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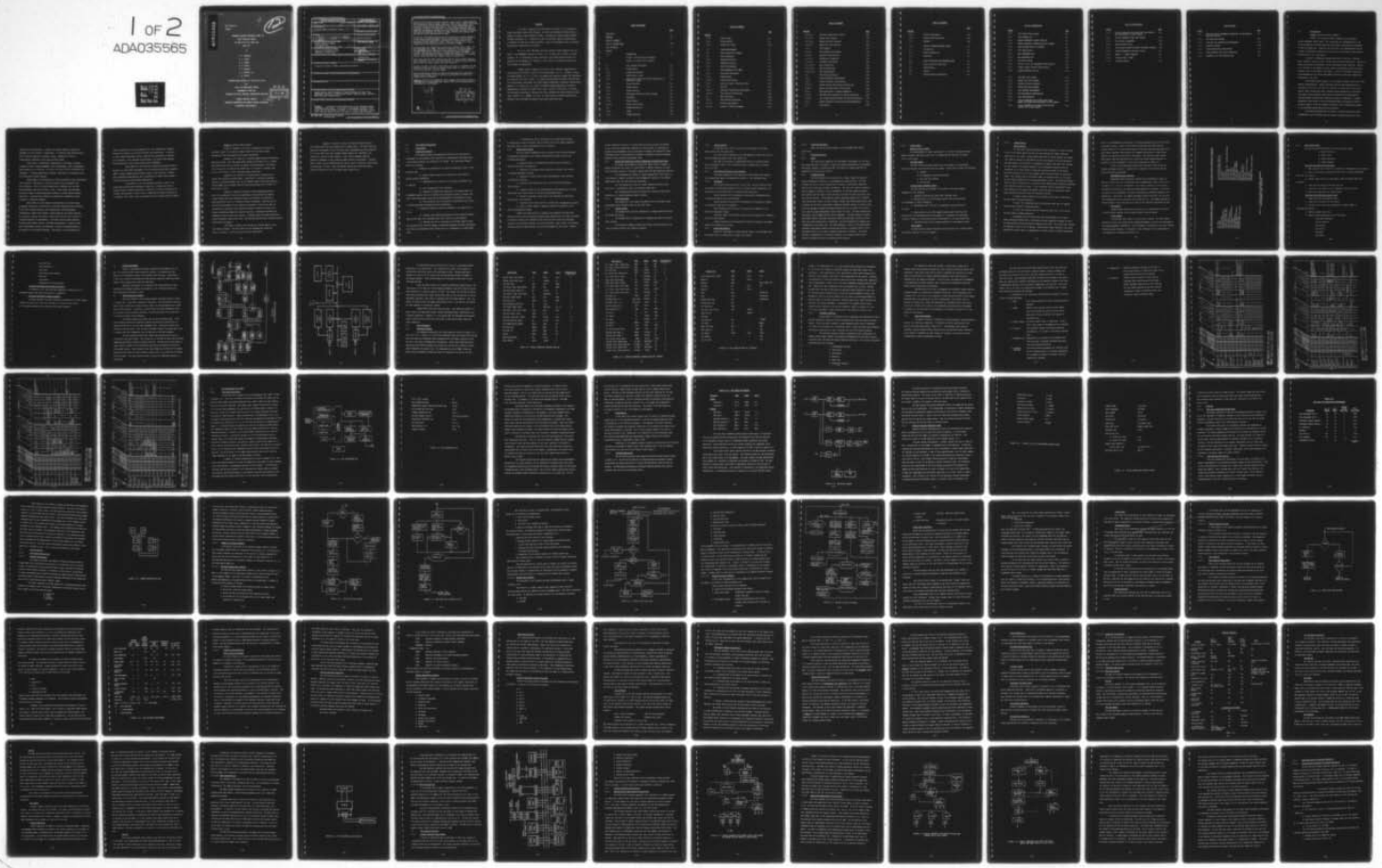

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VOLUME I

INTEGRATED ENGINE INSTRUMENT SYSTEM (U)

FINAL TECHNICAL REPORT

(23 JUNE 1975 TO 22 JUNE 1976)

JUNE 1976

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FOR

NAVAL AIR DEVELOPMENT CENTER

DEPARTMENT OF THE NAVY

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

Volume I contains the System Description of the Integrated Engine Instrument System (IEIS). In an effort to anticipate the needs of the flight crew and maintenance personnel in the 1980-85 timeframe, studies were conducted during the past five years to examine engine parameter

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definition and selection, sensor analysis, engine cycles, engine modeling, mission analysis, data trending, electronic fuel control, analog subsystems for vibration and turbine blade monitoring, display engineering, fault isolation techniques and human factors. The resulting baseline IEIS incorporates a variety of disciplines, including engine operation analysis, computers, multipurpose displays, data bus techniques, and data recording. Deck Launched Intercept and Subsonic Surface Surveillance missions were selected as typical applications for IEIS.

System user cost/benefit analysis and fault detection criteria presented in qualitative terms supplement specific system goals, such as system accuracy (±2% including sensors), probability of false alarm on the maintenance status indicator (.0005), self-test coverage (to a .98 confidence level) and system failure rate (4000 hours (MTBF).

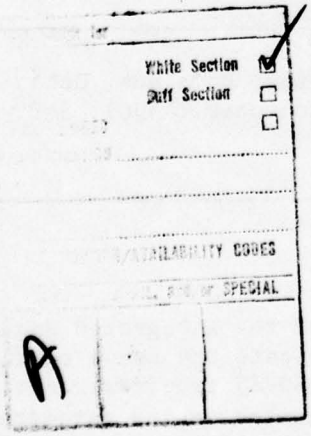
A central data bus, interfacing the Electronic Engine Control (EEC), the Data Management Unit (DMU), the display processor, the data processor, the maintenance status indicators, the keyboard and the maintenance recorder, requires a relatively low transmission speed of 40 KBPS. This bus will also interface with other aircraft data busses and will probably conform to MIL-STD-1553 type command response configuration.

Flow charts show how IEIS software would monitor four aircraft operation modes, prestart, start, in-use, and shutdown, to present engine condition and initiate corrective action upon fault detection.

Computer processor and memory requirements necessary to implement the IEI Operating System and store the average engine model are shown to be met by a 32 bit word and a 44K word memory.

Display engineering concepts for IEIS have been developed, evaluated in human factors studies of pilot reaction, and modified to reflect the optimum display techniques.

Volume II contains four appendices which document the results of Phase V investigations in engine modeling, display human factors engineering and instrumentation requirements.



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FOREWARD

This report represents the Final Report for Phase V of the Integrated Engine Instrument System (IEIS) Program. The work was performed by General Electric Company on contract number N62269-75-C-0359. The Naval Air Systems Command (NAVAIR SYSCOM), Washington, D.C., sponsored the work and provided support through Messers. G. Tsaparas Air-340D and R. Rank Air-53351A. Naval Air Development Center, Warminster, Pennsylvania, administered the contract.

Mr. W. G. Cole, AVTD NADC, has been the Naval Project Engineer for this effort. His management, Messrs. K. Priest, V. A. Frietag, and E. Rickner, provided guidance. Mr. W. Brietmaier provided assistance in the Human Factors efforts with guidance from his manager, Dr. Hitchcock. Their efforts in leading and monitoring this program are appreciated.

General Electric Company has utilized four different organizations in the execution of the Phase V portion of the IEIS program. Mr. R. L. Skovholt, acting as Program Manager, Mr. W. S. Little, who prepared the technical summary and coordinated the technical activities, and Mr. C. E. Buzzell who performed the sensor analysis task, are from Aerospace Instruments and Product Support Department, Wilmington, Massachusetts. Messers. W. A. Doerle and R. B. Cooper of Ordnance Systems Department, Pittsfield, Massachusetts, performed the human factor tasks. Messrs. M. Fine and R. E. Glusick of Electronics Laboratories, Syracuse, New York, performed the display hardware support task. Messers. H. L. McManus, Jr. and I. E. Marvin from the Aircraft Engine Group, Evendale, Ohio, performed the engine conditioning monitoring work.

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1.0 Introduction

Volume I (System Technical Summary)

Volume I is a System Technical Summary of the Integrated Engine Instrument System (IEIS). The conclusions and recommendations of the key investigations conducted during the five phases of exploratory development of IEIS are summarized. Because of the duration of the investigations and the variety of disciplines involved, the key results are contained in final reports published over a six year period.

Section 2.0 delineates leading particulars of the IEIS, including goals, benefits, costs, accuracy, failure rate and system description. Section 3.0 identifies baseline requirements for each identifiable IEIS subsystem. Section 4.0 is devoted to the summary of human factors investigations which have been a prominent part of the previous four phases. Section 5.0 presents conclusions and recommendations for future development activities which would improve the performance of the IEIS.

The System Technical Summary is not intended to detail any or all of the previous investigations. Rather, pertinent data for each subsystem such as interface definitions, performance requirements, and significant trade study results, which collectively form a baseline system definition, are assembled. Since many of the subsystems identified will eventually be incorporated in aircraft systems, defining the subsystem interfaces is emphasized. Frequent references to the source of the data presented enable the reader to refer to the final reports of the five phases for details of the investigation leading to the subsystem characteristics described herein.

The system characteristics are generic in nature because the actual implementation will be defined only for specific applications and will vary

depending on the application. However, the system complexity required to implement the IEIS concepts is represented. In addition, many characteristics may be directly applied to a specific system. Summaries of the key investigations conducted in each phase are given below.

During Phase I, preliminary investigations in the areas of engine parameter analysis, energy management, thrust measurement, sensor requirements, data management and processing, and display and human factors requirements were undertaken. A display generator was designed, fabricated, and interfaced with an off-the-shelf display terminal.

During Phase II, investigations of display and human factors requirements were conducted. Specifically, display information and presentation were given attention. The G.E. Aircraft Engine Group, Evendale, Ohio and Navy pilot personnel aided in this effort. Also, a major effort was undertaken during this phase to design appropriate hardware to provide dynamic display evaluation. A keyboard and interface box achieved this capability without the need of a dedicated computer.

During Phase III, more detailed investigations in aircraft engine performance monitoring, system design, and display engineering were conducted. In the area of engine analysis, key investigations included parameter determination, engine cycle analysis, engine modeling, and mission analysis. Deck launched intercept and subsonic surveillance missions were selected for a detailed analysis of requirements. Concurrent with the engine analysis, the IEIS system design activity, including investigations in specific areas and a technological survey, was undertaken to insure the appropriateness of the design for the intended timeframe. Specifically, the requirements for

signal conditioning, the data management unit, data transmission, computer hardware and software, and the data recorder were established. In addition to these system requirement studies, human factors evaluations of displays were conducted. Pilot reactions were obtained. The results were analysed and modifications to the display formats were recommended.

During Phase IV, work performed included system design studies necessary to relate IEIS requirements to the All Applications Digital Computer (AADC), display hardware modifications to make it more flexible, a display media technology investigation, and a continuation of human factors display evaluations using the IEIS display demonstrator.

During Phase V, the work performed included a review of the engine monitoring concepts developed in Phase III, a feasibility study of transient engine condition monitoring, a definition of sensor characteristics (present and projected) in matrix form, a human factors display evaluation in a simulated AIDS cockpit, and the preparation of this System Technical Summary.

Volume II (Current Effort Results)

Volume II documents in the form of appendices the results of the Phase V tasks in the areas of engine condition monitoring; display engineering;[1] and instrumentation and sensor definitions.

Appendix A is a report on a Transient Engine Condition Monitoring Feasibility Study. The IEIS engine model defined during Phase III is a steady-state model which does not monitor the engine during transients. The purpose of this study was to establish the feasibility of including a transient capability in this model to allow continuous engine monitoring.

Appendix B is a report on a limited study to identify ways to improve the steady-state engine model. Specifically, conclusions regarding results of on-going programs, such as the Advanced Engine Monitoring Evaluation System (ADEMS) and the LM2500 condition monitoring program, were reviewed for application to IEIS.

Appendix C describes the Phase V display engineering effort, which is an extension of the work accomplished in the previous four phases. Display formats have been developed further and subjected to evaluation by experienced Navy pilots in a simulated cockpit environment. Both the clarity and the appropriateness of the information displayed, as well as the need for information not displayed, were discussed between the narrator and the pilot subjects preceeding interactive scenario exercises. Evaluators recorded pilot responses during and after each exercise. Standard engine and flight operations, attack procedures, range cruise plots, and simulated malfunctions (including restart) constituted the scenario.

[1]The Phase V contract also provided for limited support of the IEIS display hardware. The tape reader for the equipment has failed and cannot be repaired. Various options are being investigated.

Appendix D contains a survey of presently available sensors and standard specifications summarized in a sensor matrix. The areas requiring additional development to meet the future IEIS requirements are also indicated. For the pre 1980 time-frame, standard engine sensors are considered to be technically limited for many reasons. First, sensor response times are generally inadequate to meet transient engine analysis requirements. Secondly, sensor outputs are not standardized and require special conversion, conditioning, and buffering. Thirdly, higher performance engines push operating ambient conditions beyond the limit of present sensor capabilities.

2.0 IEIS LEADING PARTICULARS

2.1 System Goals

2.1.1 System User Benefits

An Integrated Engine Instrumentation System can be justified as a replacement for the presently used collection of single-purpose instruments only if user-related benefits are achieved by the change. The identifiable benefit areas are as follows:

1. Integrate the presentation of engine instrumentation data to such an extent that:

a) Cockpit display space can be released for more directly mission-related information.

b) Comprehension and visibility of the engine information can be improved.

c) Crew training costs can be reduced.

d) Chances of unintentional operation of the engine beyond its recommended range of use can be reduced with consequent increase in engine lifetime, reduced maintenance costs and the implementation of maintenance by need.

e) Crew efficiency can be increased by reducing the time devoted to monitoring engine instruments and fuel expenditure.

2. Increase the amount of analysis performed on the engine data so as to:

a) Decrease total engine maintenance costs by requiring maintenance actions only on an as-needed basis rather than on a fixed schedule.

b) Decrease the rate of occurrence of in-flight engine failure by extrapolation of observed changes in significant measures of engine performance and taking the maintenance action indicated prior to degradation to unservicable level.

c) Decrease the rate of occurrence of in-flight engine failure by maintaining accurate individual logs of service time of all engine components and using these to require replacement prior to wear-out.

2.1.2 System Costs to User

The user benefits enumerated could be offset by costs incurred because of inadequate performance of the engine instrumentation system in any of the following particulars:

1. Excessive lags in instrumentation response times resulting in decreased efficiency of engine use.

2. Generation of inaccurate data resulting in improper crew actions or unneeded maintenance actions.

3. Generation of false alarms requiring unnecessary crew attention or maintenance checking.

4. Undetected instrumentation system faults producing misleading system outputs.

5. Frequent failure of the instrumentation system hampering or halting operational use of the aircraft or raising the maintenance costs.

6. Excessive instrument system repair time reducing the operational availability of the aircraft.

7. Excessive crew actions required to operate the instrumentation system.

8. Special flight regimes or maneuvers required to operate or calibrate instrumentation system.

Ideally one should be able to quantify these benefits and associated costs and arrive at an economically optimum system specification such that the excess of benefits returned after ownership costs incurred would provide an acceptable return on the investment required to procure the system. Such a model, rationalized on purely economic considerations, has not been attempted in this study. Instead,

we have attempted to arrive at a system model that would provide the benefits listed (with some reservations regarding the possibilities for computing all optimum energy management control strategies) attainable instrumentation system performance which are attainable and represent a reasonable compromise between ownership costs and system procurement costs.

2.1.3 Engine Fault Detection Criteria Summarized in Qualitative Terms

The engine instrumentation system will detect faults in engine or engine controllers that result in a five percent or greater reduction in gross thrust produced relative to the generic engine under the same operating condition.

The instrumentation system will detect engine faults that result in a ten percent or greater increase in fuel consumption (relative to the generic engine model under the same operating conditions).

The instrumentation system will detect engine lubrication faults which will, if uncorrected, result in excessive engine wear.

The instrumentation system will detect any condition sufficiently hazardous as to require immediate engine shutdown.

2.1.4 False Alarm Rate

The probability of the engine instrument system activating a false maintenance status indicator shall be less than .0005.

2.1.5 System Latency

The maximum delay in direct presentation of engine sensor data shall not exceed two seconds.

The maximum delay in presentation of computed data shall not exceed three seconds.

The maximum discrepancy between time labeled recorded data and true time of acquisition shall not exceed two seconds.

2.1.6 System Accuracy

The maximum error from all sources in any displayed or recorded numeric data shall not exceed ±2%.

The total error introduced by the instrumentation system (as distinct from the measuring sensors) shall not exceed 0.5%.

The rate of occurrence of undetectable errors in recorded digital data introduced by flaws in the recording process or medium shall not exceed one bit in 10^{12}.

2.1.7 Self-Check and Built-In Test Coverage

Successful completion of the System Self-Test Program shall assure a fully operational engine instrumentation system at a .98 confidence level.

2.1.8 Redundancy

The system configuration shall be such that, when utilizing the back-up reserves of interfacing systems as well as internal system redundancies, the system shall be fail operational for single failure conditions.

Sensor failures will be minimized by altering the programmed models to produce the datum of the failed sensor.

Analog converter failures will be minimized by using reserve channels in the engine controller A/D converter.

Data transmission failures will be minimized by redundancy of the Data Bus Transmission System.

Processor, memory and recorder failures will be minimized by redundancy within the AADC complex.

Display failures will be minimized by reciprocal sharing of the Master Monitor Unit Display of the AIDS.

2.1.9 Mean-Time-To-Repair

Except for replacement of engine mounted sensors, the IEIS MTTR shall be one-half hour for technicians of normal skill levels.

2.1.10 System Failure Rates

Apart from engine mounted sensors, the system MTBF shall exceed 4,000 hours.

2.2 System Description

2.2.1 Scope

This description summarizes the performance requirements for the IEIS. The system described is intended to supply the engine instrumentation, performance monitoring, analysis, recording and real time display of engine operation for application to future Naval aircraft.

2.2.2 System Functions

The IEIS provides the aircraft pilot a single, simplified display of engine performance information on a management-by-exception basis. The IEIS provides the pilot a visual presentation of present or predictable engine malfunction with associated advisory information. The IEIS will respond to operator keyset commands to produce a visual presentation of selected engine parameters, fuel reserves and the flight control actions to achieve the best practicable fuel and time utilization. During specific engine operating regimes and at scheduled times during each flight, the IEIS collects, formats and records engine sensor data as needed for off-line, ground-based "long-term trending" analysis to detect slowly occurring changes in engine performance capabilities and to predict the times at which specific engine maintenance actions should be taken. The IEIS automatically maintains a log of engine service time by component. The IEIS analysis of engine performance detects operating conditions indicating maintenance actions as these reach the point-of-need while in operation. The IEIS automatically compares fuel consumption to pre-flight plan. The IEIS maintains a record of all engine sensor readings during engine operating periods and produces a permanent record of this operating history in the event an engine malfunction is detected. The record produced is augmented by a two-minute extension of the engine operation data beyond the instant at which the malfunction was detected.

2.2.3 System Inputs

Engine(s) Sensor Inputs

The approximately 65 inputs (per-engine) to the IEIS from engine sensors, signal processors and engine controllers are enumerated and described in Section 3.2.1 of this report.

Data Bus Inputs

The IEIS utilizes air-data inputs which are assumed to be distributed within the aircraft via an aircraft data bus system. These inputs include the following:

- Airspeed
- A/C Geographic Location Coordinates
- A/C Clock Time Reading
- A/C Altitude

Ground Support Equipment Inputs

The IEIS receives and responds to data inputs from ground support equipment for the following:

1. Commands to perform and report IEIS readiness tests.
2. Modifications to the IEIS engine service time logs occasioned by replacement of engine components.
3. Maintenance crew "sign off" of maintenance actions detected by the IEIS.
4. Modifications to the IEIS computer engine models resulting from revisions of the characterization of the engine as a consequence of maintenance actions or analysis of fleet-wide records of performance of the same engine type.
5. Calibration data for any sensors replaced as a maintenance action.

