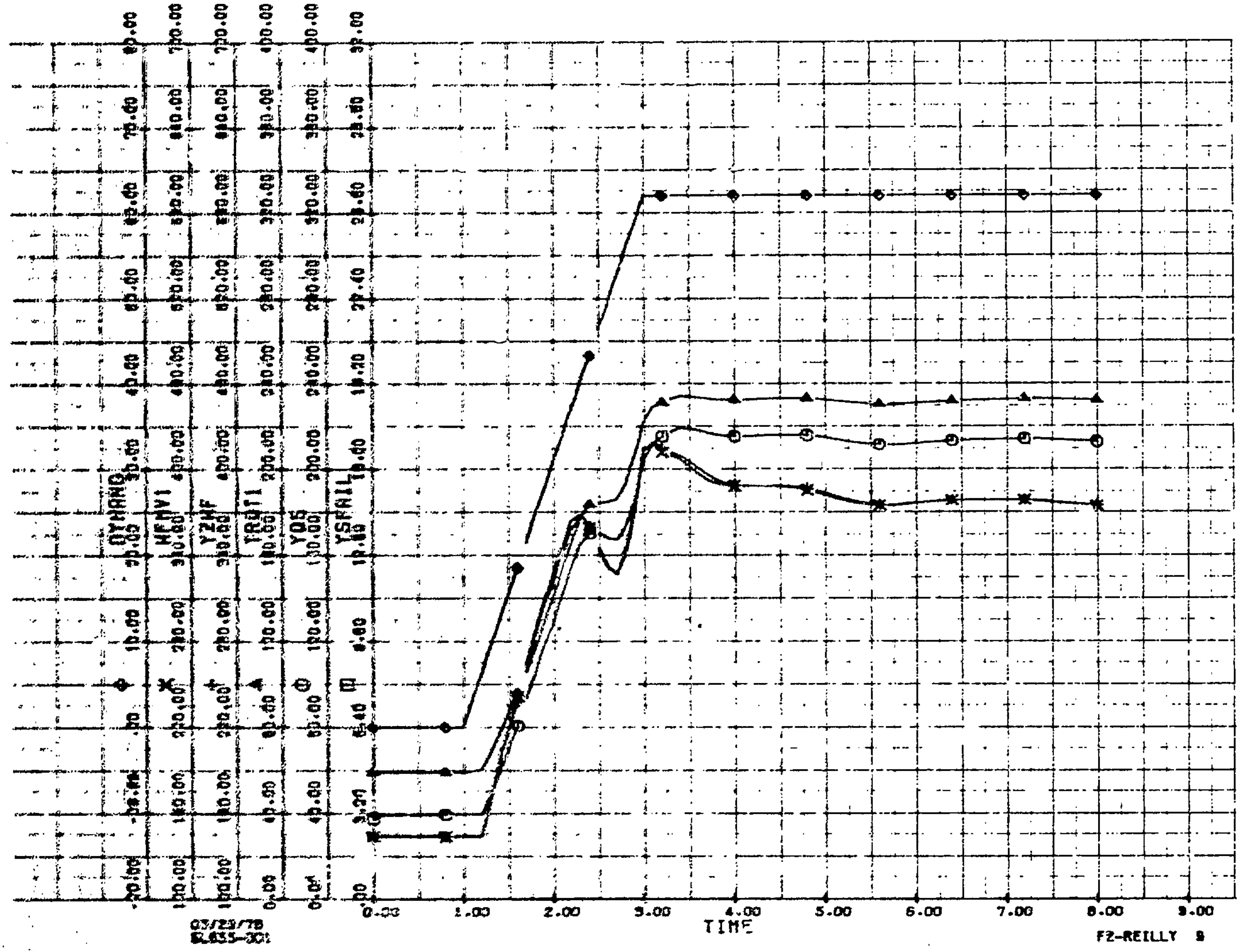


Figure 40. Run 200.01 - 2-Second Burst - 20,000 Feet RPR = 1.2 - No Failures (Sheet 3 of 3).