Pilot Inputs

The IEIS receives control information from the pilot via a keyset further described in Section 3.7 of this summary.

2.2.4 System Outputs

Data Recording

An individual "engine performance record" consists of a single reading of all of the engine sensor data and the data defining the flight conditions under which it was taken. During engine operation, all sensor outputs are sampled four times per second and transferred into the core memory of the data processor. Once each second, the processor is programmed to convert these data (four readings for each sensor) from sensor readings to the corresponding physical units as determined by the scale factors, biases and calibration curves of the sensor. The mean and deviation of the four samples taken from each sensor are then determined. The average value of the sensor output (in physical units) is the datum for that sensor appearing in the engine performance record. The engine performance record is made at engine start, at take-off and at approximately 20 equally separated time intervals during the flight. To be of greatest use for ground-based "long-term trending" of the engine performance, these data must be taken under stable engine operating conditions which are defined as follows:

- Engine rotation speed has not deviated by more than "A" RPM during the past minute of engine operation.
- Total inlet temperature has not deviated by more than "B" degrees during the past minute of engine operation.
- Total inlet pressure has not deviated by more than "C" psi during the past minute of engine operation.

A permanent record of every other one second average of all engine sensor readings extending over a five-minute interval spanning the moment at which an engine malfunction was detected is produced by the IEIS. The record thus contains 130 readings of each of the 65 sensors. During stable engine operation, the sensor readings are used as input to computations of several indices of engine performance,

such as the thermodynamic efficiencies of rotating components and correct positions of servoed controls. Limits on these derived quantities are known from the computer model of the characterized engine for whatever operating conditions exist. Other sensor readings (lube quantity, for example) are subject to fixed limits whatever the operating conditions of the engine. Each data set (every second) taken under conditions satisfying the criteria for stable engine operation is analyzed for limit exceedance of any of the items shown in Table 2.2-1.

If any of these parameters exceed their allowable limits on two successive averaging intervals, a malfunction is assumed to have occurred and the loop record dump is performed.

Maintenance Status Indicator

Maintenance Status Indicator counters can be displayed as output of IEIS in the form of a set of indicators, each corresponding to one of the entries in Table 2.2-1. They are incremented by the computer whenever an out-of-limits malfunction involving the corresponding engine parameter is detected. The counter is cleared by the maintenance crew after correcting the conditions leading to the malfunction. Physically, the summary maintenance status indicator is in the form of an annunciator readily available from outside the A/C. The summary maintenance status indicator is set when any one or more of the individual indicators are set.

MUX Outputs

Summary engine status and fuel status will be transmitted by the IEIS to other aircraft systems via the Aircraft Central Data Bus System.

Pilot Display

The principal IEIS output is to the pilot's display. The IEIS Display provides the pilot with engine status, engine performance, aircraft (AC) performance, and energy management information. This information is presented to the pilot through different display formats. A discussion of the techniques of the presentation of the information is contained in Section 4.0.

COMPUTED ENGINE PERFORMANCE PARAMETERS	DIRECTLY MEASURED ENGINE PERFORMANCE PARAMETERS
Fan Flow	Core Variable Stator Position
Core Flow	Fan Inlet Guide Vane Position
Fan Efficiency	Nozzle Area
Compressor Efficiency	Fan Speed
Turbine Efficiency (LP)	Core Speed
Turbine Efficiency (HP)	Turbine Blade Temp - Avg/Hottest/Coldest
Stall Margin	Fuel Flow Main
Lube Pump Performance	Fuel Flow A/B
Thrust Bearing Performance	Mass Unbalance 1
Gross Thrust	Mass Unbalance 2
Lube Consumption	Foreign Object Damage 1
Scavenge Pump Performance	Foreign Object Damage 2
Heat Rejection	Bleed WB 27
Fuel/Oil Cooler Performance	Bleed W3 3
	Bearing Condition 1
	Bearing Condition 2
	Lube Level
	Fuel Filter Delta Pressure
	Lube Flow
	Lube Quality
	Scavenge Filter Delta Pressure

TABLE 2.2-1 MONITORED ENGINE PERFORMANCE PARAMETERS
FOR MAINTENANCE STATUS INDICATION

2.2.5 Operational Phases

The IEIS functionsdiffer among the following flight phases:

- Engine Pre-Start
- Engine Start
- Engine Operating
- Engine Shutdown

Functions Performed During Pre-Start

1. IEIS self-test and a check for the absence of maintenance status counters.

2. Input current sensor readings as single entry in engine performance record and loop record.

3. Monitor engine check list and display items (as English text) not satisfied.

4. Input AGE data modifying service time log.

5. Input data (via Keyset) on fuel expenditure plan for flight.

6. Monitor for application of starter power.

Functions Performed During Engine Start

1. Output pre-start performance record.

2. Begin data collection for loop record.

3. Log start time (from first application of starter power to core-spool break-away).

4. Display elapsed start time.

5. Monitor engine malfunction for the following:

Lube Pump Performance

Starter Position

IGV Position

Nozzle Area

Fan Speed

Core Speed

Main Fuel Flow

Mass Unbalance 1, 2

Lube Level

Fuel Filter Delta Pressure

Lube Flow

Lube Quality

Scavenge Filter Delta Pressure

Functions Performed During Engine Operation

The complete set of IEIS functions enumerated in Section 2.2.2 is performed during those times the engine is in operation.

Functions Performed At Engine Shutdown

At engine shutdown, the IEIS displays the equivalent of the MSI display, computes and posts the flight time increment to the service time record for all engine components, and monitors pilot keyset requests.

3.0 SYSTEM REQUIREMENTS

Through a comprehensive program of exploratory development over the past six years the IEIS system concept has evolved. The program plan (see Figure 3.0-1) developed in Phase I has basically been followed. During Phase I a first cut at system requirements was made and more detailed studies were undertaken in later phases when a need was identified.

Detailed requirements of the baseline IEIS system defined in these exploratory development programs are presented in the following sections for each identifiable subsystem of IEIS.

3.1 IEIS System Block Diagram

The block diagram of the Integrated Engine Instrument System is shown in Figure 3.1-1. Each block represents a subsystem. The IEIS processor receives inputs from the Electronic Engine Controls (EEC), the Data Management Units (DMU), and the IEIS keyboard. In addition, various status and energy management inputs are received from the aircraft interface. The IEIS processor will provide data to the Data Recorder and the Displays.

The engine sensors are divided into the two following groups: those which primarily service the Electronic Engine Controllers and those which are devoted exclusively to the IEIS Data Management Unit. Some sensor signals must interface with both users. Both the EEC's and DMU's convert the analog sensor data to digital form for transmission over the Data Bus to the IEIS processor.

The Data Recorder stores both routine long term trend data and the five minute loop record dumps. The routine data is recorded at given time intervals depending upon mission length and engine stability. Routine data is also taken at squat (weight on wheels) switch activation and during the take-off (a period of high engine stress). The five-minute loop record dumps are initiated by an engine malfunction and consist of three minutes of data prior to the event and two minutes after the event. The loop record provides a history for subsequent analysis on the ground.

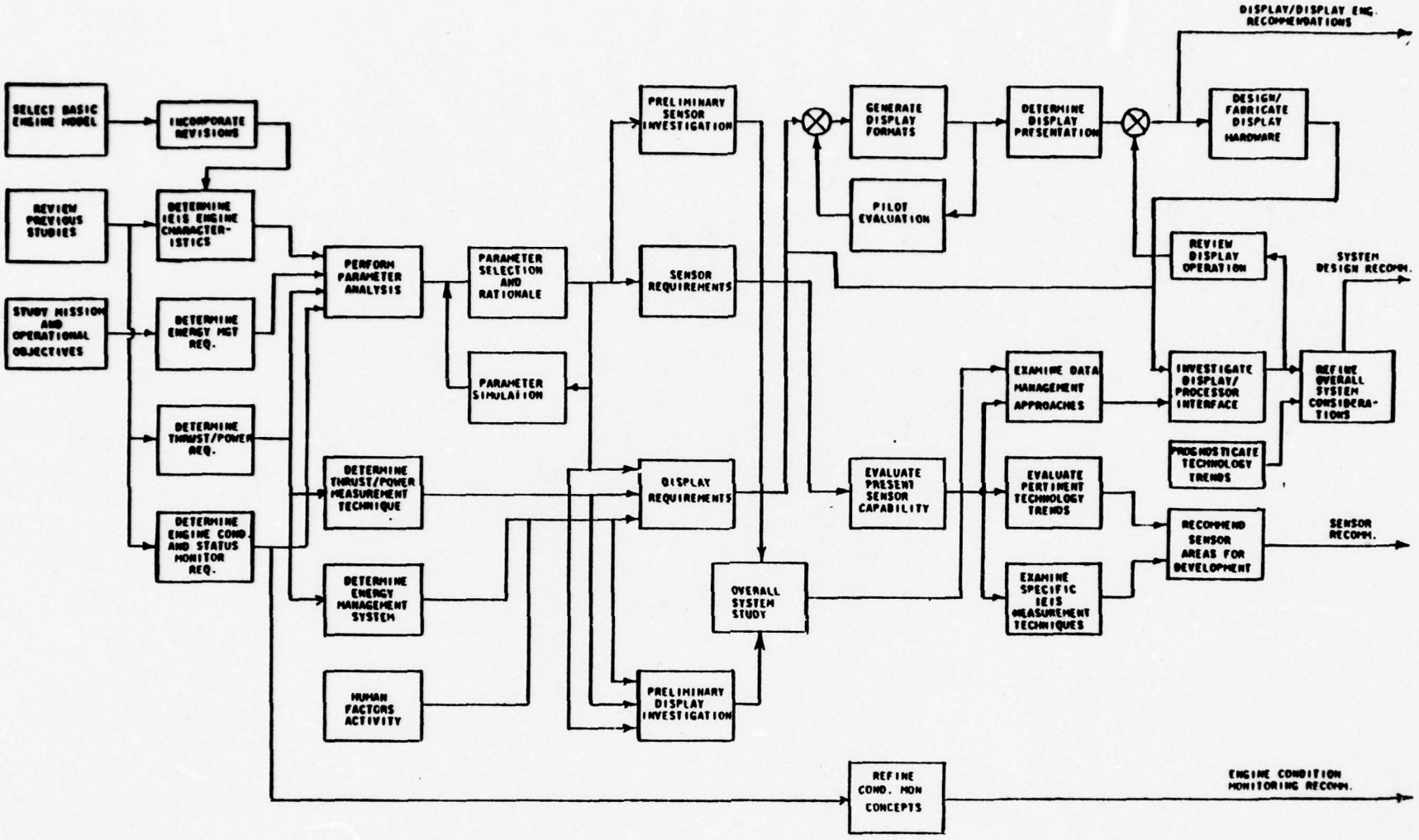
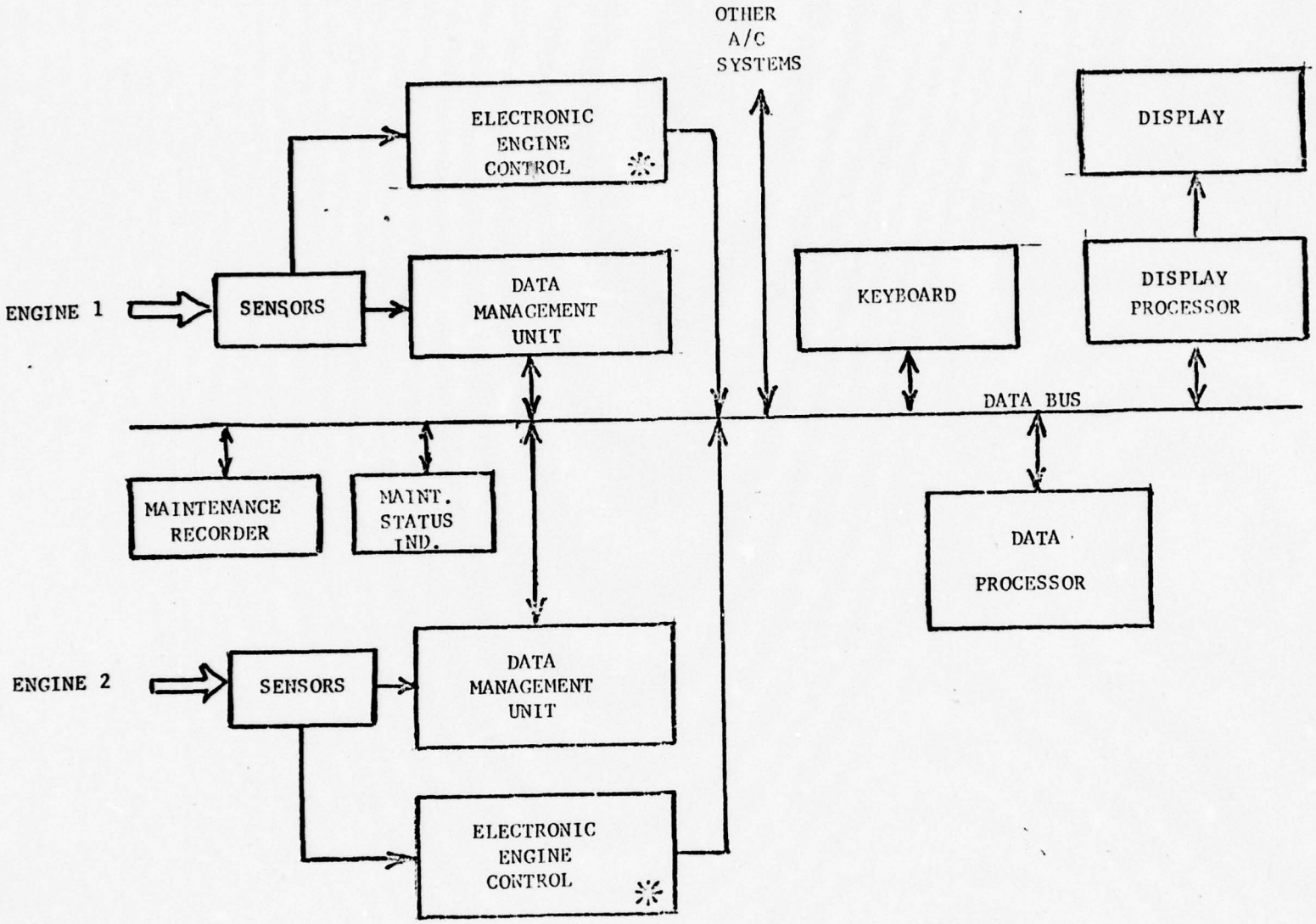


FIG. 3.0-1
IEIS PROGRAM PLAN



*REFERENCE ONLY

FIGURE 3.1-1 - IEIS SYSTEM BLOCK DIAGRAM

The Maintenance Status Indicator will serve as a maintenance-needed annunciator to the ground crew. This indicator will result in the removal of the aircraft from active service for maintenance action. During ground maintenance or at the end of the flight day, the Data Recorder should be dumped to the ground computer. These system elements are discussed in more detail in the following sections.

Since the IEIS Aircraft will include an Electronic Engine Control, the IEIS processor will make use of those engine parameters required by IEIS which have been converted to a digital format by the EEC. This scheme will relieve the DMU of some analog conversion and signal conditioning tasks, while allowing only the prime subsystems (the EEC in this case) to interface with the engine sensors. Thus, the sensor is loaded by only one signal conditioning circuit. One EEC unit per engine, has been assumed for reliability reasons.

Separate DMU's have also been specified. The conversion channel will mount close to the applicable sensor, thereby minimizing noise, interference, and erroneous conversions. Compared with one central DMU, the federated system should improve reliability and flexibility and result in only minor volume, power and weight penalties.

3.2 Input Parameters

3.2.1 Parameters/Sources

The parameters acquired by the IEIS system are listed in Figures 3.2-1, 3.2-2 and 3.2-3. Figure 3.2-1 gives those parameters which are aquired from the EEC. This list basically represents those parameters which the engine controller would use out of the total instrumentation requirements. Rather than repeating digital conversion, IEIS would interface with the EEC via its data bus to obtain the parameter information in digital form. The alphanumerics in the "NAME" column are derived from the ARP681B standard and would not necessarily be used on the IEIS

DESCRIPTION	NAME	RANGE	UNITS	REPEATABILITY (± % F.S.)
ENGINE INLET TOTAL PRESS.	P1	0+40	PSIA	2
ENGINE INLET TOTAL TEMP.	T1	-65+400	°F	1
A/B FUEL FLOW	WF6	0+70	KPPH	1
LOW PRESS. COMP. ROTOR SPEED	XNL	0+9	KRPM	.1
FAN INLET GUIDE VANE POS.	BF	-10-25	°	1
HIGH PRESS. TURB. BLADE TEMP.	TC	600+2000	°F	1
CORE ENG. ROTOR SPEED	XNH	0+16	KRPM	.1
MAIN FUEL FLOW	WF36	0+12	KPPH	1
CORE VARIABLE STATOR POS.	BC	-5+35	°	3
JET NOZZLE THROAT AREA	AB	600+1700	SQ. IN.	1.5
CORE COMP. INLET TOTAL PRESS.	PT25	0+50	PSIA	1
FAN DUCT PRESS. RATIO	PDOS	0+.2	---	5
MAIN FUEL PUMP DISC. PRESS.	PWFM	0+1200	PSIA	1.5
A/B FUEL MANIFOLD PRESS.	P6	0+1200	PSIA	1.5
IGV TORQUE MOTOR CURRENT	BFTM	±200	MA	1
MAIN FUEL TMC	WFMTM	±200	MA	1
A/B FUEL TMC	WFRTM	±200	MA	1
A8 TMC	A8TM	±200	MA	1
POWER LEVER ANGLE	PLA	0+130	°	-
STALL MARGIN	STALL	-25+50	%	-

FIGURE 3.2-1 ENGINE PARAMETERS ACQUIRED FROM EEC

Description	Name	Range	Units	Repeatability (± % F.S.)
H.P. Comp. Inter. Bleed Flow	WB27	0+7	PPS	1
H.P. Comp. Disch. Bleed Flow	WB3	0+7	PPS	1
Anti-Ice Flow	WBA1	On/Off	----	---
H.P. Rotor Pwr. Extraction	HPX	On/Off	----	---
L.P. Turb. Disch. Temp.	T5	-65+2000	^{o}F	1
Comp. Exit Total Temp.	T3	-65+1200	^{o}F	.5
Comp. Exit Static Press.	PS3	0+400	PSIA	1
Core Comp. Inlet Total Temp.	T25	-65+900	^{o}F	1
L.P. Turb. Inlet Total Press.	P49	0+100	PSIA	1
L.P. Turb. Inlet Total Temp.	T49	-65+2000	^{o}F	1
FOD Flag (2)	FOD F	On/Off	----	---
Scavenge Temp. (4)	TLS1-TLS4	-65+300	^{o}F	1
Scavenge Press. (4)	PLS1-PLS4	0+100	PSI	1
Bearing Condition (2)	BRG	0+10	---	2
Mass Unbalance (2)	MUM	0+10	MILS	2
Oil Level	OL	0+6	GAL	2
Oil Press.	PL	0+500	PSIA	2
Oil Temp.	TL	-65+300	^{o}F	1
Oil Quality	QUALO	0+100	%	---
Oil Flow	WLO	0+20	GPM	3
Oil Filter Delta Press.	LFDP	0+20	PSI	2
Bearing Race Temp. 1	BRGT1	-65+350	^{o}F	3
Bearing Race Temp. 2	BRGT2	-65+350	^{o}F	3
Fuel Filter Delta Press.	FFDP	0+100	PSID	2
Hottest Turb. Blade Temp.	T4 MAX	+600+2000	^{o}F	1
Hottest Turb. Blade Position	T4 MAX P	0+100	^{o}F	---
Coldest Turb. Blade Temp.	T4 MIN	+600+2000	^{o}F	1
Coldest Turb. Blade Position	T4 MIN P	0+100	^{o}F	---

FIGURE 3.2-2 - ENGINE PARAMETERS ACQUIRED FROM IEIS SENSORS

DESCRIPTION	NAME	RANGE	UNITS
FREE STREAM STATIC PRESS	PAMB	0+15	PSIA
HUMIDITY	HUM	0+100	%
WEATHER	WHER		RAIN, SNOW, ETC.
ALTITUDE	ALT	0+70	KFT
MACH NO.	XM	0+2.5	-
DATE	DATE	-	MO/DAY/YR
TIME	TIME	-	HR/MIN/SEC
ELAPSED RUN TIME	ERT	-	HR/MIN/SEC
ENGINE SERIAL NO.	ESN	-	-
A/C SERIAL NO.	ACSN	-	-
AIR FLOW LIMIT SWITCH	ALS	ON/OFF	-
SQUAT SWITCH	-	ON/OFF	-
POSITION	-	-	-
ACCELERATION	ACC	-	FT/SEC^2
AIR SPEED	AS	-	KNOTS
ANGLE OF ATTACK	AOA	-	DEG
FUEL QUANTITY	QF	-	LBS
A/C WEIGHT	TOGW	0+50	KLBS
A/C STORES	-	-	LBS
A/C G LIMITS	-	-	G'S

FIGURE 3.2-3 DATA ACQUIRED FROM A/C INTERFACE

display. The "Repeatability" is a sensor specification giving IEIS requirements on the ability of a sensor to repeatedly measure the same input signal level accurately. This specification is not applicable to those inputs obtained from the EEC or the airframe, since IEIS is not accountable for the sensors. However, the expectation is that the indicated levels will be met through close integration of all requirements. Figure 3.2-2 lists those parameters obtained from the IEIS DMU. Sensors for these parameters could be considered part of IEIS. The EEC and DMU share the load in providing the necessary engine parameters, while the A/C provides certain identification, status and energy management inputs. The parameters listed in the three figures are the result of evolutionary study and analysis based on the IEIS concepts of condition monitoring, fault isolation and detection, and energy management. During Phase V the engine related sensor characteristics required to provide the parameters listed in Figures 3.2-1 and 3.2-2 were established. These characteristics are defined in section 3.2.3.