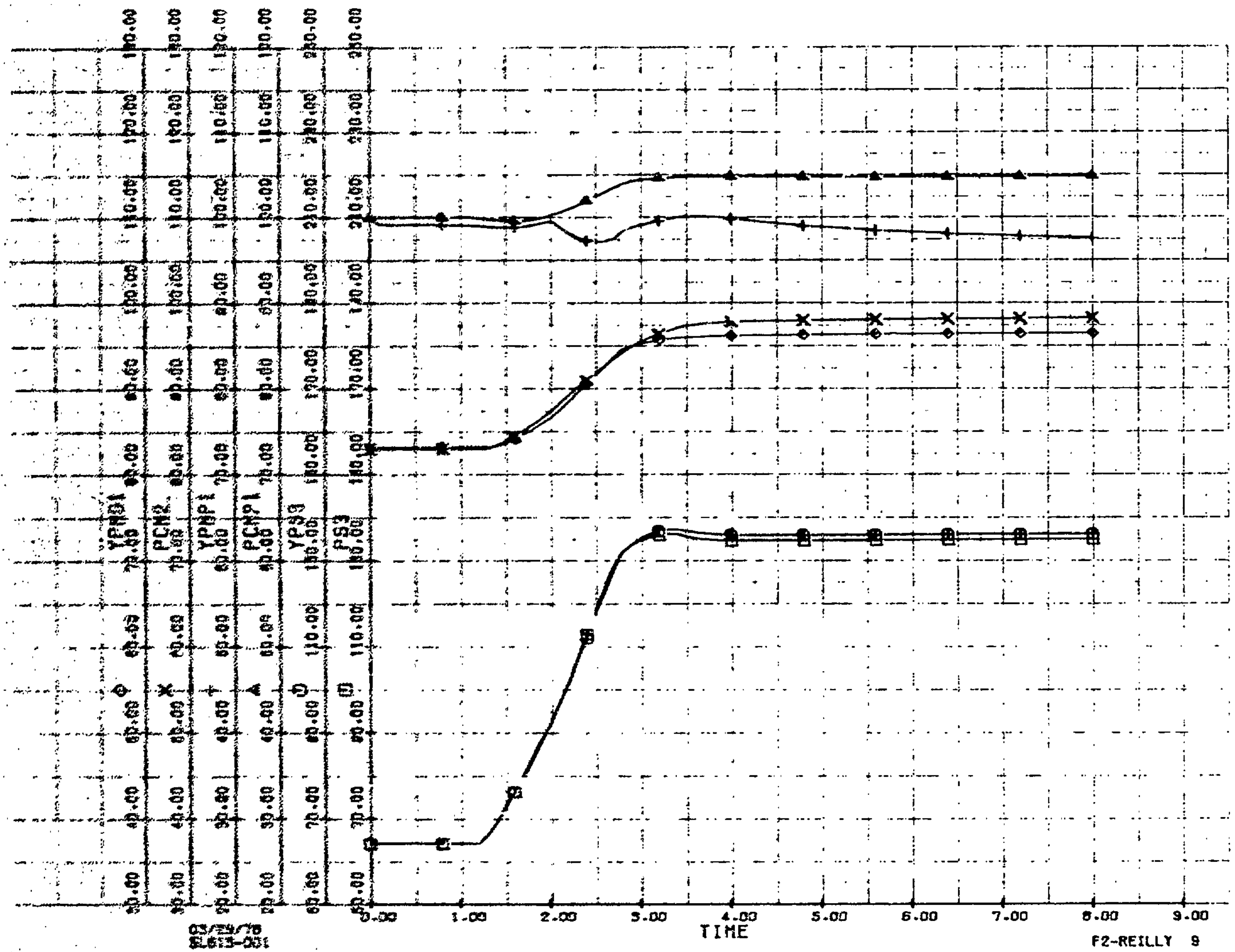


Figure 41. Run 200.02 - 2-Second Burst - 20,000 Feet RPR = 1.2 - NP Sensor Failure.

CONCLUSIONS OF TASK V

A failure detection and correction strategy based on a constant gain extended Kalman filter has been designed for an advanced turboshaft engine. By extensive simulation it has been shown that stable engine control can be maintained even in the presence of multiple sensor failures. When a sensor fails, an offset occurs between the estimated value for that sensor and the actual engine parameter. Based on flight conditions studied, NP errors of up to 5% can occur. The effect of these errors can be eliminated by using the NP signal from the overspeed system when an NP sensor failure is detected by FICA. Offset of NG, PS3, or WF due to their respective sensor failures would mean between a 3% power loss and a 2% NG overspeed when operating on topping. A failure of the T4.5 sensor produced an offset of about 90°F. This is only significant at the T4.5 limiting level and, therefore, the offset can be reduced by model refinement. With a variation of T4.5 offset from engine to engine of 0° to 90°F, all or part of the offset can be traded for a 0 to 10% power reduction while on T4.5 limiting. This is accomplished by shifting T4.5 reference when FICA recognizes a T4.5 sensor failure.

Additionally, FICA has been shown to provide excellent estimates of intermediate parameters such as T4.5G and T4.1 which have significant impact on D&CM, since these parameters are related to hot part life. The determination of these parameters to a higher accuracy represents a significant diagnostic state-of-the art advancement.

RECOMMENDATIONS OF TASK V

The following are specific areas where additional analysis could provide either simplification of the hardware implementation of FICA or an expansion of its capabilities.

One area involving simplification is the elimination of the need to measure PO if a reconstruction of NP by FICA is not required. This would make use of the fact that there are already redundant NP sensors.

Another area is that of making optimum use of a twin-engine installation. Since the engines normally run in a load sharing mode, the corresponding sensors on both engines are relatively close in magnitude. An additional check of sensor malfunction would be to compare it to the second sensor on the other engine. FICA could in effect be a triply redundant system by comparing its best estimate to sensors from both engines.

One area which could hold promise for assessment of engine health is trend analysis of the Kalman filter residuals. From the covariance of these residuals can be extracted the covariance matrix of the driving noise, which is a measure of how well the engine matches the model. Changes in the elements of this matrix may provide useful information on engine performance degradation. To adequately assess this potential, further analysis beyond the scope of this contract is required.

TASK VI - FADEC DIAGNOSTIC SYSTEM DESIGN INTERFACE

Because of the powerful computational capability included in a FADEC control, D&CM systems of considerable functional complexity can be integrated efficiently with a FADEC control. In some of the more complex systems, supplementary airframe-mounted and ground equipment may be required to complete the overall system.

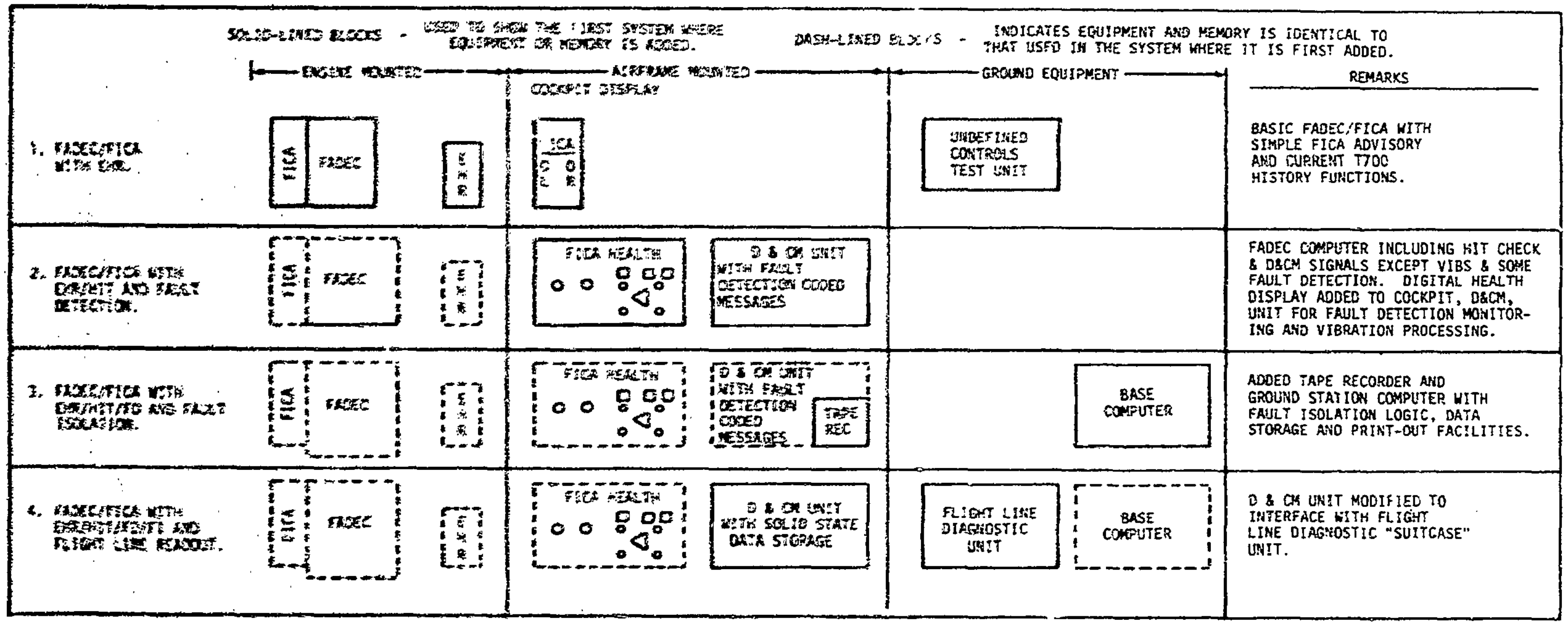
The FADEC system concept for the T700 engine, which incorporates built-in FICA capabilities, is the foundation or baseline upon which this study is formed. This conceptual baseline FADEC is described in Task IV (Table 13 and Figure 13) and its FICA capabilities described and analyzed in Task V (page 80). A graphical representation of a building block (B/B) approach to D&CM integration with FADEC is shown in Table 16. For convenience, this B/B concept is related to the D&CM functions listed on Table 3. There are, however, many other possible approaches to the integration and implementation of FADEC/D&CM, particularly with regard to D&CM display and data recording and memory provisions.

IDENTIFICATION OF D&CM OBJECTIVES AND THEIR IMPACT ON FADEC

Engine History: This FADEC concept provides all the signals required for measuring life-used in terms of two LCF counts, engine hours, pressure cycles, and stress rupture life-used. (See Task III.) It is estimated that to accomplish the LCF counts now done by T700 will require about 80 words and an increase in cycle time of about 90 microseconds. The current T700 engine hours and time-temperature counts are also very simple. Therefore, it is estimated that to accomplish all T700 engine history functions would require about 4% of the FADEC memory. For this reason, this is included in the basic FADEC concept shown as B/B system #1 on Table 16.

With all the measured and calculated parameters available, including T_3 and $T_{4.1}$ (key elements for calculating turbine blade temperature), more accurate hot part stress rupture life calculation can be made than is possible without FADEC. The availability of digital computer capability also makes possible more sophisticated Low Cycle Fatigue computations using the Rainfall or Pagoda method (Ref. 6, 7, 8) or similar techniques that account for both major and minor stress-strain cycles. The impact on FADEC cannot be accurately estimated until these are defined. However, it is assumed that it would be in the area of doubling the above calculations. The accumulation of total life counts is assumed to be done mechanically in the Engine History Recorder (EHR) as on the present T700 engine.

TABLE 16. ARMY FADEC-D&CM BUILDING BLOCK SYSTEM CONCEPT



SOLID-LINED BLOCKS - USED TO SHOW THE FIRST SYSTEM WHERE EQUIPMENT OR MEMORY IS ADDED.

DASH-LINED BLOCKS - INDICATES EQUIPMENT AND MEMORY IS IDENTICAL TO THAT USED IN THE SYSTEM WHERE IT IS FIRST ADDED.

	ENGINE MOUNTED		AIRFRAME MOUNTED: COCKPIT DISPLAY		GROUND EQUIPMENT		REMARKS
1. FADEC/FICA WITH EHM.	FICA FADEC	EHM	FICA		UNDEFINED CONTROLS TEST UNIT		BASIC FADEC/FICA WITH SIMPLE FICA ADVISORY AND CURRENT T700 HISTORY FUNCTIONS.
2. FADEC/FICA WITH EHM/HIT AND FAULT DETECTION.	FICA FADEC	EHM	FICA HEALTH	D & CM UNIT WITH FAULT DETECTION CODED MESSAGES			FADEC COMPUTER INCLUDING HIT CHECK & D&CM SIGNALS EXCEPT VIBS & SOME FAULT DETECTION. DIGITAL HEALTH DISPLAY ADDED TO COCKPIT, D&CM, UNIT FOR FAULT DETECTION MONITORING AND VIBRATION PROCESSING.
3. FADEC/FICA WITH EHM/HIT/FD AND FAULT ISOLATION.	FICA FADEC	EHM	FICA HEALTH	D & CM UNIT WITH FAULT DETECTION CODED MESSAGES TAPE REC		BASE COMPUTER	ADDED TAPE RECORDER AND GROUND STATION COMPUTER WITH FAULT ISOLATION LOGIC, DATA STORAGE AND PRINT-OUT FACILITIES.
4. FADEC/FICA WITH EHM/HIT/FD/FI AND FLIGHT LINE READOUT.	FICA FADEC	EHM	FICA HEALTH	D & CM UNIT WITH SOLID STATE DATA STORAGE	FLIGHT LINE DIAGNOSTIC UNIT	BASE COMPUTER	D & CM UNIT MODIFIED TO INTERFACE WITH FLIGHT LINE DIAGNOSTIC "SUITCASE" UNIT.

Performance: All required signals for even the most complex engine health system described in Task III, Section I (System A) are available within the FADEC concept. Increasing the computer memory by about sixty-five 16-bit words and increasing computer cycle time by about 74 microseconds, the HIT check can be added to the FADEC system. As discussed in Task IV, the cycle time can be reduced by spreading the calculations over several cycles because the performance calculation update time requirement is much less than the control cycle update time.

This capability is recommended for inclusion in the basic FADEC as shown in baseline system #2. Modular fault isolation by performance measurement, if proven feasible, would also use signals available in FADEC supplemented as a minimum by compressor discharge temperature, TS3, assuming FICA calculated TS3 is not accurate enough for modular fault isolation. Until a modular fault isolation system is designed the decision as to whether this system is ground support equipment or an integral part of FADEC cannot be determined.

Control Fault Detection: The FADEC functional design detects and accommodates control sensor failures, and provides self-test functions. In order to make the overall FADEC system reliable, additional faults must be detected and accommodated. Whether all control system faults will be accomplished within FADEC or if some additional logic is required will not be known until additional design work is accomplished. In accordance with Table 14, processing of the fuel filter bypass and fuel boost pump pressure will be required. These will be processed with small impact on the FADEC system.