3.2.2 Parameter Selection

During Phase I a preliminary set of parameters was selected which would provide information required by IEIS to determine both short and long term engine health. Short term health relates to those parameters which would be displayed in flight if they exceed a set of specified limits. These and additional parameters would also be monitored for fault isolation and long term trending purposes.

The selection process in Phase I analysed the basic subsystems of a 1980-85 attack fighter engine to determine the parameters and techniques required to perform short and long term engine condition monitoring. The six basic subsystems considered were the following:

- Thermodynamic Gas Path
- Lubrication
- Fuel/Control
- Hydraulic
- Electrical
- Mechanical Integrity

The analytical tools used included a steady state, engine cycle, computer model and previously obtained data from simulation activities and/or field experience. These basic tools were utilized to determine the sensitivity of parameters to deterioration of engine subsystem components which would result in degradation of the engine performance. From this work, the selection of parameters to be monitored for cockpit display, fault isolation and recording of long term engine health trending data was possible.

During Phase III the list of parameters was refined by using a specific candidate engine as a baseline for parameter definition. For the parameter list (Figures 3.2-1, 3.2-2 and 3.2-3) preparation, consideration was given to safe engine operation and to the prediction of time to maintenance. This current list is provided to insure that a great many parameters be considered before final selection by the customer with respect to his maintenance plan/mission mix philosophy. A rational for the selection of each parameter is contained in Section 2.7 of the Phase III Final Report.

3.2.3 Sensor Requirements

The sensors required to determine the engine parameter values defined in Section 2.2.1 have been identified. The sensors and their characteristics are shown in the IEIS Sensor Matrix, Figure 3.2-4. The parameter name, purpose, interface, current standard sensor characteristics and projected sensor characteristics needed to implement the IEIS concept are included. This matrix provides a definition of sensor requirements for IEIS.

The IEIS sensor matrix provides identification of key functional and performance data for both the aircraft industry accepted "current standard" and the future devices which will satisfy the IEIS "projected need" in the 1980 to 1985 time period. Only parameters measured "on engine" are included in the matrix. These are identified by accepted terminology and are generally grouped by the type of measurement involved, such as pressure, temperature, and position. Other IEIS inputs, such as air data, are realistically assumed to be obtained over a digital data bus and are therefore not included.

An explanation of the functional and performance headings is provided in the following paragraphs:

- Type: This column identifies the basic sensing technique employed.
- Range: Specific data provided covers the F404 engine operating envelope but should be fairly representative of future variable cycle engines of equivalent size.
- Output Signal: The basic signal format is identified. In most cases, some linearity refinements will be required.
- Accuracy: This parameter defines the required long term performance (1 to 2 years) in the service environment.
- Repeatability: Repeatability is defined as the allowable short term variation in readings including hysteresis, noise and resolution factors.
- Frequency Response: The value provided represents the -3DB band width for the sensing system. For pressure parameters, as an example the effects of probes, lines and cavaties are included.

- Temperature: Expected temperature extremes in the area of the sensing element are identified, based on an a assumed sensor location on the engine.
- Vibration: Vibration levels typical of those used for component bench qualification are provided. Normal frequency range would be 20 to 2000 Hz, but each engine application may have discrete resonances at higher acceleration levels and potentially higher frequency ranges.

FIG. 3.2-4

IEIS SENSOR MATRIX

	PARAMETER											PURPOSE									INTERFACE	CURRENT STANDARD								PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE OF	VIBRATION G	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE OF	VIBRATION G	COMMENTS
1	Engine Inlet Total Pressure	P1	E		X			X	X			TP Probe Strain Gage X'DCR	1.4 to 40 PSIA	DC 50 MV fs	1% Total Error Band	±2% fs	100	-65 to 1250	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-Linear	0.5% fs	0.1% fs	1K	-65 60 400	30	Mount Transducers Close to Probe to Reduce Line Effects
2	Core Comp. Inlet Total Pressure	PT25	E		X	X		X	X			↓	1.4 to 50 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
3	Fan Duct Pressure Ratio	PDQS	E		X			X	X			↓	0 to 0.7	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
4	Core Comp. Exit Static Pressure	PS3	E			X		X		X		Wall Probe Bourdon Ratio	0 to 400 PSIA	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	20	↓	↓	↓	↓	↓	↓	↓	↓	↓
5	Gross Thrust	FG	E			X		X		X																		See Text
6	Stall Margin	Stall	E			X		X		X		Use PS3 & PDQS Rate	Calculated Parameter - Use Rate of Change of PS3 & PDQS to Determine Impending Stall															Engine Control Response Time Not Good Enough to Recover Based on Stall Input
7	Oil Pressure	PL	E	X		X		X			X	Bourdon Ratio	0 to 500 PSID	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-Linear	3% fs	1% fs	1K	-65 to 400	30	Measure Pulsation Level to Determine Health of Pump
8	Oil Filter Delta Pressure	FLDP	E			X		X		X		↓	0 to 20 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
9	Scavenge Pressure	PLS1 to PLS4	E			X		X		X			0 to 100 PSIA															
10	Main Fuel Pump Discharge Pressure	PWFM	E			X		X		X			0 to 1200 PSIA															
11	A/B Fuel Manifold Pressure	PWF6	E			X		X		X			0 to 1200 PSIA															
12	Fuel Filter Delta Pressure	FFDP				X		X		X		↓	0 to 100 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

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FIG. 3.2-4

IEIS SENSOR MATRIX

NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE OF	VIBRATION &	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE OF	VIBRATION &	COMMENTS
	PARAMETER						PURPOSE				INTERFACE	CURRENT STANDARD								PROJECTED NEED									
13	L.P. Turbine Inlet Total Pressure	P49	E			X		X		X		TP Probe Bourdon Ratio	0 to 100 PSIA	400 Hz Sine 5 to 15 V RMS	3% fs	1% fs	10	-65 to 400	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	3% fs	1% fs	1K	-65 to 400	30	TP Probe Ahead of LP Turbine is Major Reliability Concern May Want to Include Probes in Leading Edge of Several Stator Vanes.
14	Engine Inlet Total Temp.	T1	E		X				X			RTD Probe	-65°F to +400°F	Res. Chg. with Temp. Platnium	1.0°F	0.5°F	0.2	-65 to +400	30	Wall Mounted System	Same	Variable Freq. Sq. Wave	Same	Same	10	Same	Same	See Text
15	Core Compressor Inlet Total Temp.	T25	E			X		X		X		RTD Probe	-65°F to 900°F	↓	↓	0.2°F	0.2	-65 to +900	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
16	Core Compressor Exit Total Temp.	T3	E			X		X		X		T/C Probe	-65°F to 1200°F	5 DMV DC Full Scale	5°F	1°F	0.5	-65 to 1200	↓	↓	↓	↓	2°F	0.5°F	↓	↓	↓	↓
17	High Pressure Turbine Blade Temp.	T48	E		X			X	X			Optical Pyrometer	1000°F to 2000°F	Non-linear DC 10V FS	10°F to -20°F	5°F	10K	-65 to 800		Same	400°F to 2000°F	Same	5°F	2°F	10K	-65 to 800°F Fuel Cooled	30	T/C Used to Extend Operating Temp. Below 1000°F. See Text.
18	L.P. Turbine Inlet Total Temp.	T49	E			X		X		X		T/C Harness	-65°F to 2000°F	80 MV DC Full Scale	10°F	2°F	0.5	-65 to 2000		Fiber Optic Harness	1000°F to 3000°F	Non-linear Chopped DC	5°F	2°F	10	See Comm.	↓	Sensor Tip 3000°F Maximum Scanner & Photo Detector -65°F to 200°F (Cooled)
19	L.P. Turbine Discharge Total Temp.	T5	E			X		X		X		↓	-65°F to 2000°F	80 MV DC Full Scale	↓	↓	↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	
20	Oil Temp.	TL	E	X		X		X			X	RTD Probe	-65°F to 350°F	Res. Chg. with temp. Platnium	0.2°F	.05°F	0.2	-65 to 400		Piezo Electric Quartz	Same	Variable Freq. at 100K Hz	Same	—	—	—	↓	
21	Scavenge Temp.	TLS1 to TLS4	E			X		X		X		↓	-65°F to 400°F	↓	↓	↓	↓	↓		↓	↓	↓	↓	—	—	—	→	Use Temperature Rise for Diagnostic Purposes
22	Bearing Race Temp.	BGT1 to BGT2	E			X		X		X		T/C Probe	↓	DC Milli-volts	5°F	1°F	0.5				Eliminate - Use Magnetic Particle Detector							See Text
23	A/B Lightoff Detector	ABI	E		X				X			UV Tube	Off - On	Variable Freq.	10%	1%	1K	↓	↓	Solid State UV Sensor	Off - On	Variable Freq.	5%	1%	1K	1000	30	Reduce Size and Increase Temp. Capability w/o Cooling

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FIG. 3.2-4

IEIS SENSOR MATRIX

	PARAMETER								PURPOSE								INTERFACE	CURRENT STANDARD								PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	COMMENTS
24	Foreign Object Strike	FOD	E	X		X		X		X		Piazo Electric Accel.	0 to 1000 g	20 PC per g	5% fs	2% fs	20K	-65 to 400	30	←			Same				→	Improve Vibration Integrity and Make Externally Removable
25	Mass Unbalance	MUN	E	X		X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	←			Same				→	
26	Bearing Condition	BRG	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	Use Magnetic Particle Detector								
27	Oil Quality	QUALO	E			X		X		X		No Satisfactory Use GSE Oil Quality Monitor		Airborne Standard			Or/and Soap			Magnetic Particle Detector	0 to 1.0 milligrams per hr.	Variable Freq. at 1K Hz	10%	3%	1	-65 to 400	30	
28	Oil Flow	WLD	E			X		X		X		Free Turbine Volumetric	0 to 20 GPM	Variable Freq. & Amplitude	5%	2% fs	5	-65 to 400	30	No Projected Need								
29	Oil Level	QL	E	X		X		X			X	Magnetic Reed SW & Float	0 to 6 GAL	Stepped DC 0 to 300 Ohms	2% fs	1% fs	2			Solid State	Same	Variable Freq. at 10K Hz	←	—	Same		→	See Text
30	Main Fuel Flow	WF36	E	X		X		X			X	Angular Momentum Mass Flow	0.3 to 12 KPPH	Indicator System Output 0-5 VDC	1% fs	0.5% fs	1			Fluidic & Density	↓	Variable Freq's	0.5% fs	0.2% fs	10	Same	Same	
31	A/B Fuel Flow	WF6	E	X		X		X			X	Angular Momentum Bypass Mass Flow	1 to 70 KPPH	↓	↓	↓	↓			↓	↓	↓	↓	↓	↓	↓	↓	
32	Anti-Ice Flow	WBA1	E		X	X		X		X		Pneumatic Assisted Elec Regulating	On - Off	NA	NA	NA	10			←		Same					→	Simplification Improvements Needed
33	H.P. Compressor Interstage Bleed Flow	WB27	E			X		X		X		Orifice Pressure Diff. Bourdon	0 to 7 PPS	400 Hz AC Ratio	3%	1%				Orifice Diff. Pressure Crystal XDCR	Same	Variable Freq. at 100K Hz	Same	Same	Same	Same	Same	
34	H.P. Compressor Discharge Bleed Flow	WB3	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	

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FIG. 3.2-4

IEIS SENSOR MATRIX

NUMBER	NAME	SYMBOL	LOCATION	PARAMETER: DISPLAY	PARAMETER: ENGINE CONTROL	PARAMETER: FAULT DET/ISOL	PURPOSE: RECORD KEEPING	PURPOSE: HEALTH TRENDING	PURPOSE: ENGINE CONTROL	PURPOSE: IEIS DEDICATED	INTERFACE: AIRCRAFT SYSTEMS	CURRENT STANDARD: TYPE	CURRENT STANDARD: RANGE	CURRENT STANDARD: OUTPUT SIGNAL	CURRENT STANDARD: ACCURACY	CURRENT STANDARD: REPEATABILITY	CURRENT STANDARD: FREQUENCY RESPONSE HZ	CURRENT STANDARD: TEMPERATURE °F	CURRENT STANDARD: VIBRATION g	PROJECTED NEED: TYPE	PROJECTED NEED: RANGE	PROJECTED NEED: OUTPUT SIGNAL	PROJECTED NEED: ACCURACY	PROJECTED NEED: REPEATABILITY	PROJECTED NEED: FREQUENCY RESPONSE HZ	PROJECTED NEED: TEMPERATURE °F	PROJECTED NEED: VIBRATION g	COMMENTS
35	Fan Inlet Guide Vane Position	BF	E	X	X		X				LVDT on Actuator	-10 to -25°	AC Sine 400 Hz Linear	0.5%	0.1%	100	-65 to 400	30	Magnetic Digital	Same	TTL Serial Digital	10 Bit	2 Bit	Same	Same	Same	LVDT Reliability Marginal Linkage Slop Introduces Additional Errors
36	Core Variable Stator Position	BC	E	X	X		X				↓	-5 to +35°	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
37	Jet Nozzle Throat Area	AB	E	X	X		X				↓	600 to 1700 In. Sq.	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
38	Power Lever Angle	PLA	E	X	X		X				Synchro	0 to 130 Deg.	2φ AC 400 Hz Sin/Cos	.1°	.05°	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
39	Fan Speed	XNL	E	X	X	X		X	X		X	Reluctance or Eddy Current Pickup	0.9 to 9K RPM	Variable Freq. & Ampl. Sine Wave	0%	0%	10K	↓	↓	←	—	Same	—	—	—	—	→	Increase Temperature Capability
40	Core Speed	XNH	E		X	X		X	X			Alternator Winding Output	1.6 to 16K RPM	4.5 to 105V RMS Sine 2440 Hz fs	Note 1	↓	↓	↓	↓	←	—	Same	—	—	—	—	→	
41	Fan IVG Torque Motor Current	BFTM	E			X	X		X			Permanent Magnet PWM EXC	200 Ma Peak 0 to Continuous	400 Hz Variable FW SQ Wave	3% FS	1% fs	500	↓	↓	←	—	Same	—	—	—	—	→	Ultimate Trend Toward Direct Drive Motors
42	Core IVG Torque Motor Current	BCTM	E			X	X		X			↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
43	A8 Torque Motor Current	A8TM	E			X	X		X			↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
44	Main Fuel Torque Motor Current	WF36TM	E			X	X		X			↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
45	A/B Fuel Torque Motor Current	WF6TM	E			X	X		X			↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
46	Humidity	HUM	E			X	X		X			Chemical Crystal	0 to 100%	Resistance Change	5%	2%	.05	↓	↓	Thermo-electric Quartz Crystal	Same	Variable Freq. at 100K Hz	2%	1%	10	Same	Same	

NOTE 1 - Accuracy and Repeatability are High Since the Interface Electronics Counts Pulses.

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3.3 Data Management Unit (DMU)

3.3.1 Functional Description

A functional block diagram of the Data Management Unit (DMU) is shown in Figure 3.3-1. This unit is primarily described in the Phase III report and the name has been changed from Analog Conversion Unit (ACU) to DMU to be more descriptive of its multiple functions. The sensor input signals are specified in Figure 3.2-2 and the output parameters are specified in the Sensor Matrix, Figure 3.2-4. There are a total of 40 output words of which 37 are engine parameters and three are spares (or BITE outputs). Signal preprocessing is accomplished by the ac and dc signal conditioning circuits and the vibration and temperature processing circuits. The signals are converted to a 0 to $\pm$ 5 volt level and applied to an analog multiplexer. A 40-channel analog multiplexer will provide for spares and BITE inputs. Four samples per second of each channel has been deemed sufficient for condition monitoring purposes. Therefore, the minimum channel conversion rate is 160 conversions per second. A conversion accuracy of 0.1% from multiplexer input to digital output will satisfy IEIS needs and presents no technological challenge. For ease of computer interface, the CMU will contain a small buffer memory of 40 words, thereby allowing block data transfers every 250 ms. The DMU will be mounted near or on the engine and will communicate with the IEIS data processor over the Data Bus. Low pass filters in the signal conditioning circuits will limit the signal bandwidth at the input of the multiplexer to two Hz.