Oil-Wetted Parts Fault Detection: Oil system monitoring requires six additional signals in accordance with Table 14. Processing of these signals is estimated to increase the FADEC parts count by about 10% and should therefore be included in the FADEC design. Logic to detect exceedances would be small and, therefore, should also be included in the base design, as shown in baseline system #2.

Fault Isolation:

Controls: Twenty-one signals are planned to be available within FADEC for control system fault isolation. The FICA analysis documented under Task V concluded that the following control system sensor failures could be detected and fault isolated: PS3, T4.5, WFFB, VGFB, Q_1, NP and NG. In addition, the 21 signals can be utilized for fault isolation of the other control system LRU's as described in Task III. Based on other studies of analog systems, fault isolation of the entire engine system can require a computer similar in size to the current FADEC. Since this system is not required on a continuous basis and consistent with the concept in Table 16, fault isolation is considered part of ground equipment.

The accuracy or effectiveness with which faults can be isolated should be very high for the T700 FADEC/D&CM systems B/B #3 and #4 described herein. In the case of a non-FADEC T700 control, the fault isolation accuracy or effectiveness would probably be lower. In either case, an analysis following the general outline in Task III would be required. The fault isolation logic is currently planned to be in the ground support equipment, not on the airframe-mounted equipment. In System 3, it would be in the base computer. In System 4, it would be in the flight line diagnostic unit.

Modules: Fault isolation to the module level involves the following types of monitored parameters and logic:

1. Performance: Monitoring to isolate degradation to the compressor high-pressure or low-pressure turbine is discussed under performance (above) and in Task I.

2. Vibration: Monitoring to isolate an out-of-limits unbalance problem requires two accelerometers: one on the accessory gearbox and one on the exhaust frame.

   With proper filtering and logic, fault isolation to the module and/or LRU level should be effective. Accelerometer signal conditioning is not a function requiring components or wiring common to other D&CM/FADEC except for AD signal conversion. The signals are very susceptible to distortion or noise from external sources. It is recommended that FADEC not include vibration signal conditioning and analysis.

3. Oil-Wetted Parts: Failures or incipient failures involving the lube/scavenge pump and filter can be fault isolated with signals recommended for inclusion in FADEC. Isolating bearing failures to the sump involved, however, can best be done on the ground by visual inspection of the scavenge screens at the scavenge pump inlets. The alternative, installation of chip detectors in each of the six scavenge lines, would not be cost effective. The combination of a Master Chip Detector signal and a high vibration reading (not processed in FADEC) would be a positive fault isolation indication. However, an externally mounted accelerometer would be sensitive only to severe bearing problems which, in almost every case, would have previously caused a chip detector alarm and resulted in an engine power reduction. The effectiveness of this fault detection technique is questionable, at best.

4. Modular Life Usage: Measuring LCF and hot parts life used on key compressor, HP and LP turbine module components.

IDENTIFICATION OF CANDIDATE PARAMETERS AS RELATED TO FADEC

Parameters to be Sensed: Table 14, "Candidate FADEC and D&CM Signals", lists 33 signals identified in this study for probable inclusion in a T700 FADEC/D&CM system to meet the system objectives defined by contract.

Used by FADEC/FICA	21
Used only for D&CM	12
Total	33

Signals to be processed in FADEC	31
Signals to be processed elsewhere	2
Total	33

Further systems analyses in the following areas may result in changes to the list of required parameters:

Modular Performance Fault Isolation
Control LRU Fault Isolation
Further FICA System Analysis per Task V, page 125

Parameter Characteristics

In general, the accuracy requirements for engine control systems sensors are more stringent than for D&CM sensors. Since two thirds of the T700 FADEC/D&CM system sensors are required for control as well as D&CM, it can be stated generally that D&CM does not require unique sensor accuracy. One potential exception to this may be in the area of Modular Performance Fault Isolation. Detecting small performance changes in a compressor or HP turbine may impose difficult accuracy and stabilization time requirements on sensors. Table 14 contains the signal accuracy requirements as presently known. It is believed that all are within current state of the art, again with the possible exception noted above.

Pressure transducers and thermocouple response rates are governed by dynamic control analysis. Current T700 sensor response rates are adequate unless control system design logic is changed. D&CM functions are not response rate critical except for accelerometers where the response rate will be governed by the frequency range of 50 - 5000HZ.

INTEGRATION WITH FADEC - BUILDING BLOCK APPROACH

The impact of integrating D&CM objectives with FADEC is minimal and is discussed in the description of the four D&CM System concepts. The impact is also depicted graphically in the Building Block Chart (Table 16). In brief, once a turboshaft engine D&CM building block concept is adopted, the small additional allowance for D&CM functions can be easily designed into the FADEC unit so that it becomes a generic control for all applications of that engine.

Table 16 is a graphical representation of the manner in which a basic GE FADEC turboshaft engine control could be integrated within more complex D&CM systems. System 1 (Figure 42) includes current T700 type history recorder function plus inherent fault detection in FICA. System 2 (Figure 43) adds to System 1 those items which are recommended for inclusion in FADEC in this study:

- HIT check
- All D&CM signal processing
- Additional control system fault detection and annunciation
- Other fault detection and annunciation as practical. A LCC study is required to define what D&CM functions should be included in the FADEC. However, based on current T700 usage and experience it is expected that a minimum of the following functions would be included in a FADEC:

  Overtemperature
  Overspeed
  Chip Detector
  Oil and Fuel Filter Bypass
  Oil Pressure and Temperature Exceedance

Systems 3 (Figure 44) and 4 (Figure 45) indicate potential support equipment which LCC studies might indicate are cost effective. The dash-line blocks indicate equipment identical to that used in the preceding and simpler D&CM system.

The D&CM Systems concepts are arranged in order of increasing cost, complexity, and capability. They represent the basic types of D&CM systems currently being developed in this country. For example, System 1 is similar to D&CM System on T700 and F100 engines; System 2 is similar to the A-7E/TF41 IECMS and B-1/F101 CITS except that it lacks the in-flight recording and ground printout and analysis functions. System 3 is similar to A7-E, TF39 (ADEMS) and F101 (CITS).

System 4 is similar to the Northrop EHMS for T38 and A-10 aircraft. If the basic FADEC units are built with provisions to handle the future additions of the added D&CM functions, the necessity for choosing a given concept for a particular application does not become critical in the FADEC development process.

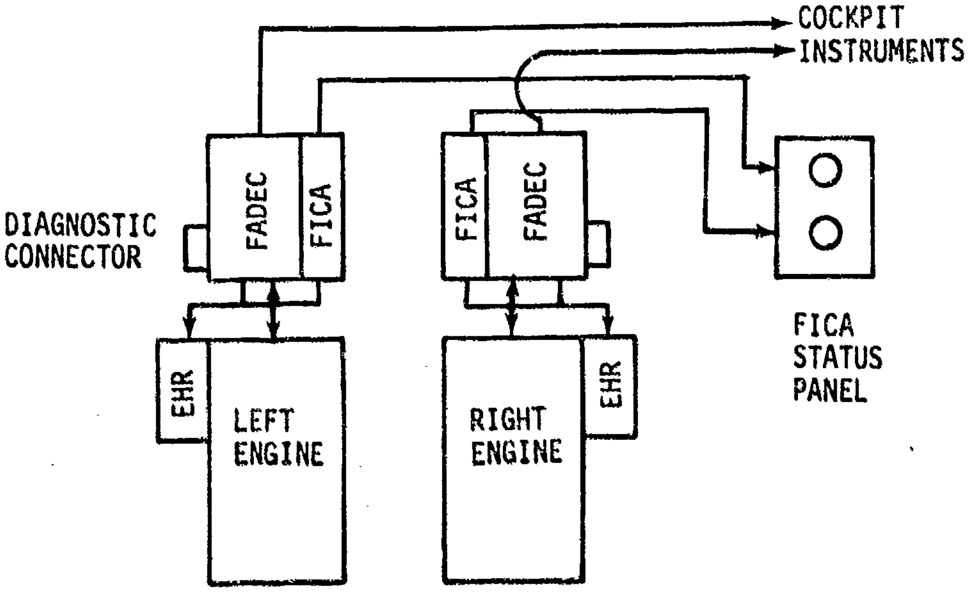


Figure 42. System 1 - FADEC With Engine History Recorder (EHR).

System 1 is the basic system incorporating the FADEC and FICA function and the electronics to process and compute the Engine History Recorder functions which are displayed and recorded mechanically on the engine-mounted EHR unit. A cockpit light advises pilot of a sensor failure detected by FICA and identifies the engine involved.

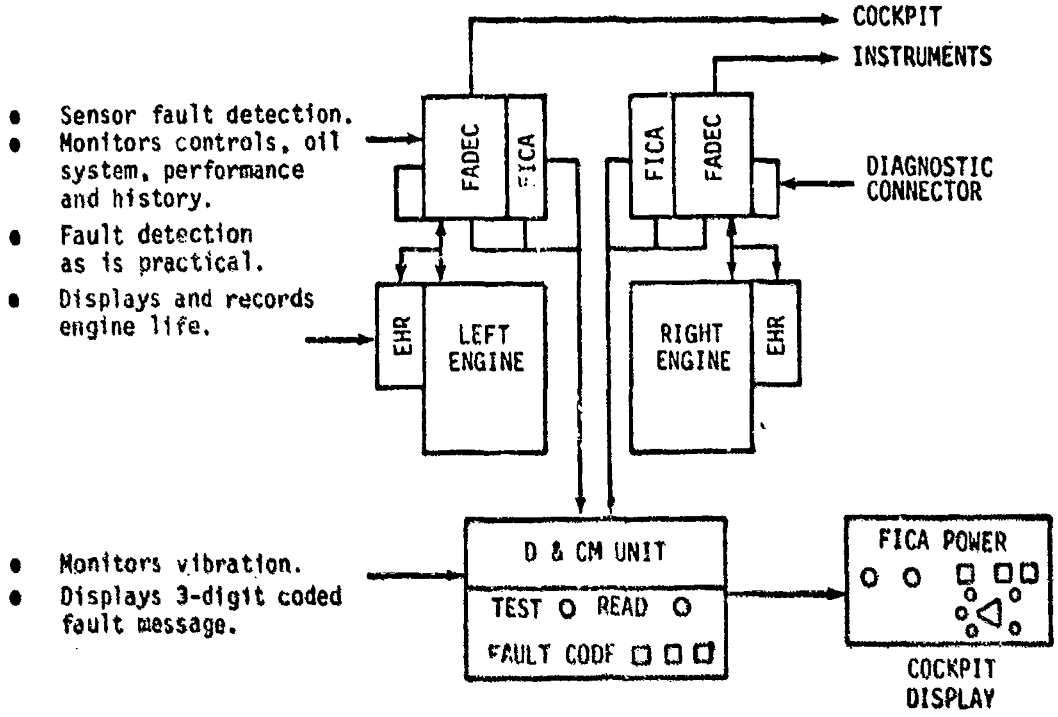


Figure 43. System 2 - Baseline System - FADEC, FICA, EHR, HIT, and Fault Detection (FD).

This system is the baseline for future designs. In addition to those items in System 1 it includes those items from the following list which a future LCC study determines cost effective: HIT check, all D&CM signals, and fault detection. An additional D&CM unit, probably airframe-mounted, processes vibrations as required and displays coded maintenance messages that identify a malfunction or limit exceedance. The system does not produce a permanent record of engine events, nor does it have extensive fault isolation capability. The extent of its practical fault isolation ability will not be known until a more detailed engineering study can be made.

System 3 - "Full House" System With Fault Isolation (FI) - FADEC, FICA, EHR, HIT, FD, and Base Shop Diagnosis

System 2, with the addition of in-flight tape recording and a computerized ground station, would become System 3. This system requires an airframe-mounted tape recorder unit to record in-flight events and provide a communications link with the ground station. It would meet all requirements of Contract DAAJ02-79-C-0065 for performance and mechanical monitoring and fault isolation. Fault isolation logic functions would be performed on the base computer.