A summary of the DMU characteristics is given in Figure 3.3-2. The device has adequate capacity to allow for expansion in the number of input channels, which would require a corresponding increase in buffer memory. The multiplexer settling time has been included in the calculation of channel capacity although the multipler could be switching to a new channel during the ADC conversion time. The sample and hold module would then be in the hold mode, and the multiplexer

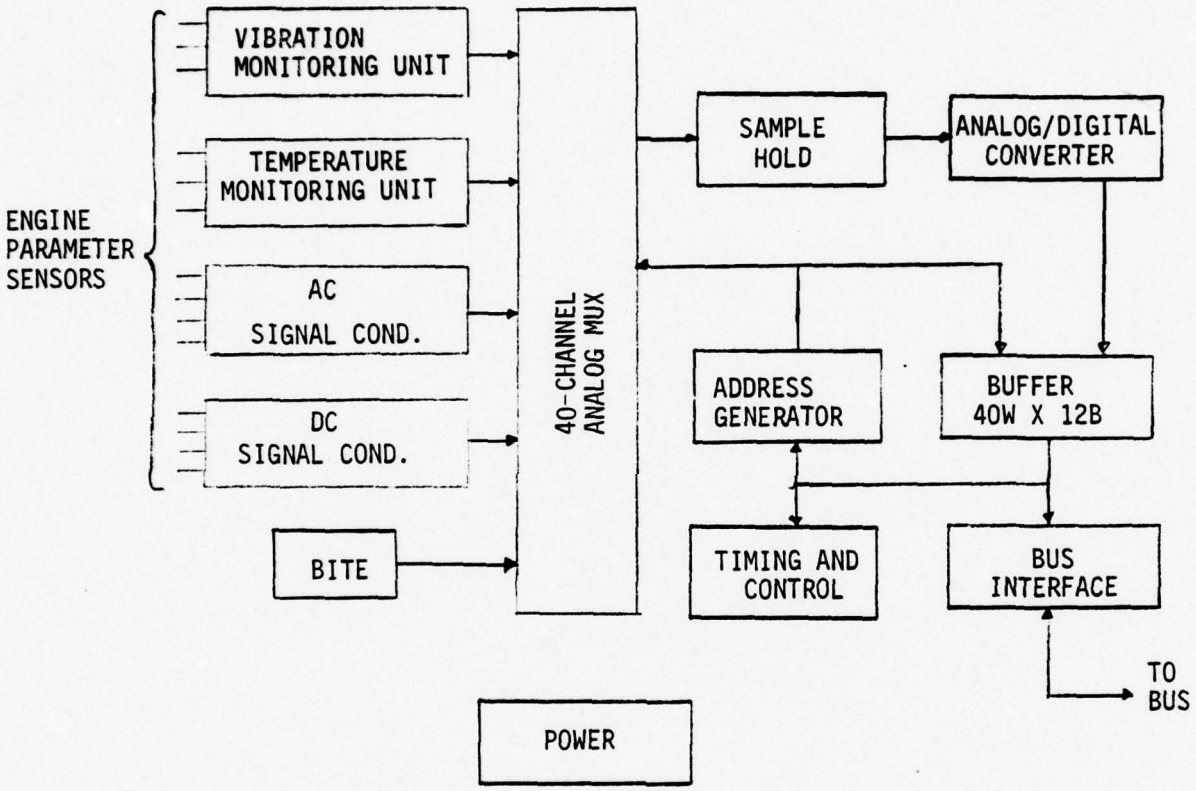

FIGURE 3.3-1 DATA MANAGEMENT UNIT

NO OF INPUT SIGNALS	40
ADC CONVERSION SPEED	200 μs
SAMPLE-HOLD ACQUISITION AND SETTLING TIME	5.5 μs
MULTIPLEXER SETTLING TIME	10 μs
CHANNEL CONVERSION TIME	216 μs
MAXIMUM CHANNEL CAPACITY	4.6K conversions/sec
SAMPLE-HOLD APERTURE TIME	40 ns
ADC RESOLUTION	12 bits
BUFFER MEMORY SIZE	40W x 12B
CHANNEL ACCURACY	0.10%

FIGURE 3.3-2 DMU CHARACTERISTICS

settling time would be transparent in channel operation. The memory buffer write cycle could be as long as the channel conversion time, with no loss of converted samples. That is, the buffer could be writing the last sample while the ADC processes another. The read cycle time will be dictated by the I/O bus transfer rate. For example, if the serial bus transfers data at a one MBPS rate, the read cycle must be less than 12 μs.

The buffer memory will facilitate information transfer to the computer. The intended mode of operation of the DMU will be sequential conversion of all input channels, followed by transmission to the computer. All input channels can be sampled and converted in 8.64 ms with the DMU characteristics assumed. This scheme will allow 241 milliseconds for data transmission, a process which should take no more than one millisecond at slow (100 kbps) bus speeds. Thus, the channel conversion speed could be reduced to six milliseconds while still maintaining an adequate data transmission margin. The buffer memory will allow the analog conversions to proceed at a leisurely pace while allowing a reasonable transmission speed.

The DMU can be configured with start and stop registers to facilitate data transmission and retry. That is, the block transfer command from the computer could contain a start and stop address so that only a portion of the buffer is transmitted. This capability would facilitate retry when only several words are questionable and the entire block is not needed. Alternatively, the buffer could be divided into halves or quarters so that the retry command would point to a specific set of words.

The Vibration Monitoring Unit analyzes the signals from accelerometers mounted near the engine bearings, and its operation is discussed more fully below. The Temperature Monitoring Unit processes the optical pyrometer output for additional information and is also discussed below. The ac and dc signal conditioning circuits provide the necessary analog buffering, scaling and ac to dc conversion. The low

pass filters with 2 Hz bandwidth are also placed here. These signal conditioning circuits provide a common output voltage range to the 40- channel analog multiplexer. The Built-In Test Equipment provides the self-test functions for the DMU. One common technique is to provide a stable test voltage of known value at the input to the multiplexer. The bus interface provides the necessary serial/parallel conversions, transmitter/receiver circuits, etc., for proper data transmission between the DMU and the IEIS data processor. The details of the DMU design can be found in Section 3.1.3.2 of the Phase III Final Report.

3.3.2 Preprocessing

In the ideal case, sensor signals would be digital or normalized analog signals and all of the processing necessary to derive the engine parameters would be accomplished in the IEIS data processor. This approach is the most efficient but because of economic and technical limitations in the proposed time frame certain sensor preprocessing is required. The ac and dc signals (Figure 3.2-4) must be detected, filtered (2 Hz), normalized to be compatible with the multiplexer input. The turbine blade temperature and accelerometer signals require more extensive preprocessing which is described in detail below.

Evaluation of the computer capacity required to perform these two functions digitally was conducted in Phase IV and it was concluded that it was not feasible. (See Sections 2.4.1 and 2.4.2 of the Phase IV Final Report.)

3.3.2.1 Vibration Monitoring

The VM circuit receives those signals and provides those outputs listed in Table 3.3-1. The VM circuit monitors the engine mounted accelerometer outputs and provides the analog processing to indicate FOD and bearing condition mass unbalance. The VMU employs multiplexing techniques whenever possible and requires interface with the fan and core speed sensors.

TABLE 3.3-1 - VMU INPUTS AND OUTPUTS

Parameter	Name	Range	Units
Inputs			
Vibration 1	Vib 1	0+500	G's
Vibration 2	Vib 2	0+500	G's
Outputs			
FOD Flag 1	FODF 1	On/Off	----
FOD Flag 2	FODF 2	On/Off	----
Bearing Condition 1	Brg 1	0+10	----
Bearing Condition 2	Brg 2	0+10	----
Mass Unbalance 1	MUM 1	0+10	MILS
Mass Unbalance 2	MUM 2	0+10	MILS

The high output impedance charge signals proportional to acceleration from the two engine mounted accelerometers are accepted by the VMU and converted to low impedance voltage signals by independent charge converters and voltage amplifiers. These amplifiers provide the initial buffering for subsequent multiplexing and further processing. A block diagram of the VMU is shown in Figure 3.3-3.

The Foreign Object Damage analysis section of the VMU provides continuous monitoring of each input vibration channel. This function cannot be time multiplexed due to the random nature of the phenomenon. The input signals are peak detected and then compared to a threshold to determine the presence or absence of FOD. The peak detector is automatically reset after an appropriate interval by the FOD flag to allow further FOD indications. This interval is determined by the downstream digital sampling rate. A minimum 250 ms delay is required by the present DMU-IEIS design.

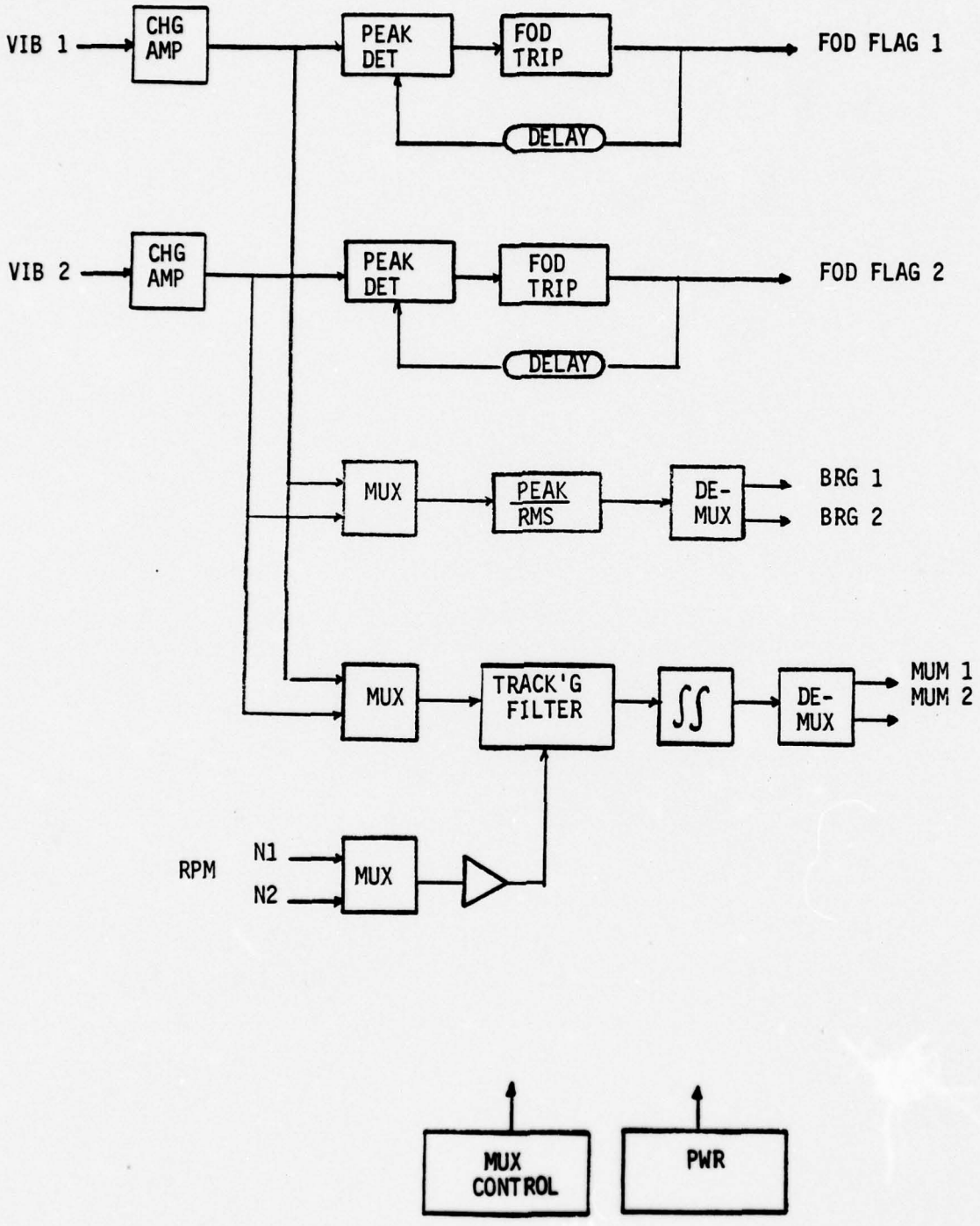

FIGURE 3.3-3 VMU BLOCK DIAGRAM

The bearing condition is determined using multiplexing techniques. The analog processing computes the acceleration signal Impact Index, a normalized dimensionless quantity. The value of this index is indicative of bearing condition. The Impact Index is a ratio of the peak value to the RMS value of the complex vibration signal. Normally, this Index is less than three.

The VMU contains multiplexed unbalance monitors for measuring the narrowband fan and core displacement. This displacement is determined by double integrating the multiplexed acceleration signals and filtering at the once/rev. frequency using narrowband tracking filters. These filters are tuned using synchronizing signals derived from the fan and core speed sensors. Only the vibration energy associated with the relevant fan and core speed is allowed to pass.

3.3.3 Analog To Digital Conversion (ADC)

Several different configurations of ADC were investigated and tradeoffs made to determine which is the most cost effective approach. The multiplexer, sample and hold and slow speed A/D converter configuration was selected. This circuitry is shown in the DMU functional block diagram, Figure 3.3-1.

The basic engine time constant -- several seconds from idle to take-off RPM -- governs most of the changes in parameters which IEIS monitors. In addition, trending and condition monitoring will only be performed at stable flight conditions. The sampling of each parameter is done at four samples/second. With 40 input signals, the required capacity of the DMU is 160 conversions/second which requires a conversion time of 6.25 ms. This channel conversion period is made up of multiplexer settling times, as well as the analog to digital conversion time. The conversion period for the proposed DMU is 216 micro-seconds and typical A/D converter and sample and hold specifications are shown in Figures 3.3-4 and 3.3-5 respectively. To meet this requirement the multiplexer delay must be 10 μsec. which is readily attainable. This circuitry will provide the 0.1% parameter accuracy requirement including both static and dynamic errors. The static error is estimated to be

Quantization Error	$\pm$ ½ LSB
Resolution	12 BITS
Linearity (@ 25°C)	$\pm$ ½ LSB
Gain Drift (0-70°C)	$\pm$ 7 ppm/C°
Offset Drift (0-70°C)	$\pm$ 2 ppm/C°
Linearity Drift (0-70°C)	$\pm$ 3 ppm/C°
Input Impedance	$10^8 \Omega$
Dynamic Signal Range	10 V
Conversion Speed	200 μS

FIGURE 3.3-4 - TYPICAL 12-BIT ADC PERFORMANCE SPECIFICATION

DYNAMIC RANGE	± 10 VOLTS
INPUT IMPEDANCE	10^8 OHMS
BIAS CURRENT	30 NA
GAIN DRIFT	± 20 μv/°C
OFFSET DRIFT	± 25 μv/°C
DROOP RATE	20 μv/MSEC (MAX)
DROOP RATE DRIFT	DOUBLES EVERY 10°C
APERTURE TIME	40 NS
ACQUISITION TIME	
10 v STEPS TO 0.005%	4 μs
20 v STEPS TO 0.005%	5 μs
DYNAMIC NON-LINEARITY @	
1000 us HOLD TIME	± 0.005% of 20 v
SETTLING TIME TO 1 MV	500 ns

FIGURE 3.3-5 TYPICAL SAMPLE-HOLD SPECIFICATIONS

0.059% which allows 0.041% for dynamic errors. The typical sample and hold circuit and A/D converter, and an analog multiplexer and signal conditioning amplifer, with combined output impedance of 1000 ohms were considered in arriving at the static error.

3.3.4 Data Bus

3.3.4.1 IEIS Data Transmission Requirements

Preliminary estimates of data rate requirements are given in Table 3.3-2. An 18- bit interface is indicated, although it may actually vary from subsystem to subsystem. The main conclusion to be drawn from this list is the very low transmission requirements placed on the IEIS processor interface.

The 18 kbps total data is a preliminary estimate and represents an average requirement. Display formats will be pointed to as subroutines by the IEIS processor. The display generator will contain its own Format and Parameter Tables and will provide the display refresh function. The Data Recorder will operate in a burst mode, recording approximately 70 parameter averages over a five-minute interval. The data recorder will not operate continuously but will record data on exception and at specified flight conditions. Similarly, inputs from A/C systems are not required continuously. Allowing a 100% margin in the total estimate still represents a relatively simple I/O traffic problem.

3.3.4.2 IEIS Data Bus Architecture

IEIS Data Transmission requirements are quite small in relation to the overall requirements of the information transfer system for the IEIS aircraft. IEIS is not self-sufficient in the sense that it must relay on other systems for data inputs and outputs. Thus, although there will be a "local" IEIS data bus, the system must eventually interface with "other" A/C data buses. The existence of "other" buses implies system integration at a level higher than IEIS, and the standardization of data bus interface for all A/C systems.

TABLE 3.3-2

IEIS DATA BUS TRANSMISSION REQUIREMENTS

SUBSYSTEM	NO. OF WORDS	BITS/ WORD	AVERAGE SAMPLE RATE (HZ)	TOTAL BITS (BPS)
DATA MANAGEMENT UNIT 1	40	18	4	2880
DATA MANAGEMENT UNIT 2	40	18	4	2880
ELECTRONIC ENGINE CONTROL 1	20	18	4	1440
ELECTRONIC ENGINE CONTROL 2	20	18	4	1440
A/C INTERFACE	211	18	4	1512
KEYBOARD	1	18	4	72
IEIS DISPLAY	100	18	4	7200
DATA RECORDER	130	18	.5	1170
MAINTENANCE DISPLAY	1	18	.1	2
				18596

IEIS consists of the Computer, Display and Keyboard, Data Management Units, Maintenance Status Indicator and Data Recorder. The other A/C systems of Figure 2.1-1 are on "other" buses. The IEIS Data Bus architecture would probably conform to the MIL-E-XXX Data Bus (similar to MIL-STD-1553) specification command response configuration (see Figure 3.3-6). This bus architecture will more than adequately meet the data transmission requirements and a block diagram is shown in Figure 3.3-6. Bus control would reside in the IEIS processor with remote terminals in IEIS subsystem units. The computer would communicate with each unit and other aircraft systems. The modulation scheme will be the Manchester code which has self-clocking ability and easy bus interface. The transmission media will be shielded twisted pair, unless the problems of fiber optics are overcome and its capabilities are demonstrated. The bus would operate in a bit serial, word serial fashion. The time division multiplexed system would operate at base-band with a one MBPS bit rate. This is more than adequate for IEIS needs.

3.4 Data Processing

3.4.1 IEIS Software Definition

3.4.1.1 Software Requirements

Preliminary functional requirements of Engine Monitoring Computer Program (EMP) were established during Phase III in sufficient detail to provide a basis for estimating the data processor memory capacity processor utilization (based on 1MOPS machine) necessary to implement the IEIS system. During Phase IV these requirements were reviewed and estimates of memory capacity and processor utilization were revised based on projected improved efficiency of the program and use of the All Applications Digital Computer (AADC).

The major functions of the EMP Program are to sample appropriate input signals at an adequate rate to determine unambiguously the present engine use condition among the following possible modes:

- Pre-Start
- Start
- In-Use
- Shutdown

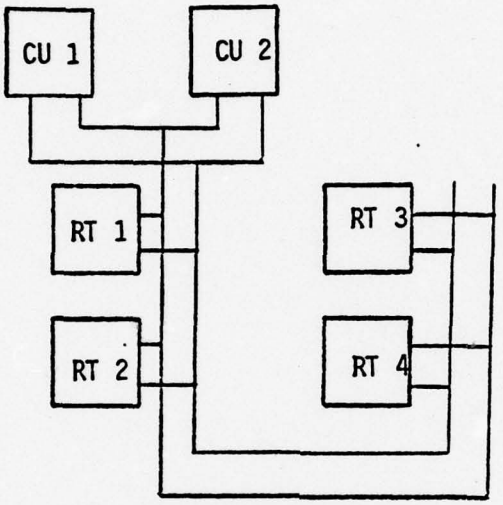

FIGURE 3.3-6 COMMAND RESPONSE DATA BUS

For each mode, the program must perform, at appropriate rates, all the actions needed to maintain a routinely required display, compare measured engine operating parameters against model-predicted values, record parameters useful for long-term engine performance prediction (by ground analysis), perform short-term engine performance trend analysis, generate special displays if engine abnormalities are evident either immediately or from short-term trend analysis, maintain engine performance records, respond to crew initiated requests for display of selected data and results concerning engine performance or energy management predictions, perform readiness and self-test checks on the hardware elements of the IEI System (including the computer itself) and to initiate appropriate corrective actions whenever faulty operation is detected.

3.4.1.2 Summary of Software Elements

A preliminary definition of the software elements needed to satisfy the requirement defined above was accomplished during Phase III. The operational IEIS software elements are identified in this section by English language flow charts and flow chart descriptions for each phase of engine operation. A more detailed definition of the software elements is contained in Section 4.3.7 of the Final Report Phase III.