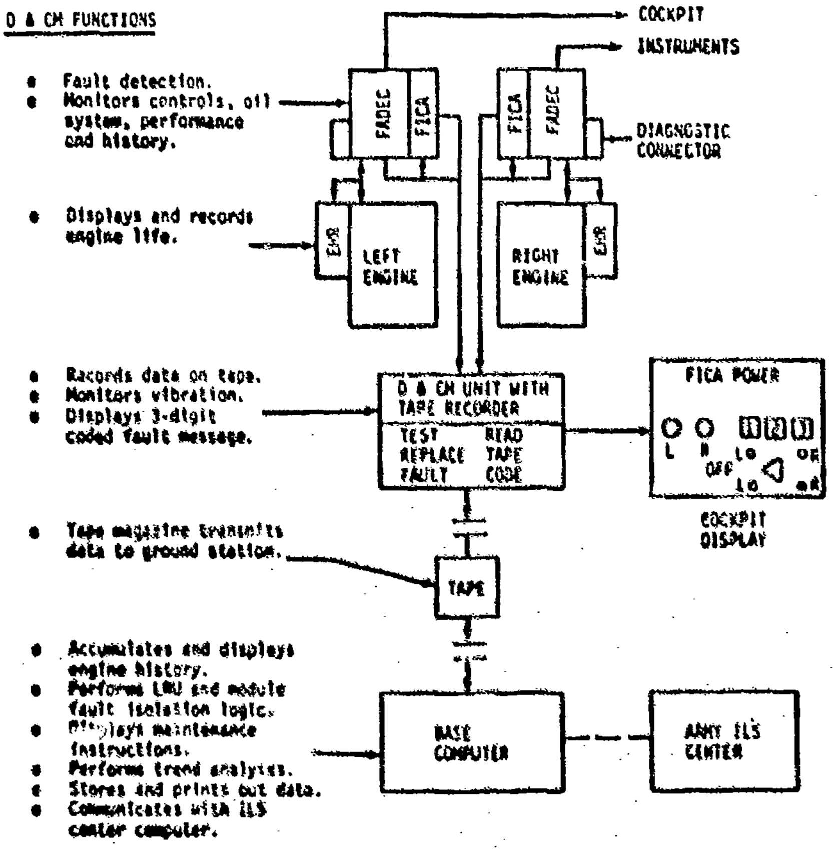


Figure 44. System 3 - "Full House" System With FADEC, FICA, EHR, HIT, FD, and Base Shop Fault Isolation

System 4 - "Full House" System With Flight Line Readout - FADEC, FICA, EHR, HIT, FD, FI, and Base Shop Printout

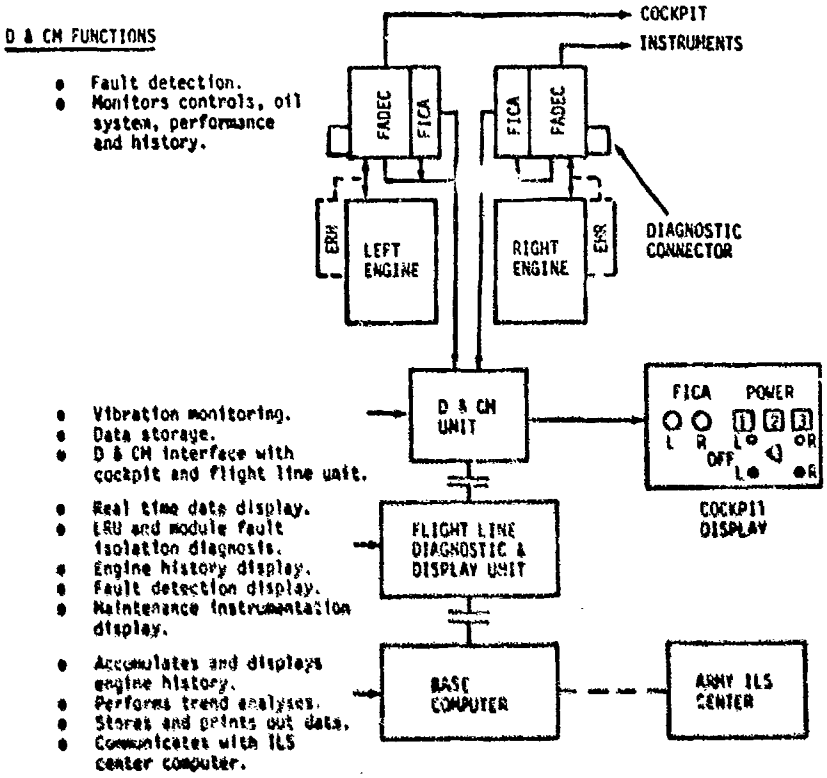


Figure 45. System 4 - "Full House" System With Flight Line Readout - FADEC, FICA, EHR, HIT, FD, FI, and Base Shop Printout.

System 4 meets all of the intended requirements for performance and mechanical monitoring and diagnosis. This system requires a modified airframe-mounted D&CM unit with solid state data storage; a ground diagnostic "suitcase" unit that will interface with the airframe-mounted unit and perform LRU fault diagnosis and real time data readout; and a base computer with readout, printout, computation, and tape storage capability.

TASK VII - SENSOR DEVELOPMENT REQUIREMENTS

GE's FADEC hardware programs have progressed sufficiently to show that there are feasible sensors currently available for a FADEC system. This has been demonstrated under the NASA-sponsored QCSEE program which has completed 175 hours of engine running with a digital control system. The FADEC program sponsored by the Navy has provided additional sensor refinements which will be demonstrated during engine testing in 1979. Additional sensor developments, however, are recommended on a longer term basis in order to reduce sensor cost and improve reliability and performance. In order to assure that sensors are compatible with the engine system space, weight, and environmental requirements, the engine manufacturer must provide technical guidance and surveillance. With the digital control system, the signal processing and conditioning should be considered as part of the control system and therefore sensors must be developed in concert with the FADEC system. For instance, pressure sensor linearizing and temperature compensation can now be performed cost competitively by software instead of select fit resistors as being demonstrated in the Navy FADEC program.

Speed and torque signals are frequency or phase related signals which can be converted to digital format without Analog to Digital (AD) conversion. Since these signals are of sufficient accuracy and response rate, additional development is not recommended.

The FADEC design senses WF feedback as metering valve position and VG feedback as an actuator position. GE's FADEC development, using linear variable phase transformers (LVPT) for position signals, provides an adequate base for position sensing. The LVPT transforms a position into a phase signal which can be conveniently handled by a digital system.

The NASA QCSEE program used analog pressure sensors, while the Navy FADEC program is demonstrating the feasibility of digital pressure transducers. In order to obtain the accuracies required in conventional engine control systems, the pressure sensors, either analog or digital, are very expensive. Therefore, future development of less-expensive digital pressure transducer technology is desired. As mentioned above, the development of specific transducers must be with control system development. This coordinates environmental requirements consistent with control schemes.

Present FADEC systems use analog temperature sensing devices. Conversion to digital temperature sensors is not currently practical; however, future developments could change this decision. The development of digital temperature sensors could reduce FADEC cost by eliminating the need for A-D conversion.

1. Magnetic Master Chip Detector: The T700 Master Chip Detector has been almost 100% effective in providing an early warning of impending OWP problems, primarily bearing problems, occurring during engine development and flight test. During flight test, no bearing failures were missed and no engines were removed because of false indications. However, as cited on page 22, many false or nuisance indications occurred caused by random manufacturing or assembly debris. Strict adherences to maintenance procedures identified these events as non-failures but at the cost of flight delays and ground engine runs. A CIP program is underway in T700 Engineering authorized by EPM #CIP E7 to locate or develop an improved device that will discriminate between nuisance and real incipient failure events. Because of the unique characteristics of the T700 engine, the capacitor discharge or "fuzz burner" type of chip detector, proven useful in other applications, is not applicable to this engine. In view of the on-going CIP chip detector program for the present T700 engine, no development program is required for an FADEC-equipped T700 engine.

2. Accelerometers: There are no unique requirements for engine vibration sensing accelerometers for a FADEC-equipped T700 engine. Miniaturized accelerometers are available with adequate output signal strength, frequency response and high temperature tolerance. Accelerometers with built-in charge amplifiers (a desirable feature) are under development, but are currently lacking in tolerance for the typical engine temperature environment. An improvement here would be desirable, but it is not a unique requirement for FADEC.

3. Ignition Sensor: Fault detection and isolation of the ignition system can be partially accomplished as is done in the A7E IECM system by using induction coils around each ignition load. Sensing the characteristic or voltage (or current) rise versus time may enable some LRU fault detection and isolation to be accomplished. An analytical and testing program would be required to determine to what extent faults in the power supply, exciter input, output, leads or igniter plugs could be detected and isolated. Sensor design and qualification would follow provided the fault isolating capability of the sensor was judged to be cost effective.

4. The following Table 17 shows the status of sensors required for FADEC/ D&CM system development.

TABLE 17. STATUS OF SENSORS REQUIRED FOR FADEC/D&CM

Sensed Parameter	Type of Processing	Remarks
Torque	Digital	Current sensors are available with sufficient accuracy and acceptable cost
Speed	Digital	Current sensors are available with sufficient accuracy and acceptable cost
Position (WF and VG)	Digital	LVPT is adequate
Pressure	Analog Digital	Currently very expensive for accuracy required by control concepts considered in this study
Temperature	Analog	Currently used in FADEC systems
	Digital	Not currently available; development desirable to reduce system cost
Chip Detector	Digital	Development of discriminating detector desirable
Accelerometers	Analog	Improvement in temperature sensitivity is desirable
Ignition Current	Analog	No sensor or sensor output characteristics available.

In summary, the current state of the art of sensors has been shown to be adequate to support future FADEC development. Two areas would benefit from general development in support of long-range FADEC goals:

1. Digital pressure transducer cost reduction without sacrifice of required accuracies, response and reliability.
2. Digital temperature sensor development covering the following required low and high temperature ranges.
    a. Inlet sensor range is from $-65^{\circ}F$ to $+160^{\circ}F$.
    b. T4.5 range is $-65^{\circ}F$ to $1550^{\circ}F$.

While some basic work in both these areas is desired, specific sensor development should be completed as an integral part of the basic FADEC development, as different control system approaches can significantly change accuracy requirements.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. LRU fault isolation by means of an electronic diagnostic system is considered feasible for the current T700 engine. However, it has not yet been established that the D&CM system to accomplish the diagnostics would be cost effective.

2. Fault isolation to the engine module level is feasible based on vibration, life usage and oil-wetted part diagnostics. Though modular performance fault isolation appears to be feasible, further analytical studies are required for verification.

3. The D&CM requirements for both module and LRU fault isolation for a FADEC-equipped T700 engine are simpler than for the current T700 engine. Further analytical and computer simulation studies are required to fully exploit the inherent diagnostic capabilities of the FADEC system.

4. Integration of D&CM functions into the FADEC system provides an opportunity to expand D&CM functions at an implicity lower cost and weight, as well as a greater reliability than in a standard hydromechanical/analog electrical control system. The FADEC system inherently offers a cost and weight saving because approximately 70% of the signals required for a D&CM system are already available for control purposes as opposed to the current T700 system where approximately 25% of the required signals are presently in the required electrical form. The FADEC system also provides a logical area for processing the D&CM signals not required by the control system, with the exception of vibrations, at a minimum increase in FADEC parts.

5. The FADEC system can accomplish the following D&CM functions efficiently:

   a. Engine history functions

      1) LCF counts

        2) Hot part life

        3) Engine hours

    b. Detection of failures of most control system sensors by using FICA.

    c. Detection of some control system failures by self-test.

6. Integration of the following D&CM functions is practical and is most cost effective when considered at FADEC design inception:

    a. Performance checking for engine health (HIT checks).

    b. Tracking of oil pressure vs NG to detect oil system problems.

    c. Detection of low or high oil pressure, overtemperature, fuel or lube filter bypass and chip detection signal.

7. FICA not only indicates control sensor failure, but allows safe engine operation with any single sensor failure of NP, NG, PS3, T4.5, WFFB, and Q1. With the failure of any sensor, except T4.5, at least 97% power can be obtained. With the T4.5 sensor failed, at least 90% power can be obtained during T4.5 limiting, and this can be improved through FICA refinements. The system has also indicated satisfactory operation with multiple sensor failures.

8. In addition to the available sensed parameters, there are intermediate parameters calculated by FICA which are useful to the D&CM functions. FICA calculates T3 and T4.1 which can be used to estimate more accurately gas generator turbine blade temperatures. With this additional information and FADEC's computational power, potentially more accurate stress rupture calculations which are compatible with the FADEC system can be introduced.

9. Work completed on the D&CM system, including FADEC, provides a conceptual basis from which an integrated system could be designed. Preliminary life-cycle-cost estimates and fabrication and test of key system components could then be carried out.

10. Sensor state of the art is compatible with anticipated needs of future FADEC development; however, it is prudent to study further the potential for digital pressure transducer cost reduction and digital temperature sensor development. The current T700 CIP program to develop a magnetic master chip detector which would discriminate between a real failure event and a "nuisance event" should be considered as a potential sensor improvement. Also, engine-mounted accelerometers with built-in charge amplifiers which are more tolerant to the engine temperature environment require further improvement.