3.4.1.2.1 Pre-Start Operational Software

The IEIS pre-start operational software is flow charted in Figure 3.4-1. Entry to this segment of the operational program results from the power-on start of the computer system. Self-test of the IEIS is accomplished first. System reconfiguration to by-pass detected faults is accomplished, if needed, by sharing non-IEIS resources as follows:

- Within the AADC System for processor/recorder or memory faults
- Within the AIDS for display faults
- Within the Data Bus System for data transmission faults
- By modification of the linkage table for the engine model subroutines for sensor faults

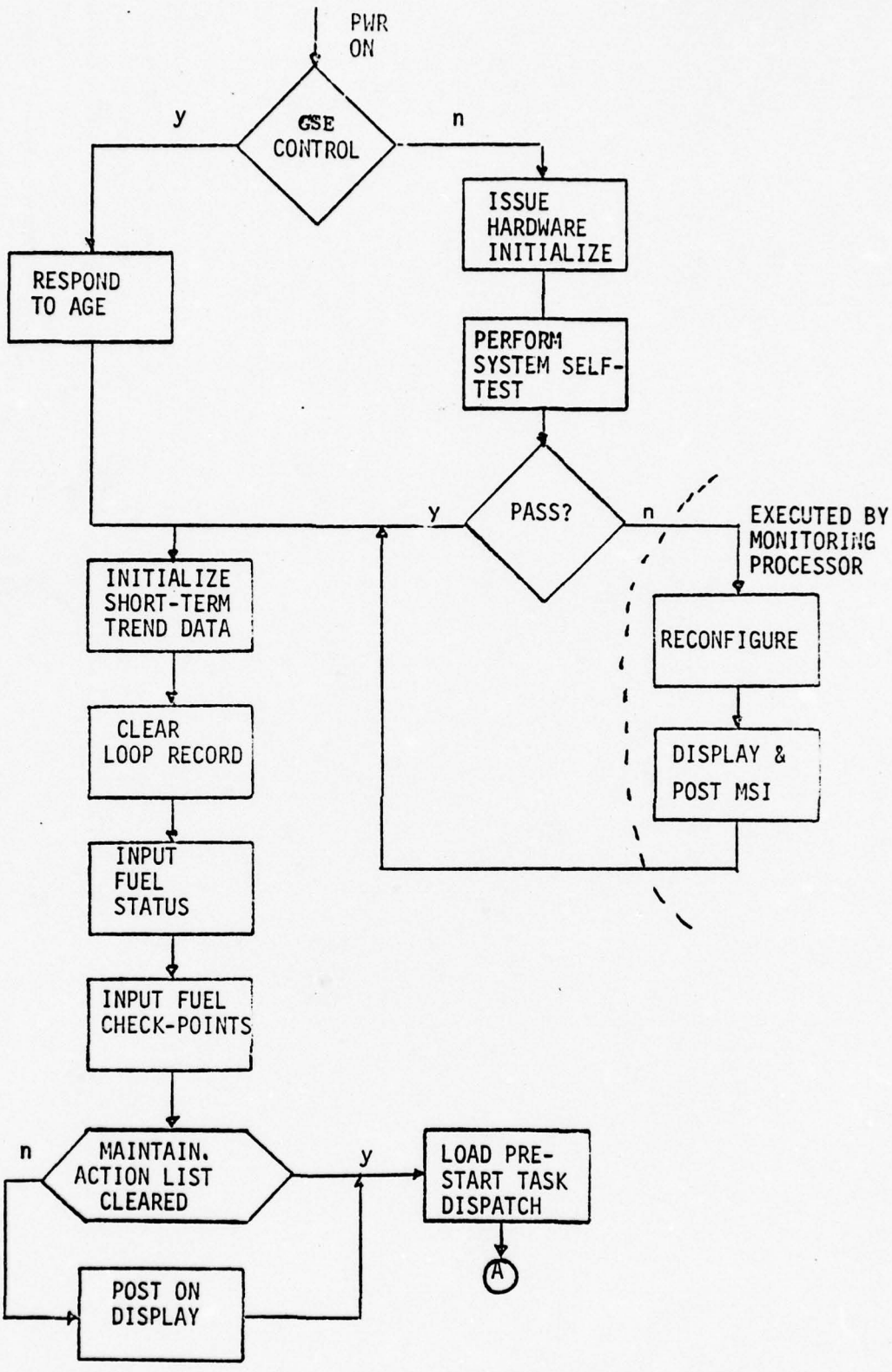

FIGURE 3.4-1 PRE-START FLOW DIAGRAM

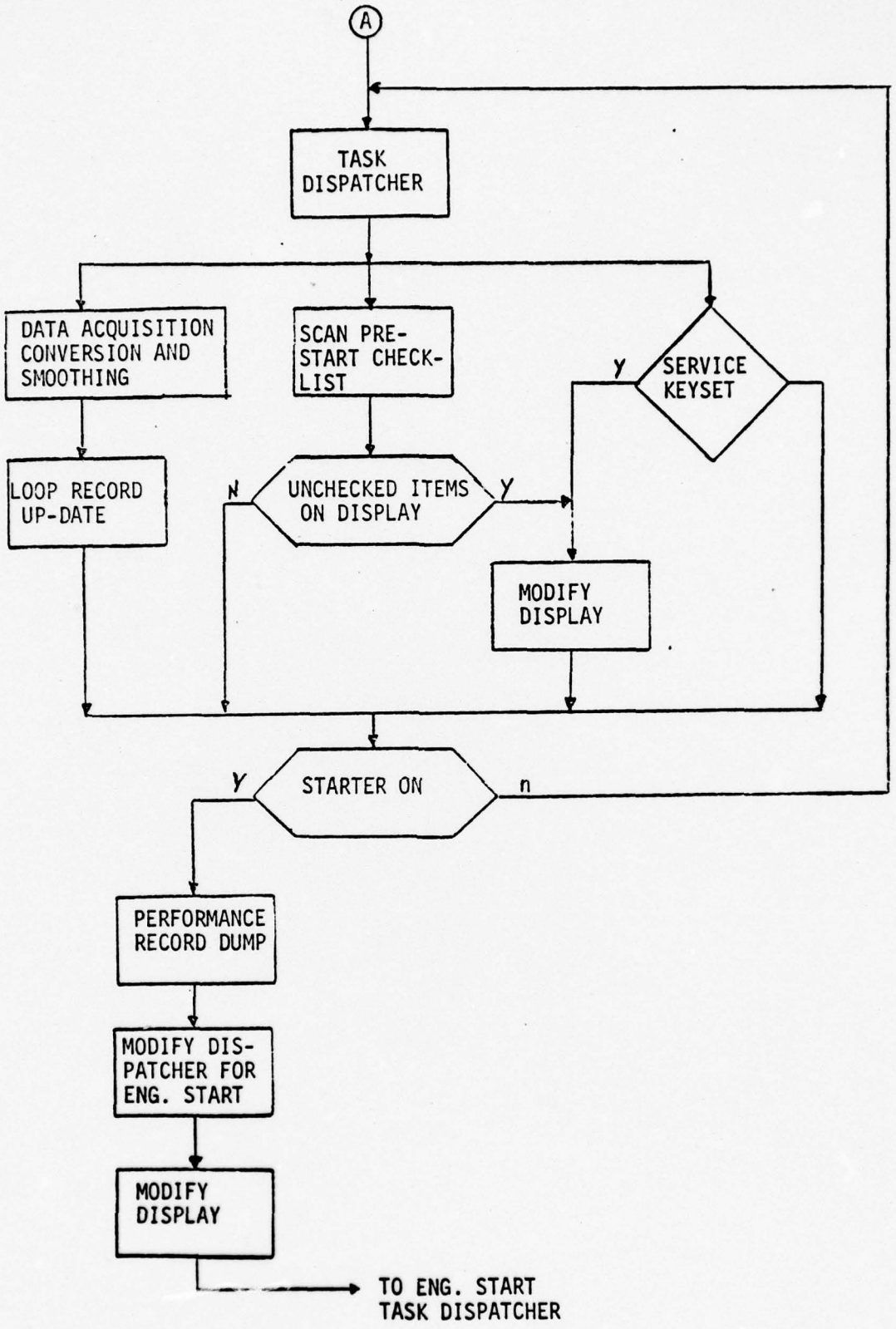

FIGURE 3.4-1 PRE-START FLOW DIAGRAM (Cont'd)

Once the IEIS is found to be operational, initialization of data tables for the following is accomplished:

- Short-term trending records
- Loop record
- Pre-flight fuel consumption schedule

A check for uncleared MSI flags is made and a warning is displayed if any flags are found. The operating system for scheduling the iterative tasks during pre-start is then loaded and control transferred to it.

Iterative tasks are limited to the following:

- Reading current values of all engine sensors and posting these as the first (and only) entry in the loop record.
- Scanning the entire pre-start engine check-list and displaying all unsatisfied entries.
- Responding to pilot keyset requests for display sensor data.

Each iterative task is followed by a step to test the signal indicating application of starter power.

Once the application of starter power is sensed, the current loop record data set is transferred to the recorder as the first (pre-start) performance record. The pre-start display is replaced with the identifiers for the parameters displayed during engine start and control is transferred to the engine start routine.

3.4.1.2.2 Engine Start Software

The flow-chart of the software executed during engine start is shown on Figure 3.4-2.

The process is a single iterative task composed of data collection from all engine sensors and cumulative time of attempted start. This data is preserved as a loop record. In addition the current values of the following are displayed:

- Core RPM
- Fan RPM

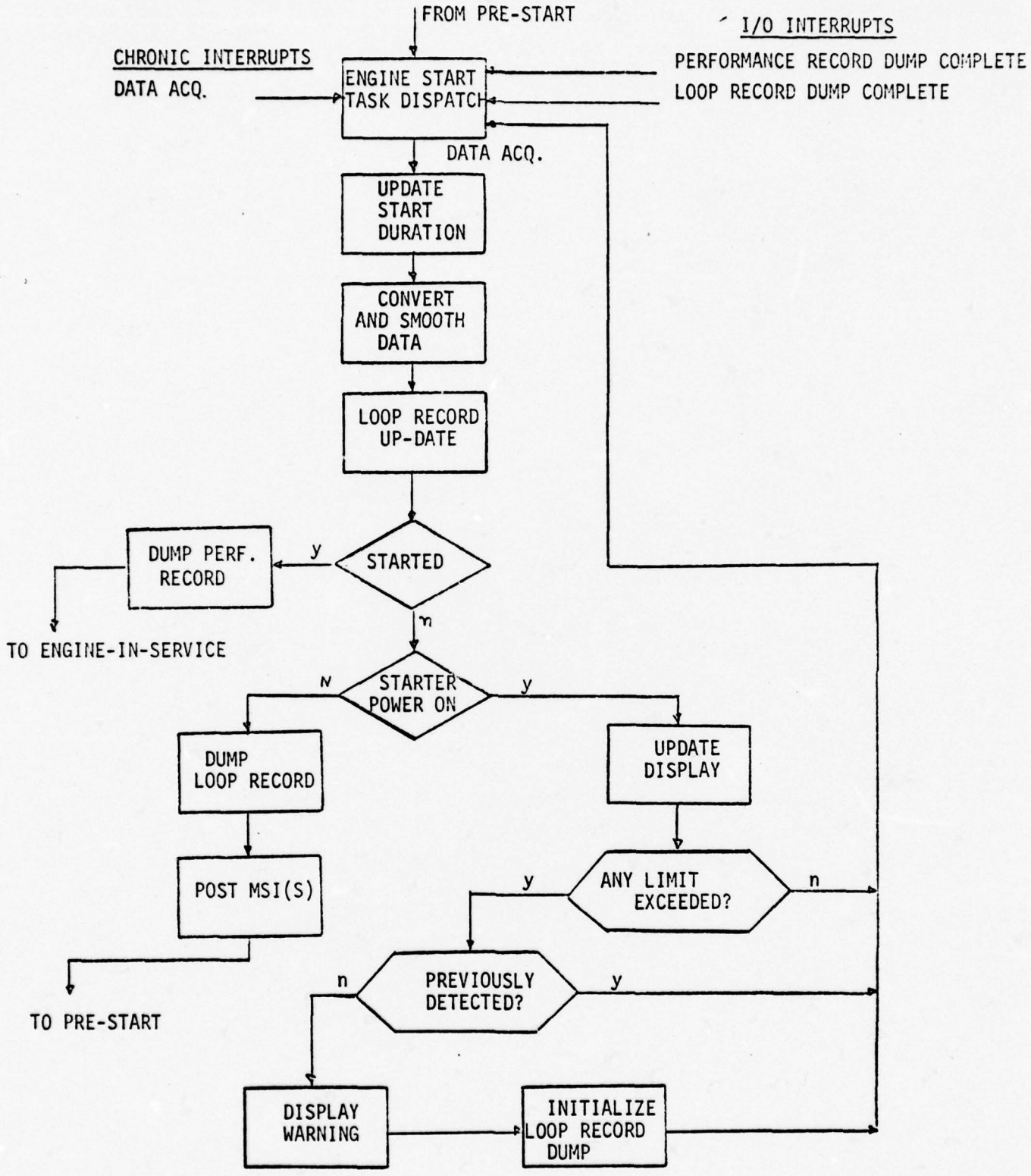

FIGURE 3.4-2 ENGINE-START FLOW CHART

- Turbine Blade Temperature
- Ignition Input
- Lube and Fuel Flow
- Elapsed Start Time

Further out-of-limits checks are made on the following parameters:

- Fuel-Flow
- Ignition Input
- Lube Pressures
- Lube Flows
- Elapsed Start Time

If any parameters are out-of-limit, a warning display is produced and the loop record dump is commenced. The condition for successful start (core speed exceeds a threshold value) is monitored as well as the continuation of starter power. If starter power is removed without a start having been achieved or if abnormal temperatures are reached at start, the loop data record is made available for external analysis and the corresponding MSI flags are set. Control is returned to the pre-start program. If a normal start is achieved, a performance record is transferred to the recorder. This record is augmented by the time-to-start datum and is identified by a unique header. Program control in this case is transferred to the Engine-in-Service Program.

3.4.1.2.3 Engine-In-Service Software

A flow chart representation of the computational tasks performed while an engine is in service is shown as Figure 3.4-3.

The principal routines are the following:

- Sensor data processing scheduled every second
- Fuel status check — Irregularly scheduled on basis of elapsed flight time only
- Performance record — Scheduled approximately each 1/20 of planned flight duration plus interrupt on take-off

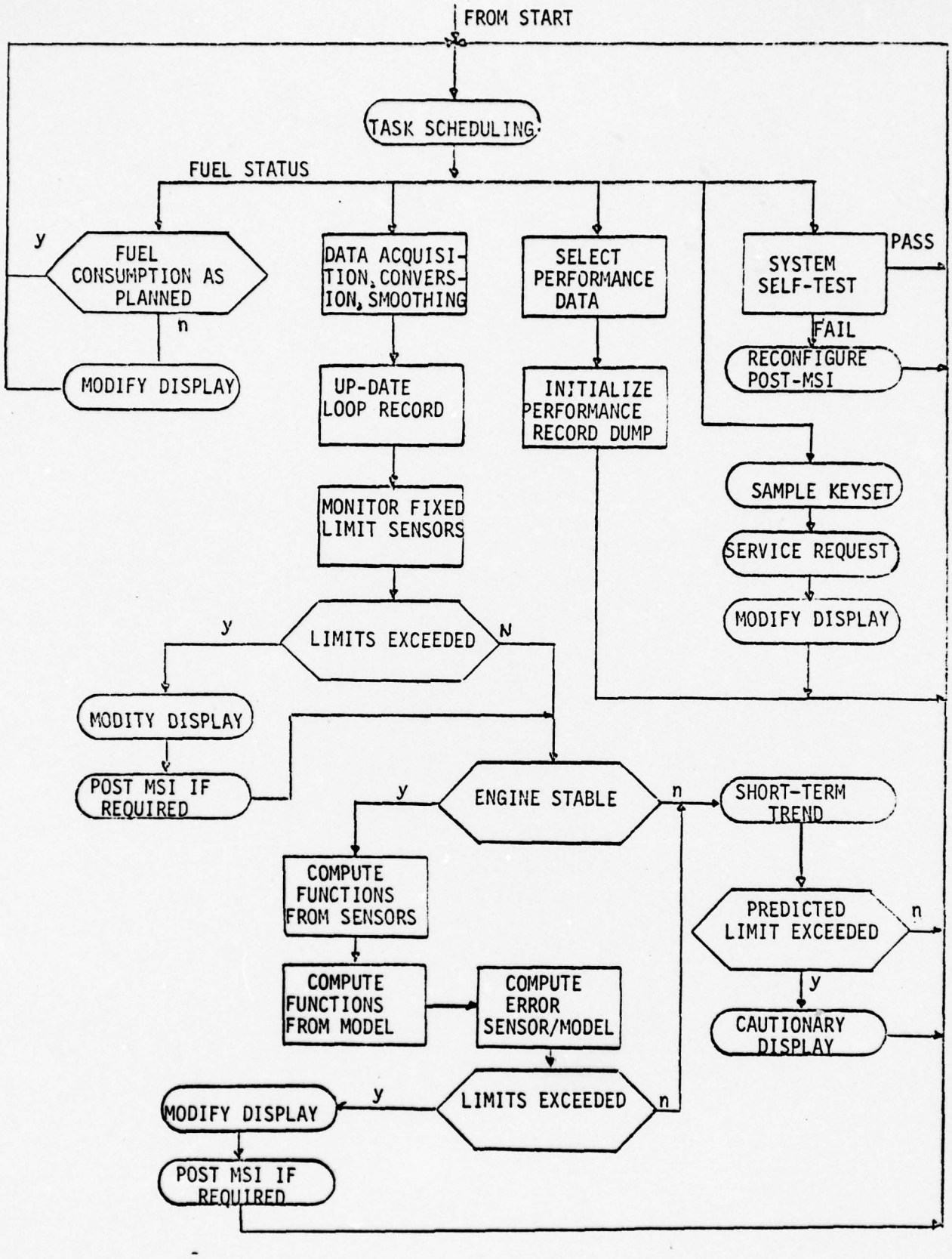

FIGURE 3.4-3 ENGINE-IN-SERVICE SOFTWARE

- Sample keyset requests — Interrupt, generated unpredictably
- System Self-Test — Background-run only if no other purpose is required

Sensor Data Processing

Sensor data processing commences once each two seconds when the data acquisition equipment has obtained four samples from each of the engine sensors and has stored these in digital form. The first operation is to convert the stored number to the value representing the original physical variable measured in the appropriate units. This operation generally involves correction of bias errors and multiplication by a scale factor. More elaborate calibration curve corrections are needed in some instances. The mean and deviation of the four measurements are then computed for each sensor. Checks for hard failure of a sensor and the computation of the deviation in the samples constitute a continuous operation monitoring of the sensor. The mean of the four samples is stored in the computer memory as the entry in the loop record for the measurement for the current one-second interval.

The fuel quantity and fuel flow rate measurements are combined in accord with a suitable smoothing procedure to form the best estimate of fuel remaining.

The current rate-of-change of the engine model "trigger" input variables (over the three-minute period spanned by the loop record) are computed and stored for later use if needed in selecting the best data set for permanent recording as part of the engine performance and long-term trending record.

Those measurements that can be compared against fixed limits are then checked for limit exceedance. Foreign object damage flags, air bleed rates, mass unbalance measurements fall in this category.

If a limit has been exceeded, then the corresponding changes to the maintenance status display and the pilot's display are made.

Next, the conditions for stable engine operation are checked. Stable engine operation requires that the rate of change of the following "trigger" parameter are near zero:

- Fan Speed
- Inlet Total Temperature
- Inlet Total Pressure

Also, fan speed must be above idle. If operating conditions are stable, the programmed engine model is run whenever a significant change in its trigger (input) variables has occurred. The outputs of this programmed model are the numerical values of sensor parameters (and quantities directly derivable from them) that an average engine would have had when new and operated under identical input conditions.

The relative errors between sensor readings (or data derived from sensor readings) and the corresponding output of the engine model are then computed. If these relative errors exceed their respective assigned limits, the corresponding display changes and advisories are made and the MSI record posted.

In the event that the engine ingests rain, sleet or snow, a number of gas-path parameters will simultaneously show out-of-limit behavior. The characteristic pattern of these apparent failures is recognizable. Hence, the occurence of any one of them will not result in display changes and loop record dump until a programmed check is made.

The final operation is to update the extrapolation of those parameters that are subject to short-term trending. If the extrapolated value (three minutes ahead) lies outside of acceptable limits, a cautionary display of a predicted out-of-limit condition is made. Short-term trended variables include the mass-unbalance and vibration signals.

Status Check

The flight plan check-points for fuel expenditure trigger the programmed fuel status check. The comparison between predicted and actual fuel consumption is made and the result displayed for a sufficient interval to insure pilot attention.

Performance Record

Each entry in the performance record of an engine consists of a full set of averaged sensor readings and a record-leader identifying the time, position, and flight conditions at which the record was made.

One such entry is made for each engine on each flight using the data set containing the highest value of turbine blade temperature from among those observed during the three minutes preceding and the one minute following the sensing of take-off. Take-off is sensed by load relief on the landing gear or support structure, in the VTOL case.

An additional entry is made whenever the one-minute least-squares estimate of the rate of change of the stability criteria first reaches a sufficiently small value. Each two minutes thereafter, so long as the stability criteria remains satisfied, another entry is made.

At the end of each period equal to one-twentieth of the planned flight time, an examination is made to determine the current number of flight performance records stored. If fewer than N+2 entries have been made, where N is the number of periods, a new data set from among the 90 sets stored as the loop record is entered. Selection of the set to be entered is determined by checking stability parameters. The set with the smallest deviations from stability is chosen.

System Self-Test

When scheduling conditions are such that no predictable task will be required within the run-time-interval of the IEIS self-test, the self-test program is run.

The program tests the Data Management Unit and its communication pathway, processor arithmetic and logic operations, processor memory (sampled), recorder electronics and status, and outputs from some regions of the display surface.

3.4.1.2.4 Engine Shutdown Software

A flow-diagram of the software procedure following detection of engine shutdown is shown as Figure 3.4-4.

If the shutdown occurs while air-borne, a display of the data required to judge the feasibility and safety of air-restart is presented. Then parameters indicative of successful re-start are monitored and if restart occurs, program control is returned to the engine-in-service procedure. If the restart is unsuccessful, normal engine shutdown procedures are performed when the aircraft is landed. Engine component service time records are updated as a part of the normal shutdown. Program control is then transferred to the pre-start routine.

3.4.2 IEIS Computer

3.4.2.1 IEIS Computer Requirements

Based on the software definition, initial estimates of the computer requirements to implement the IEIS operational system were made during Phase III. The processing time to accomplish the software tasks were estimated on the basis that certain hardware features were available.

The software performance numbers are based on the following assumptions: the basic CPU performs dyadic operations at the same rate as monadic functions (i.e. the processor has more than one data transfer path to the arithmetic unit); shift operations are "one-pass" regardless of length; floating point hardware permits maximum parallelism in execution of floating point add/subtract/multiply/divide; fixed-point multiply and divide are performed at least two-bits per microstep; exponential/log operations are hardware aided such that one bit of result is produced for each two microsteps; bit and byte addressing of memory and registers

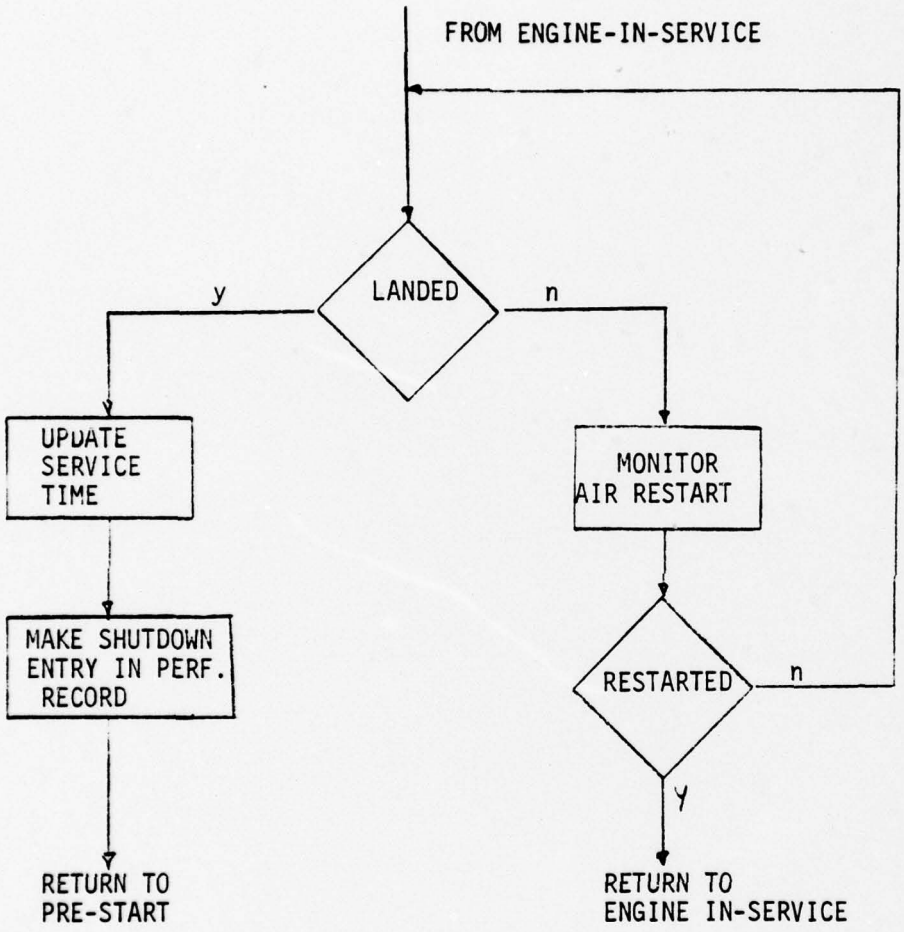

FIGURE 3.4-4 ENGINE SHUT-DOWN SOFTWARE

provided; concurrent I/O control operations are performed with single word memory access for each word transferred (i.e. the I/O processor has sufficient local storage for its bookkeeping operations); interrupt processing and priority level detection is hardware aided to the extent that transfer from the interrupt routine to a higher priority interrupt routine or return to main line is accomplished in a single average instruction execution time and hardware means exist to generate "chronic" interrupts. The effects on software execution time of not having these computer hardware fixtures will have to be assessed when the hardware fixtures are identified.

The memory requirements were estimated in terms of program storage and working storage. This approach was taken to better define the type as well as the amount of memory required. Program storage will require non-volatile type memory so that programs are retained permanently. Types of non-volatile memories to be considered for application in IEIS include the following:

- MNOS
- Plated Wire
- Core
- Closed Flux Memory
- Semiconductor ROM

Memory access times should be consistent with the processor speed requirement and the memory hierarchy employed in the computer. The processor accuracy requirements can be met by a 32 bit word.

A summary of the processing time and memory requirements is shown in Figure 3.4-5. There are two estimates. One is based on a dedicated IMPOS computer and assumes a constant memory access time for program and working storage. The other estimate is based on the 2 MOPS AADC configuration. The non-volitale Bulk Oriented Random Access Memory (BORAM) for the AADC is page oriented with 256 words/page

	PROGRAM STORAGE WORDS (K)	PROGRAM STORAGE BORAM PAGES	RAMM WORKING STORAGE PER ENGINE (WORDS)	EVALUATION TIME (MS) A	EVALUATION TIME (MS) B	EXECUTION INTERVAL (SEC.)	UTILIZATION (%) A	UTILIZATION (%) B
TASK DISPATCHER	.75	3	100	.05	.18	.05	.100	.360
INPUT LIST			560	NE				
DATA CONVERSION	.25	1		19	.12	.25	.040	.048
LOOP RECORD			6300	NE				
ENGINE MODEL	13.5	54	65	400	292	60	.667	.487
LUBE MODEL (FLUID)	3.5	14	50	40	25	60	.067	.042
LUBE MODEL (PRESS.)	6	24	50	280	192	60	.467	.320
FUEL MANAGEMENT	1	4	25	.9	.5	1	.090	.050
DISPLAY SCENE BASE	.5	2		NE				
DISPLAY FEATURE SELECT	1	4	100	.1	.27	.5	.025	.054
DISPLAY EDITOR	.5	2	1000	.4	.23	1	.040	.023
MAINTENANCE RECORD	.25	1	200	.05	.09	300	.000	.000
SELF TEST	.25	1		3	.1	2	.150	.005
SUB-TOTAL	27.5	110	8450				1.546%	1.257%

TOTAL = 27,500 + 2 (8.25) = 44K (K = 1024 WORDS)

NE = NOT EXECUTED

A = 1 MOPS MACHINE

B = AADC MACHINE

FIGURE 3.4-5 - IEIS RESOURCE REQUIREMENTS

and page transfer times are significant for short programs. This characteristic partially accounts for the ratio of processing times not being equal to the ratio of operating speeds (2:1). Other differences should be also noted. The Self Test feature is more extensive for the 1 MOPS machine because the complete system is tested. The AADC estimates assume that the self-test is accomplished by a higher level system computer.

3.4.2.2 Computer Characteristics

Rapid Interrupt Response

The IEIS software is directed to perform the most urgent task ready at any instant by hardware interrupts. The programming burden that interrupt service imposes is, in general, the following:

Preserve the current state of the machine so that it can resume the interrupted routine at a later time; and condition the I/O interrupt enables so that the interrupting routine may itself be interrupted only by routines of higher priority than its own.

The first of these tasks can be accomplished by non-interruptable hardware or microprogram transfer of the contents of all central registers, the current state of the I/O interrupt register and its enabling mask and the machine status register and instruction address to a set of reserved memory locations. Such a solution is not without problems. For example, if the reserved locations serve all levels of interrupts, the interrupting routine must run interrupt insensitive until it can transfer the contents of the reserved locations to some other place in memory. Otherwise, the return data may be overwritten by a second interrupt. A somewhat better solution is to reserve a set of memory locations for each interrupt and have the hardware or a microprogram do the safe store upon recognition of an interrupt. An ideal solution would be to have completely separate sets of central registers or

push-down stacks for every level of interrupt. Then, when an interrupt is recognized, a base register is changed to point to the set serving the interrupting routine while the register set serving the interrupted routine is simply abandoned as is, but ready for return to use at any time.

The second task, conditioning the I/O state in a way suitable for the interrupting routine, can be a simple hardware or microprogram action requiring one more reserved memory location. Surprisingly, few machines have this feature. A rather awkward and dangerous substitute is to grant (by hardware) freedom from interruption of the first instruction following recognition of an interrupt or alteration of the interrupt enable state.

Without efficient hardware aid in interrupt transfers, otherwise high speed machines may suffer 50-100 μs software overhead delays in responding to interrupts and thus be seriously impaired in real-time applications like IEIS.

Chronic Interrupt Generation

The IEIS software requires a number of periodic interrupts of various periods. Hardware clocks can be provided to handle a few such interrupts by having separate registers and compare logic for each of them. When there is a need for several such interrupts, the temptation to share the comparison logic becomes quite high. An associative memory performing a "less than" search against the real-time clock each time it changes state would be one possibility. Another would be to obtain the same effect by completely rotating a hardware shift-register and comparing each stage of it against the clock whenever the clock changes its count. A third alternative which would not require special hardware but which would be quite helpful is to include a machine language instruction as follows:

> Decrement memory and transfer if zero, replace on transfer from next memory location.

In the absence of such an instruction, the supervisory program has to execute a subroutine which, in the worst case, could be the nine following instructions:

STORE	Register-to-Memory (to make register available)
LOAD	Register-from-Memory (current "clock" reading)
DECREMENT	Register
TRANSFER ON ZERO	to A
STORE	Register (updated to clock location)
LOAD	Register-from-Memory (to restore original contents)
A LOAD	Register (interrupt period)
STORE	Register (to clock location)
LOAD	Register (to restore original contents)

Such an instruction would also be useful in setting up control of fixed-number-of-iteration loops in a program.

Monadic Operations On Memory

IEIS programs, in common with practically all others, can save an overhead pair of register (safe-store and recover) instructions if all monadic operations can be performed on any memory location by microprogram use of central registers that are not accessible to the normal program. A fairly complete set of monadic operations are the following:

- Logical Invert
- Arithmetic Complement
- Absolute Value
- Normalize
- Shift (All Variations)
- Increment
- Decrement
- Convert Fix-to-Float
- Convert Float-to-Fix
- Square
- Square Root

Single Pass Shifting

In a floating point machine which performs shift operations in a time proportional to the length of the shift, the time required to perform additions and subtractions becomes indeterminate. Hence, the only way to establish the running times of arithmetic subroutines is by statistical methods. In the IEIS case, as for most other real-time systems, the possibility of having extreme running times for some subroutines leads to the possibility of scheduling difficulties and occasional system blow-ups. If the machine is equipped with the hardware needed to perform shifts in a single operation, instruction execution times become determinate and precisely predictable. Data independent instruction execution times are highly desirable, if not mandatory, for good system design and single pass shifting is a sine-qua-non to reach this goal in a floating point arithmetic machine.

Hardware (Firmware) Library Functions

Library subroutines normally encompass the most frequently used functions of analysis. A typical set includes the following:

- X^Y
- Sin X
- Cos X
- Tan^{-1} X
- Cosh X
- Sinh X
- $Tanh^{-1}$ X
- e^x
- Ln (X)
- $\sqrt{X^2 + Y^2}$
- $\sqrt{X}$

The trigonometric functions are of special importance to IEIS since certain multidimensional look-up tables could be replaced by multidimensional Fourier series approximations if high speed evaluations of the trigonometric functions were available.

The functions of the form X^Y are valuable in any model of thermodynamic processes.

The generalized multiply operation of J. Meggitt provides an algorithm for evaluating these functions in a digit-by-digit fashion well suited to special purpose hardware implementation or microprogramming. Another implementation possibility is microprogrammed evaluation of Chebychev polynomial approximations for these functions. Which approach is better depends upon machine capabilities. A fast shift network generally predisposes one to choose the Meggitt algorithm.

A special problem occurs with a system required to produce a numerical display. The human user needs the data presented to him in decimal form. The machine has numbers in a base two floating point form. Conversion from machine floating point to a sequence of ASCII coded decimal digits is a time-consuming editing function when done by normal software means. The desirability of a firmware aid in this chore should be examined.

Loop Indexing

A large part of the IEIS Program involves the performance of a small subroutine on each element of a list of data. The machine language program can be significantly reduced by an index manipulating instruction that steps the index, tests it for completion and returns control to the top of the loop if runout has not occurred and proceeds otherwise. The typical machine program would read as follows:

Add to index from memory	(Add the step increment)
Compare with memory	(Compare loop limit)
Transfer on not greater to top of loop	

The entire process can be specified by a single instruction with a field to designate the index register to be operated upon and a memory address field to point to the first of a three-word sequence which stores in order the step size, the stopping

value of the index, and the address for the first instruction in the range of the loop. Microprogramming of the process saves two instruction fetches and gives at least a three-to-one improvement in program compactness. A variation of this instruction for a step size of unity (the most frequent case) would require only two memory locations.

Subroutine Linkage Instructions

The IEIS Programs, as is true for most large programs, must be written with free standing, re-entrant, pure procedure subroutines which can be called by a variety of using programs or linked in different sequences as required. When a subroutine can be called by a multiplicity of using programs, the following technical problems must be solved:

- A mechanism must be provided so that once the called subroutine is executed, control can be returned to the correct using routine.
- A mechanism must be provided for the using routine to transfer all the needed starting arguments to the called routine.
- A mechanism must be provided for the using routine to obtain the results generated by the called routine.
- A mechanism must be provided to prevent interruption of the called subroutine by a program which will call the same subroutine, or else conventions must be made about locating the input and output lists so that such re-entry is harmless.
- Finally, conventions must provide a clear understanding as to which registers the called subroutine may use and those which it must not alter.

The extent to which automatic machine aids are given to the solutions to these problems must be limited to the absolute minimum. If complex machine aids are given, they inevitably lead to more programmer problems than they solve. The minimum usable solution is the existence of a "subroutine transfer" instruction which stores the return word at a location specified by the contents of a particular register, say R1, and transfers control to the first instruction of the called subroutine (specified in the address field of the transfer instruction).

The calling program must previously have stored the subroutine input data at locations (R1) + 1, (R1) + 2, ..., (R1) + K.

The called subroutine is written to access its input data relative to (R1) and to store its output data relative to (R1) commencing with an additional offset of K. The called subroutine is terminated with a return instruction whose effect is to transfer control to the instruction addressed indirectly via R1 and to restore machine status from the non-address field portion of the word at R1.

With these two instructions and the associated programming conventions it is entirely possible to have the called subroutine interrupted by an entirely different program which later calls the same subroutines. The interrupting program must, or course, safestore R1 prior to using it as the link to the different region of memory which it uses for communication with the subroutine.

Memory Relocation Aids

The IEIS software is structured subject to the assumption that the computer system includes an "independent" I/O controller whose function is to attend to the step-by-step minutiae involved in transferring lists of data from computer memory to or from the peripheral subsystems. One capability that could be incorporated into the design of such a controller and which would be advantageous to IEIS (or any system with alphanumeric display requirements) is the ability to perform autonomous scatter-gather operations. In the IEIS context, the problem arises in connection with operator generated requests for display of specific parameters. The sequence in which such requests are generated is completely unpredictable. Thus, at the end of each data acquisition cycle, it is necessary to gather the current values of a subset of the instrument data scattered in a random way throughout the list of input data, and output these to the display system in a suitably edited format.

The main program can attend to such operator generated requests by simply entering them in a "numeric request list." The bookkeeping would involve a record of where the end of the list is in memory. On new requests this record is augmented and the new request stored as a pointer to its position in the loop-record. (A permanent table translating operator request codes to parameter position in the loop record is required for this purpose.) On erase requests, the corresponding item is deleted from the list. The last item in the list is transferred to the vacated position and the list length record decremented.

When the displayed numeric is to be updated, the I/O routine can now index its way through the "numeric request list" but use the entries therein as indirect references to the parameter value list in the loop-record. The request code must also be used as the pointer to a "header" list to generate the identifier text for the display and take account of the effect its length imposes on the x-coordinate of the displayed numeric.

The important feature is that the I/O controller should be able to interpret a variety of address modifications rather than the customary index from a specified base.

If, as is most likely, the entire IEIS Programs and data cannot all be simultaneously in main core, supervisory control will frequently encounter the overlay problem. This involves transfer of parts of the program currently needed but presently available only in external storage, into main-core, thus displacing some part of the program presently resident in core but (hopefully) not immediately needed. This problem is somewhat eased by permitting only block transfers of fixed, uniform size. Such block-oriented transfers can be inefficient if the transferred segment occupies only a fraction of the block. It would, occasionally, be desirable to combine the contents of two or more partially occupied blocks. This involves a memory-to-memory relocation of a segment. Rather than perform this operation word-by-word, using the supervisor program running in the CPU, it would be desirable to assign the actual moving to the I/O controller and allow the process to be completed while the CPU is free to perform more productive tasks.

Micro-Diagnostics

It has been pointed out elsewhere that the ability of a microprogrammed machine to perform diagnostic or readiness tests at the microprogram level shrinks the untestable hard core from roughly 75 percent to two percent.

Microstep Maintenance Aids

We have found that mean time to diagnose a computer malfunction can be drastically reduced if the maintenance technician has at his disposal the ability to cause the machine to advance through the execution of any instruction on a micro-step by micro-step basis with the entire machine state displayed following each step.

I/O Echo Checks

Periodic on-line test of the integrity of data transfers is greatly enhanced and maintenance diagnosis facilitated if the I/O controller can be directed to repeat (echo) the data transferred to it. Similar benefits accrue if transfers from I/O controller to device controller can be similarly checked.

Continuous I/O Error Check

Continuous check of data integrity is possible if all I/O transfers have parity generation/checking. Limited error correcting capability is possible if orthognal (bit column) parity is generated/checked on all multiword transfers. These features are testable only if the machine has a special instruction to transmit words with erroneous parity.

I/O Transfer Emulation

Software diagnosis is facilitated if the I/O controller is able to send and also to receive and check "canned" test words (with and without correct parity).

I/O Interrupt Emulation

Software test of the machine's response to I/O interrupts is not possible unless instructions are available to generate artificial interrupts.

3.4.2.2.1 Comparison of Computers

In the following table, we compare an older machine, two representative contemporary machines and an advanced machine relative to the foregoing list of desirable attributes and some other features elsewhere identified as desirable or essential to the IEIS application. The old machine is represented by the CP 901/ASQ-114, a Navy inventory machine manufactured by Univac. Contemporary machines are represented by the 1602 Rugged Nova manufactured by ROLM Corporation and the CP-32 manufactured by General Electric. The advanced machine is represented by the AADC processing element which is currently in advanced planning stages by Raytheon Company. The known computer characteristics are compared in Table 3.4-1.

3.4.2.2.2 IEIS/AADC Architecture

3.4.2.2.2.1 AADC Architecture

The AADC is a modular computer whose elements can be configured in a variety of processing structures. The various AADC elements are described below.