RECOMMENDATIONS

1. For the current T700 (non-FADEC) engine as well as for a T700 with a FADEC, the following steps are recommended:

   a. Extend existing studies to select and evaluate an approach for performance isolation to the module level for the T700 engine.

   b. Refine existing fault tree analysis for the T700 control system suitable for incorporation into an automated computational system.

   c. Define an integrated fault tree analysis and diagnostic logic for each module and LRU and assess the fault isolation effectiveness.

   d. Define the preliminary design of an automated computational fault isolation system to implement the fault tree analysis of (c) above. The design should be of sufficient detail to estimate size, weight, functional scope and cost effectiveness.

2. In addition to the above, the following steps are recommended for the FADEC-equipped T700:

   a. Design, fabricate and test an engine-mounted digital history recorder. Such a program will:

      1) Demonstrate that HIT check, LCF, stress rupture, and engine hours can be calculated with an engine-mounted computer.

2) Provide a device useful to the T700 program by expanding current history recorder functions.

3) Complete a logical step in FADEC-D&CM technology development and provide the potential for early field testing of an advanced concept.

b. Initiate a study to increase the FADEC system's ability to detect and provide corrective action for control system failures not detected by FICA or self-test. Such a system would maximize control system reliability, increase D&CM capability, and minimize the need for a hydromechanical backup system.

c. Initiate investigations suggested in this report in order to:

1) Improve stress-rupture calculations consistent with FADEC parameters and computational capability.

2) Refine FICA designs to include the effect of bleed and variable geometry.

3) Determine the necessity for measuring both PO and PT2 within FICA.

4) Determine the procedure for handling stalls within FICA.

5) Evaluate the potential for determining engine health from Kalman filter residuals.

6) Improve low cycle fatigue measurement system accuracy by developing algorithms (logic flowcharts) for counting NG speed excursions and for computing LCF on the basis of "Master Cycles" which combine the effect of partial as well as major speed cycles.

3. In the area of sensor development, undertake preliminary studies to determine the potential for digital pressure transducer cost reduction and the practicality of digital temperature sensor development in conjunction with a FADEC-D&CM development program.

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GLOSSARY OF TERMS

Engine Parameters

SHP	Shaft Horsepower
T3	Compressor Discharge Temperature, Gas
T4.1	Gas Generator Turbine Inlet Temperature, Gas
NG	Gas Generator Speed
NP	Power Turbine Speed
T4.5	Gas Generator Turbine Discharge Temperature, Measured
T4.5G	T4.5 Gas Temperature
PS3	Compressor Discharge Static Pressure
Q1	Torque (Engine No. 1)
Q2	Torque (Engine No. 2)
T2	Compressor Inlet Temperature
PT2	Compressor Inlet Total Pressure
PL	Lube Oil Pressure
TL	Lube Oil Temperature
FL BP	Lube Oil Filter Bypass
V	Vibration
MCD	Master Chip Detector
AI	Anti-Ice
WFD	Fuel Flow Demand
LDS	Load Demand Signal
NPD	NP Demand
OS	Overspeed
CB	Customer Bleed
WF FB	Fuel Flow Feed-Back
VG FB	Variable Geometry Feed-Back
PAS	Power Available Spindle Signal
FWF BP	Fuel Filter Bypass
VGD	Variable Geometry Demand
PO	Pressure Altitude (Ambient)
IPSP/T	Inlet Particle Separator Blower Delta Pressure or Temperature
OAT	Outside Air Temperature

GLOSSARY OF TERMS - Continued

FADEC-D&CM System Components

HMU	Hydromechanical Unit
D&CM	Diagnostics and Condition Monitoring
ECU	Electrical Control Unit
FICA	Failure Indication and Corrective Action
FADEC	Full Authority Digital Electronic Control
GSE	Ground Support Equipment

D&CM Generated Signals

ESM	Engine Status Messages (warning, caution, advisory, failure, exceedance, and maintenance)
EHD	Engine Historical Data (performance, trending, and life used indices)
FC	Failure Code
T4B	Gas Generator Turbine Blade Temperature

Miscellaneous

LVPT	Linear Variable Phase Transformer
TM	Torque Motor
SBV	Starting Bleed Valve
LRU	Line Replaceable Unit
CC	Cockpit Commands (data display, record, ECU disable)
CITS	Central Integrated Test System
MATS	Military Air Transport Service
$\frac{1}{S}$	Laplace Operator
f ( )	Function of
Δ	Delta (change in)
AD	Analog to Digital (Conversion)
β	Beta (Helicopter Collective Pitch)
TMI	Torque Motor Current
EHR	Engine History Recorder
AGB	Accessory Gearbox
B/B	Building Block
HPT	High Pressure Turbine
LPT	Low Pressure Turbine
VG	Variable Vane Position
ALT	Alternator Power - ECU

GLOSSARY OF TERMS - Continued

SOAP	Spectrometric Oil Analysis Program
APU	Auxiliary Power Unit
OWP	Oil-Wetted Parts
FD	Fault Detection
FI	Fault Isolation
CGEKF	Constant Gain Extended Kalman Filter
LCC	Life-Cycle Cost

Computer-Generated Plots

Plot Symbol	Equivalent Symbol	Name
PS3E1	PS3	Compressor Discharge Static Pressure
YPS3		FICA Generated PS3
PCNP1		Percent Power Turbine Speed
YPNP1		FICA Generated PCNP1
PCNG1		Percent Gas Generator Speed
YPNG1		FICA Generated PCNG1
T45EL1	T4.5	Measured Gas Temperature
YT46S		FICA Generated T45EL1
T45E1	T4.5G	Gas Generator Turbine Discharge Temperature
YT45		FICA Generated T45E1
TEMP		Indication of Turbine Inlet Temperature
YTEMP		FICA Generated TEMP
YSFAIL		Sensor Failure Indicator
TRQT1	Q1	Shaft Torque
TRQP1		Gas Torque
YQ6		FICA Generated TRQT1
WFM1	WF	Fuel Flow
ZWF	WF FB	Fuel Flow Feed-back
YZWF		FICA Generated ZWF
DYNANG		Dynamometer Angle proportional to applied load (equivalent to collective pitch for a helicopter)