The DPE

The DPE is composed of a PMU (Program Management Unit), an AP (Arithmetic Processor), a TM (Task Memory), and a Channel. It is a general purpose processor capable of performing all operations needed for processing sequentially organized tasks. The DPE provides a significant improvement in processing speed and efficiency through the use of a parenthetical control technique. That is, a fewer number of program instructions will be needed since many unnecessary memory loads and stores will be eliminated and memory access requirements will be reduced.

The Task Memory

The DPE task memory consists of 4K words of storage, 36 bits per word and is used to store program segments during execution. The TM is also used for temporary data storage.

COMPUTER FEATURES

FEATURE	CP901 (30 BIT)	SUPER NOVA (16 BIT)	CP-32 32 BIT	AADC
CONTROL REGISTERS	A,Q, 7 INDEX	4 (2 INDEX	2 SETS 16 EACH	16 REG STACK;12 REG PMU
FLOATING POINT HARDWARE	NO	NO	YES	YES
PROGRAMMABLE CLOCK	ONE	ONE	ONE	?
MONADIC OPERATIONS TO MEMORY	REPLACE INSTRUC.	ADD/SUBT.		NO
LIBRARY FUNCTIONS (HARDWARE)	SQ. ROOT	NO	NO	ITERATIVE POLYNOMIAL EVAL.
SINGLE PASS SHIFTS	NO	NO	NO	NO
LOOP CONTROL AIDS	SUBTRACT & SKIP	UNIT STEP ONLY	YES	BY ARRAY DEFINITION CARRIED WITH DATA
SUBROUTINE LINKAGE AIDS	YES	YES	YES	AUTOMATIC FOR ROUTINES FITTING IN QUEUE
PARAMETER PASS AIDS	NO	YES	YES	SAME
MICRO-DIAGNOSTICS	NO	NO	YES	?
INTERRUPT AIDS	SET LOCK-OUT NO NESTED INTER.	YES	YES	NONE DESCRIBED
MEMORY ERROR PROTECT	NO	NO	YES	?
ADDRESS ERROR PROTECT	NO	NO	NO	?
MICRO-STEP CAPABILITY	NO	NO	YES	?
I/O INTERRUPT EMULATION	NO	NO	YES	?
I/O CONTROLLER FEATURES				
I/O TRANSFER EMULATION	NO	NO	OPTIONAL	?
ECHO CHECK	NO	NO	OPTIONAL	?
ORTHOGONAL PARITY	YES	YES	YES	?
SCATTER GATHER	NO	NO	OPTIONAL	?
I/O CONTROLLED MEMORY RELOCATION	YES WITH WRAP AROUND CHANNELS RESERVED	NO	OPTIONAL	?

TABLE 3.4-1

The Arithmetic Processor

All arithmetic and logical computation for the DPE is performed in the arithmetic processor. This capability includes performing array operations, polynomial manipulations, vector and matrix arithmetic, complex arithmetic, subroutine operations, and bit, byte, halfword, and fullword processing. In addition, the AP performs arithmetic operations on fixed point, floating point, or mixed data formats.

The DPE PMU

All control functions of the DPE, including normal instruction and operand fetching, execution of program management type instructions, and interfacing with other elements via the Main Data Bus are controlled by the PMU. It also has its own instruction set which includes arithmetic and logical operations on both 16 and 32 bit operands.

The BORAM

BORAM (Block Oriented Random Access Memory) stores procedure and constants for all programs in pages of 256 words each. BORAM is completely programmable, with an off-line write time of about 2 milliseconds per 256 word page. When accessed by a DPE, BORAM will load 256 word program segments into the TM. As the DPE sequences through the program segments (which are not in TM), the need for another page of the program resident in BORAM may arise due to branching needs or end of resident TM page. Other program pages are then transferred into TM on a demand basis. Transfers from BORAM to TM are via the Main Data Bus at an uninterrupted rate of 150 nsec per word. A BORAM page transfer to TM will take approximately 42 microseconds.

The RAMM-PMU

The main data storage for the system is the RAMM (Random Access Main Memory), consisting of a series of memory modules, each 8K or 16K words by 36 bits. A PMU acts as the RAMM's "smart front end", performing all RAMM control functions.

The Bus

The AADC Bus System contains two Main Data Buses and an I/O Bus. The Main Data Buses are bidirectional Buses which provide for all data and control information transfers between the various AADC elements. Bus transfers occurs during a 150 nsec time slot. An element that desires to use the Bus raises an internal demand line, and awaits notification of Bus assignment on a rotational Bus grant priority list. Elements having no demand for the Bus are merely skipped as their turn arrives; in this manner, all time slots are used. When two elements desire to communicate, then either Bus may be used, depending on which is free. When transmitting information, there is no need to know if an element is busy; small input queues on each element accept data and hold it whether the element is busy or not. This arrangement eliminates wasting Bus time in determining whether a destination device is busy or not.

The I/O Bus is dedicated to I/O functions allowing another degree of parallelism in the AADC; processor transactions continue while I/O functions are performed.

The Channel

A channel element interfaces each of the AADC elements with the AADC Bus System. The primary function of the channel is to handle source/destination information, that is, to ensure that information traversing the Bus is accepted by a specific channel, while rejected by all others. Likewise, a channel must appropriately decide when information can be placed in a time slot on the Bus.

Virtual Addressing

A basic feature of the AADC is the memory addressing scheme. Addressing is performed either virtually or directly, and virtual addressing is considered the more prevalent mode. An instruction in the program sequence is obtained in the following manner: the low order 8 bits of the DPE Program Counter (PC) specifies an address within the page; an 8 bit page register specifies the present active

page; by concatenating these two fields, a 16 bit address is achieved; and the required location within TM can then be reached with this address. If a page boundary is crossed, or a branch instruction encountered, a 16 bit address of the kernal word is formed by appending the upper 8 bits of the PC (called the kernal word address) to the 8 bit kernal page register (two variable bits preceded by six ZEROS). When that kernal word is located in TM, the residency bit is checked. If this bit is set, then the required BORAM page is already resident in TM; in this case, the 8 bit new page address located in the kernal word is used to find the next instruction. Once this instruction is found, the virtual process for acquiring RAMM data is again undertaken. If the residency bit is not set in the kernal word, then a 20 bit BORAM address is taken from the kernal word and sent over the Bus to BORAM. BORAM sends the proper page back to the DPE, and places it in TM. The location of page placement depends upon which pages are available in TM; if TM is filled to capacity, replacement algorithms determine which page should be replaced. When this page is found, it is written over with the new page. The present page address register is then updated and addressing continues as described above. If the instruction needs data on which to operate, the 8 bit kernal word location field (which is a part of the instruction word) is appended to the 8 bit kernal page register, to form the kernal word address for the data. If the data is page oriented, the residency bit is checked, and the addressing sequence is essentially the same as described above for procedure. If the data is word oriented, it is not resident (only page oriented data may be stored in TM) and the 8 bit displacement field of the instruction is added to the 20 bit RAMM address in the kernal word. The result is used to access the correct RAMM location. The data is operated on as soon as it is received from the main data bus.

Security

The virtual addressing scheme serves as the basis for the security system in the AADC. The program kernal word must supply RAM addresses in order to obtain data from RAM. Areas of RAM which are not permitted access by a particular program are made inaccessible by not providing an address for this area in the kernal word.

In addition, the security system is further enhanced by providing a read and write protect bit within the kernal word. When the read-protect bit is set, the program is not allowed to read the desired information from memory unless permission is granted by the system master executive. An attempt to read when this bit is set will result in a bypass of that instruction. Similarly, when the write-protect bit is set, the program cannot write into the indicated virtual segment until permission is received from the system master executive.

3.4.2.2.2.2 AADC Configurations

The elements of the AADC can be used to fashion a variety of processing structures, however three basic configurations exist: the minicomputer or minimum configuration; the simplex processor; and the multiprocessor.

The AADC minimum configuration (see Figure 3.4-6) consists of a RAMM (Random Access Main Memory), a PMU (Program Management Unit), and a DCM (Data Communicator Module).

The RAMM constitutes the main data storage for the system and has a read-write cycle time of approximately 250 nsec. The PMU contains sufficient arithmetic processing capability to process data on a stand-alone basis (as a minicomputer). In addition, the PMU controls the routing of incoming and outgoing information, as well as performing other controller functions. The DCM serves to interface the RAMM-PMU combination with up to 64 peripheral devices of many types, including another AADC system and/or a NTDS (Naval Tactical Data System) device. The DCM can communicate in a parallel (including fullword, halfword, or byte) or serial mode, can transmit and receive information simultaneously and can store a limited amount of data.

The DPE (Data Processing Element), the BORAM (Block Oriented Random Access Memory), the internal Bus system, and the Channels constitute the Simplex Processor/configuration. This system is unique in that one DPE performs processing, but several RAM's and BORAM's are accessible.

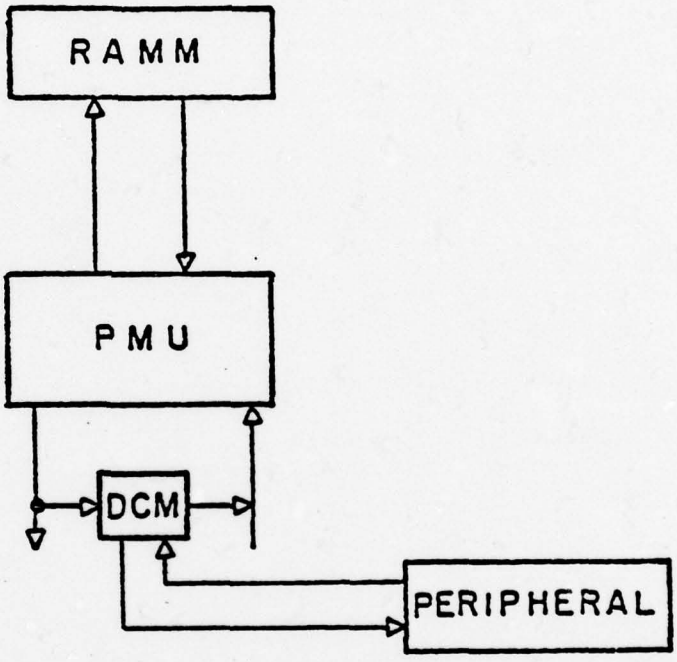

FIGURE 3.4-6 PMU MINICOMPUTER CONFIGURATION

A multiprocessor configuration is structured with numerous DPE's on the internal AADC Bus (See Figure 3.4-7) other elements such as RAMM's and BORAM's can also exist in any quantity. A maximum of 256 elements with channels, each element containing 64K words of memory can be placed on the internal Bus.

The AADC baseline indicates that the DPE will accept procedure from the BORAM and data from the RAMM. Programs will be executed by the DPE with the results stored in TM, outputted directly, or returned to RAMM. All communications between two AADC elements will be via the internal Bus. In order for an element to communicate on the Bus, it must interface through a channel.

3.4.2.2.2.3 IEIS Configuration

It is assumed that the AADC configuration for an AIDS equipment aircraft will be the multiprocessor configuration. Therefore the IEIS program storage will be in BORAM while the working storage will be either in the RAMM or TM depending on whether or not the data is needed by other program modules than the one currently operating. Since the TM is always available only BORAM and RAMM requirements will be changed to IEIS.

Using the multiprocessor configuration requires that processing time estimates take into consideration the time needed to move pages of program from BORAM to TM. The processing speed will be dependent on the type of program being executed since the DPE is a combination of a PMU and an AP. The PMU will execute the control sections of a program, handling data movement and most decision instructions while the AP will execute the arithmetic routines. The PMU runs at an average speed of about 1 MOPS while the AP runs at 2 MOPS.

3.5 IEIS Display Generator

3.5.1 Display Generator Requirements

A series of operations must be performed in order that mapping of information from the level of the IEIS data processor to the human level on the display surface can be accomplished. The display generator generally will perform the following functions related to this transformation:

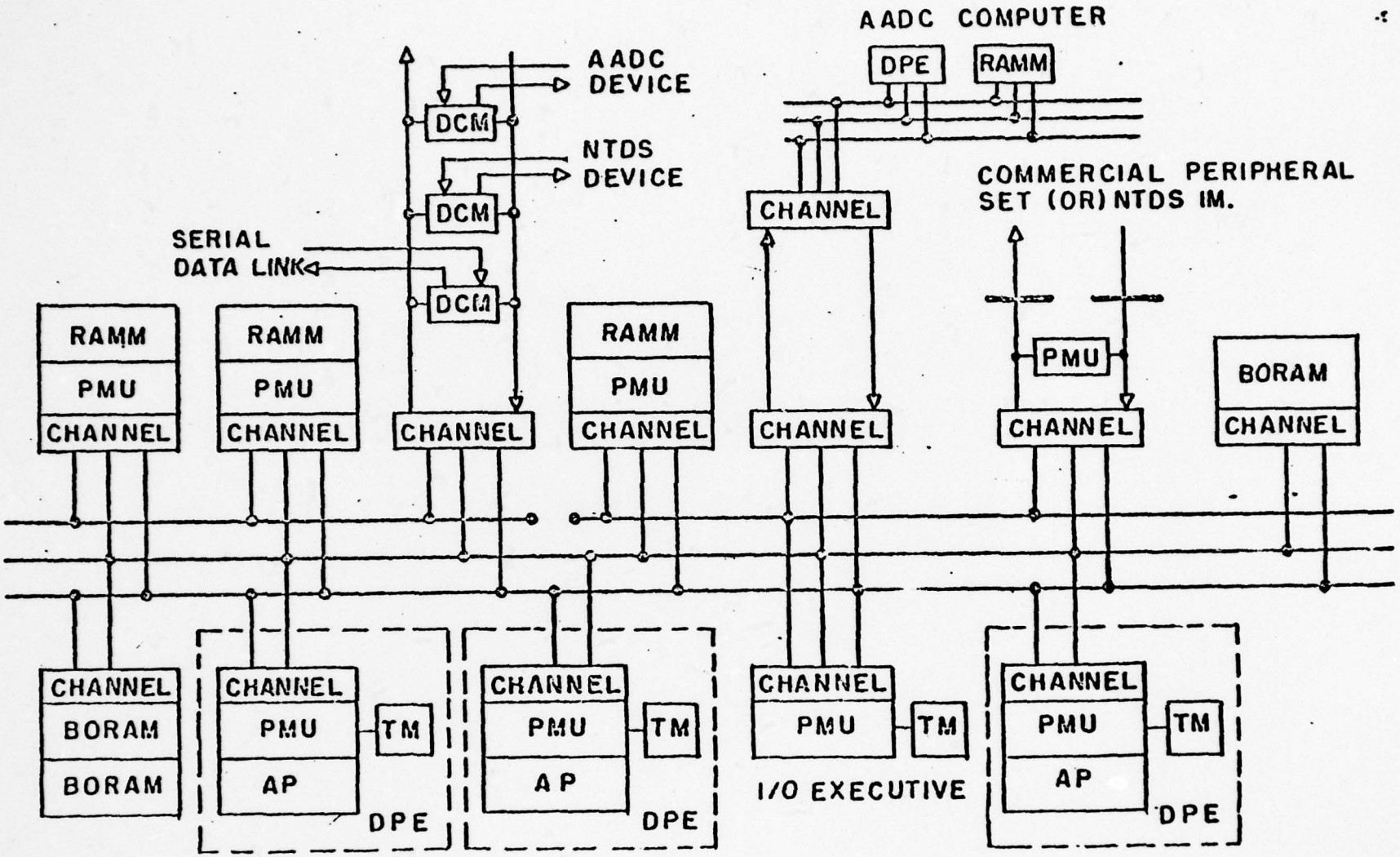

FIGURE 3.4-7 AADC MULTIPROCESSOR

- Display Data Base Storage
- Character Generation
- Vector Generation
- Display Formatting
- Refresh Storage
- Digital to Analog Conversion
- Display Control (XYZ)

Some or all of these functions could be performed in data processor and several architectures are developed in subsequent sections to examine the trade-offs of processor - I/O utilization and display generator complexity.

3.5.2 Display Generator Architectures

3.5.2.1 Random Position Beam Control Architectures

The first type of display generator to be considered is a display generator employing a random access local memory and the random position method of beam control. A block diagram for this type of display generator is shown in Figure 3.5-1. This type of display generator was employed in the IEIS Demonstration Equipment developed during Phases I and II of the IEIS Contract.

This display generator uses coded display instructions stored in the RAM to control the x, y and z inputs to the CRT. The display information is initially loaded into the RAM via the external address and external data inputs from the bus interface. Once the RAM is loaded, display refresh is accomplished under local control. For each frame the timing generator first initializes the address counter and then increments the address to sequentially read the display instructions from the RAM. Display elements such as alphanumeric characters and line segments are produced in response to the decoded display instructions, until an end of frame instruction is decoded. Upon execution of the end of frame instruction the display generator is idle until the start of the next frame. During the idle period the memory is available for updating by the CPU. Since the display information is stored as coded display instructions many updates will involve changing only a small number of words in the RAM. The I/O bus loading for this method of display generator is therefore very light.

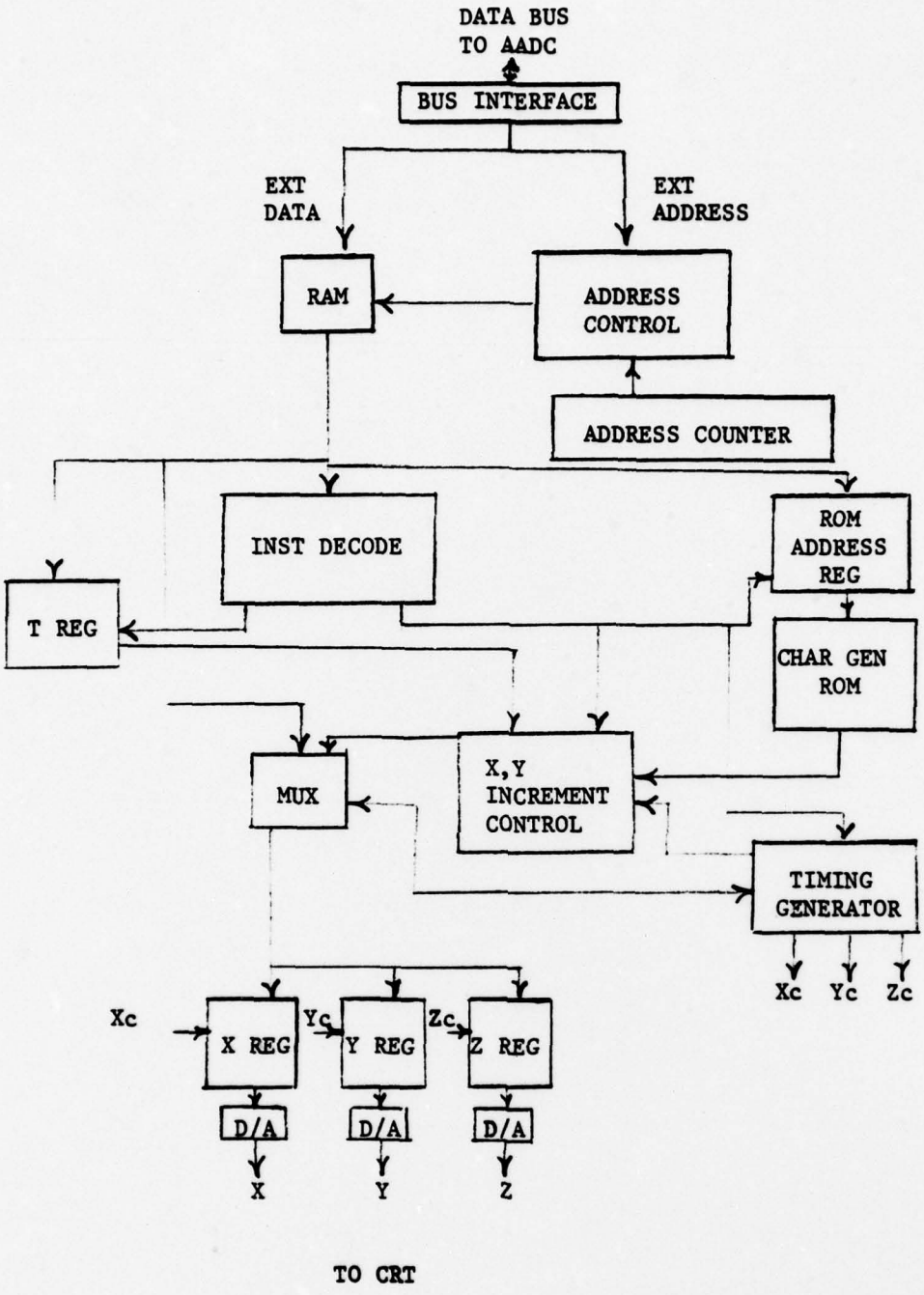

Figure 3.5-1 DISPLAY GENERATOR WITH RANDOM ACCESS LOCAL MEMORY AND RANDOM POSITION METHOD OF BEAM CONTROL

Figure 3.5-2 shows a variation of the random position display generator in which the local memory has been eliminated. In this case the CPU must supply control codes to the display generator at a rate consistent with the instruction execution cycle. Although this method of display generation results in a sizable increase in I/O traffic, the processor utilization and memory requirements are not significantly increased over the case employing a local memory.

The next logical step in simplifying the display generator hardware while employing the random position method of beam control is the extreme case where the bus interface is connected directly to the x, y and z registers. The CPU must now supply fully decoded position and intensity information at a rate consistent with the CRT dot control circuits. Operation in this mode will impose very high loads on both the I/O and the processor.

3.5.2.2 Raster Scan Beam Control Architectures

The block diagram for a display generator based on the raster scan method of beam control and employing a shift register refresh memory is shown in Figure 3.5-3. The architecture employs three levels of storage. The first level of storage is random access and contains the display list, that is, the list of display codes that completely define the display content. This display list can be identical to the display codes used in the random position method of Section 3.5.2.1, thus the functioning of the central processor would be the same. The utilization of the display codes is considerably different in this case, however, since all the display information must be formatted into a bit pattern which can be synchronized with the raster. In order to accomplish this formatting the second level of storage is used. This storage is also random access and may physically be part of the same memory structure used for the display list. Distinction is made because this level of storage is accessed only by the display generator. In operation, the display generator decodes the instructions in the display list and by applying conversion

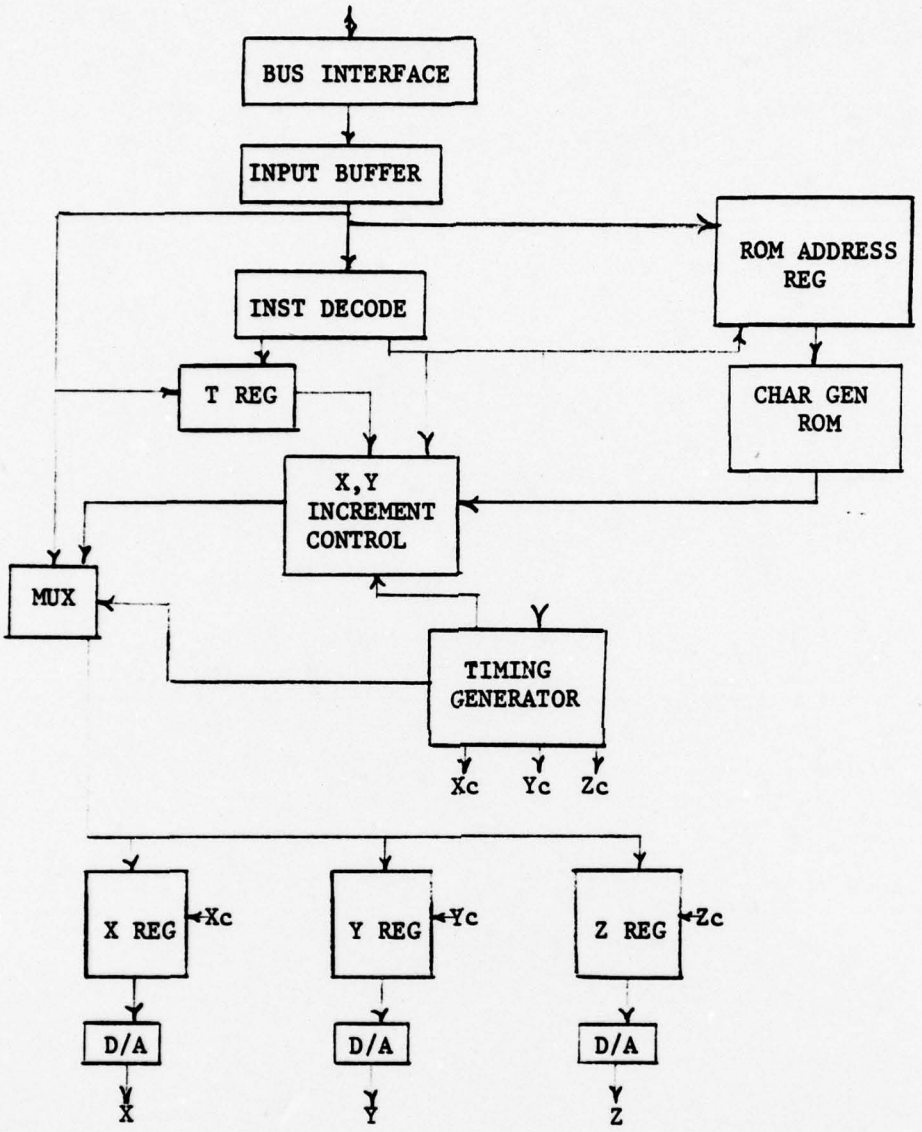

FIGURE 3.5-2 DISPLAY GENERATOR WITH RANDOM POSITION BEAM CONTROL AND NO LOCAL MEMORY

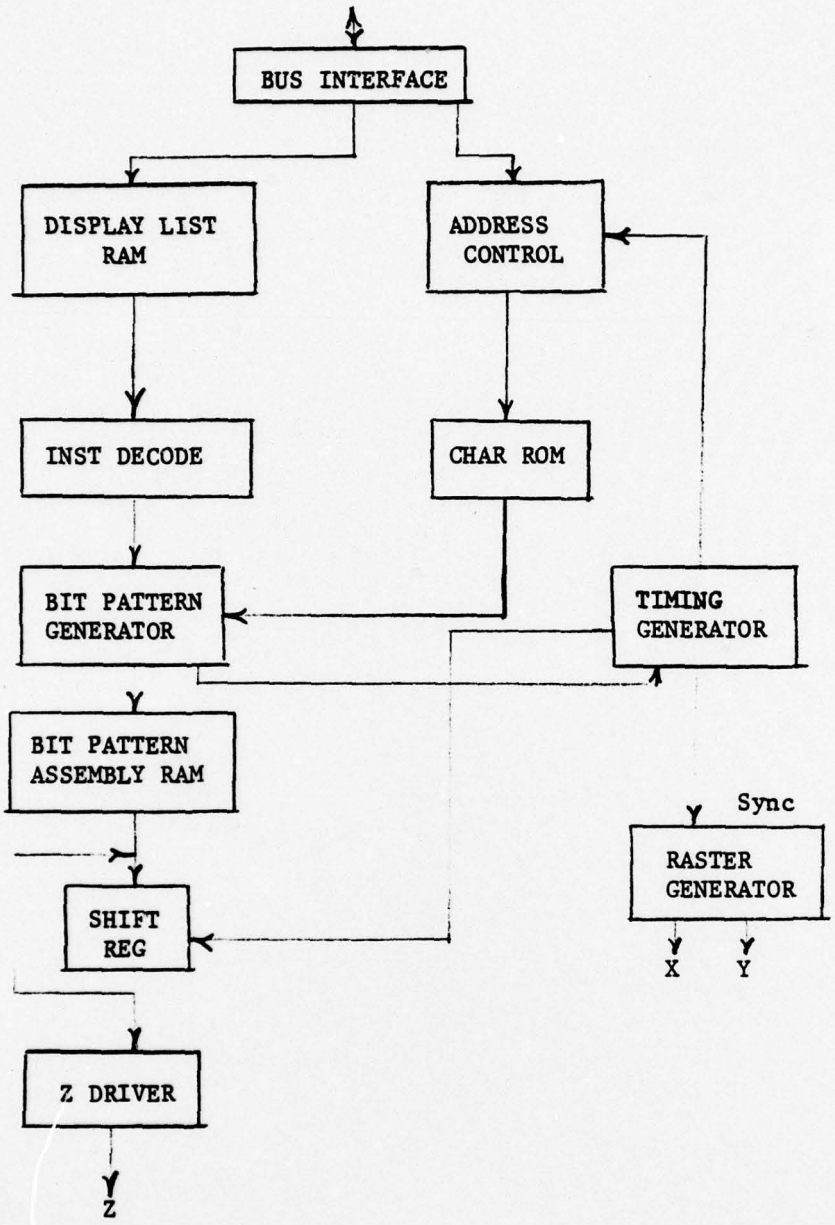

FIGURE 3.5-3 DISPLAY GENERATOR WITH RASTER SCAN BEAM CONTROL AND THREE LEVELS OF LOCAL STORAGE

algorithms or by drawing on bit pattern information stored in ROM (for characters) a bit pattern is generated that matches the intensity versus time function required for controlling the z input to the CRT. Once the proper bit pattern has been assembled in RAM it is transferred to the third level of storage, that is, the refresh shift register.

The refresh shift register recirculates in synchronism with the raster timing and thus is the only portion of the display generator besides the raster generator that must continuously operate at the frame rate. The three levels of storage allow each section of the display generator to operate asynchronously. The display list RAM can be loaded at a rate consistent with the data bus capacity. The bit pattern generator will operate at a slower rate since the only concern here is for the introduction of latency thus the capability to process a complete display format change in less than 100 ms is adequate. Once the required bit pattern has been constructed in RAM it can be transferred to the shift register in one frame time.

Once the initial loading of the shift register has been accomplished, display update requires only that those display codes involved in the update be reprocessed and that the shift register be selectively reloaded.

A variation of the display generator just described can be conceived where the display list RAM is eliminated. The effect of this change would be to require that the transfer of display codes from the central processor by synchronized with the operation of the bit pattern generator. The actual data transferred would not change so the processing required is the same. The I/O control would be more complex however, since a means of providing for the proper timing of code transfers would be required. A common means of handling this type of data transfer control is through the use of interrupts. The display generator would send an interrupt to the central processor whenever it is ready to accept a new display code input.

The central processor would respond to the interrupt either by sending a new display code or if no display update is immediately needed the central processor would simply remember that the display generator is ready to receive updated codes so that when the need for a display change occurs the new display code can be sent immediately.

The function of the bit pattern generator can be accomplished either by special purpose hardware or by programmed processor. This function could be performed by the central processor if the increase in processor utilization can be tolerated. With this approach data from the bus interface would be loaded directly into the shift register with no more than a two word buffer required.

The ultimate reduction in display generator hardware would result if the shift register were reduced in length to equal the word length of the data received from the data bus. In this case the shift register would not recirculate but would be reloaded by parallel entry from the data bus each time a word is shifted out. This scheme would result in the highest I/O bus utilization of any display generator architecture considered.

The AADC resource requirements for the above display generator architecture are addressed in Section 2.2.4 of the Phase IV Final Report.

Although the raster scan architectures described above were shown to produce separate x, y and z inputs to the display in order to maintain similarity between these and the random position schemes it may in some instances be desirable to consider the raster generator as part of the display rather than part of the display generator. In this case the x and y lines would be replaced by the sync line as a display generator output or if the number of interface lines were to be minimized at the expense of additional hardware the sync and intensity (z) signal could be combined into a composite video signal similar to a conventional TV signal. The choice between these variations requires consideration of the comparative complexity of the display switch versus the signal combining and sync separation circuits.

3.5.3 AADC Application to Display Generation

3.5.3.1 AADC Resource Estimates for Display Generation

In this section the AADC resources required for each of the display generator architectures described in Section 3.5.2 is presented. In order to simplify reference to the various architectures, Table 3.5-1 has been constructed assigning each an arbitrary Type #. The program module that is hardware dependent is the Display Editor. The other display modules, that is, the Display Feature Base and the Display Feature Select modules are not affected by the display generator architecture.

The baseline resource estimate was made for the case where the display generator architecture minimizes the processor requirements, that is, types 1 and 4. The other estimates are made relative to this baseline and indicate a relative complexity.

The following assumptions were made in calculation of the baseline resource requirements:

- All execution is done in a Program Management Unit (PMU) at a 1 MOPS rate.
- Display updates are required at an average rate of 1 per second.
- Each update requires changing 10 display codes with the execution of 10 instructions required for each code change.
- I/O bus capacity is 320 MBPS.

For the display generator architectures requiring direct refresh the following additional assumptions were made:

- Refresh rate is 50 frames per second.
- Display resolution is 256 x 320

AD-A035 565 GENERAL ELECTRIC CO WILMINGTON MASS AEROSPACE INSTRU--ETC F/G 21/5
INTEGRATED ENGINE INSTRUMENT SYSTEM. VOLUME I.(U)
JUN 76 R L SKOVHOLT, W S LITTLE, W A DOERLE N62269-75-C-0359
UNCLASSIFIED NADC-76180-30-VOL-1 NL

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TABLE 3.5-1 DISPLAY GENERATOR ARCHITECTURES

Type #	Description
1	Random position beam control, local memory, coded inputs.
2	Random position beam control, no local memory, coded inputs.
3	Random position beam control, no local memory, fully decoded inputs.
4	Raster scan, display list storage, coded inputs.
5	Raster scan, no display list storage, coded inputs.
6	Raster scan, refresh storage only, fully decoded inputs.
7	Raster scan, no refresh storage, fully decoded inputs.

Table 3.5-2 presents the resource estimates for each type of display generator considered in Section 3.5.2. As can be seen a rather wide range of processor utilization and I/O bus loading is represented. The very high processor utilization for Type 3 and 7 arises from the assumption that the complete display is regenerated each frame. This means that no refresh memory exists either in the display generator or in the central computer and the full burden of display refresh is placed on the processor. This high utilization could be reduced to 1-2% by providing refresh memory in the RAMM but the other alternative was chosen to illustrate the extreme case.

3.5.3.2 Use of AADC Hardware Modules for Display Generation

The 75% processor utilization that results from requiring the display refresh to be handled by a processor suggests that this would be a reasonable task for a dedicated processor. With the assumption that all instructions executed by the Display Editor would be PMU instructions, to consider building a display generator which contains a PMU that will perform all the processing required to refresh the display operating directly from a coded display list is possible. All storage requirements for the display generator can be accommodated by an AADC Task Memory. This approach is applicable to either the random position or raster scan methods of beam control. A generalized block diagram for a display generator utilizing AADC hardware modules is shown in Figure 3.5-4.

TABLE 3.5-2 AADC RESOURCES FOR DISPLAY GENERATION

Display Generator Type #	Display Editor Program BORAM (Pages)	Display Editor Program RAMM (Words)	Display Editor Program Processor Utilization (%)	I/O Bus Loading (Kilobits/sec)	I/O Bus Loading (% of Capacity)
1	2	2K	.023	0.5	0.00015
2	2	2K	.023	600	0.001875
3	7	3K	75.0	14000	4.375
4	2	2K	.023	0.5	0.00015
5	2	2K	.025	0.5	0.00015
6	7	3K	1.5	1.2	0.00037
7	7	3K	75.0	18000	5.76

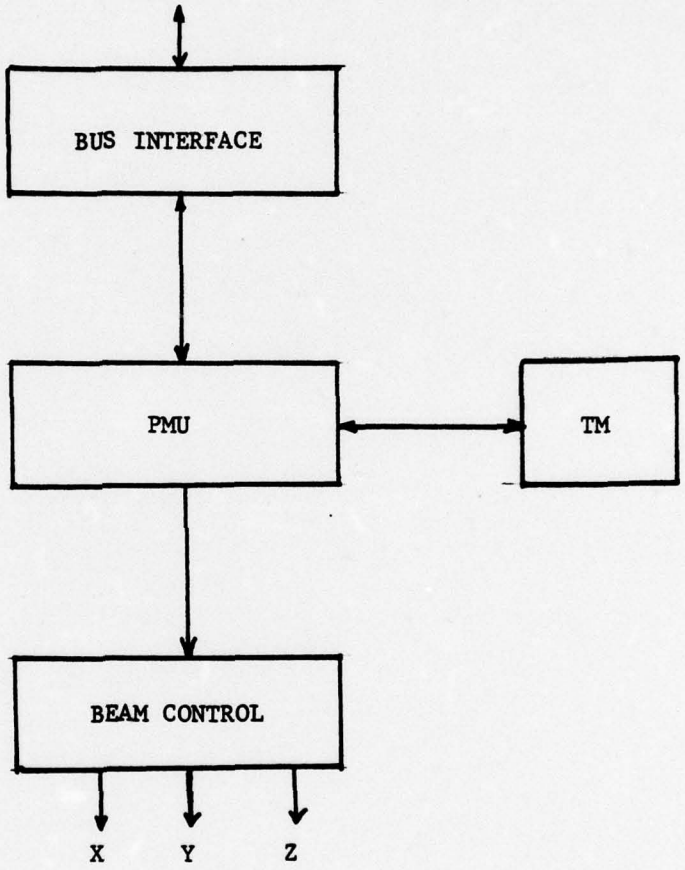

FIGURE 3.5-4

DISPLAY GENERATOR USING AADC MODULES

3.5.4 Display Generator Conclusions and Recommendations

The display generator investigation has shown that the AADC is capable of supporting a wide variety of display generator architectures even to the extent of requiring the processor to refresh the display directly. The tradeoff between processor loading and external hardware complexity usually indicates that the computer should handle as much work as possible. However, operational experience with systems employing computers has shown that over the life of a system the processing requirements tend to increase with improvements in system capability. When the processing requirements begin to exceed the hardware resources available, expensive hardware retrofits become necessary. For this reason, functions like display refresh should be handled by external hardware rather than by the central processor even though initial studies might indicate that the processor could accomplish the function.

I/O bus loading tends to be a direct function of the processor loading. As the amount of work done by the central processor increases the amount of data that must be transferred over the I/O bus also increases. The use of external display generator hardware relieves the bus loading.

The use of AADC hardware modules in the display generator depends on two factors. First, can the module perform the function, and second, does efficient use of the module result. In the case of using an AADC Program Management Unit (PMU) as the major portion of the display generator hardware, the answer to both questions is "yes" with the qualification that the display generator be structured such that the PMU accepts a coded list of display instructions and processes the list on a real time basis. An architecture in which the PMU is used just to restructure the display information for a refresh memory would result in under-utilization of the PMU. To be efficient the PMU must be forced to regenerate the full display each frame. This approach is reasonable in that the amount of memory required in the display generator is minimized. A 4K Task Memory is sufficient for the display generator.

The recommended approach to display generation is therefore to employ AADC modules, specifically the PMU and TM modules, which will operate from a coded display list stored in the TM. The resources required for the central processor will be those shown in Table 3.5-2 for display generators Type #1 or 4.

3.6 IEIS Display

3.6.1 Display Requirements

The Phase IV display investigation consists of a review of the principle display media which were identified as IEIS/AIDS contenders. The primary requirements are listed in Figure 3.6-1

3.6.2 Display Technology Survey

A survey of technology applicable to the IEIS Display was conducted during Phase IV. Figure 3.6-2 lists the IEIS display parameters discussed in Section 3.6.1 in the first column on the left side of the table and the IEIS requirements for these parameters in the third column. In the second column is a list of numbers from 1 (most critical) to 10 (least critical) which indicates the relative performance value assigned to each of the IEIS parameters.

Across the page from left to right are listed the display media which are most likely contenders for the IEIS display application. The display media considered were monochrome cathode ray tubes, color-cathode ray tubes - voltage penetration, light emitting diodes, liquid crystal, digisplay, DC plasma panel, and AC plasma. By scanning the rows and columns, comparisons can be quickly made between the various display media and the IEIS requirements.

Experience has demonstrated the fact that no display is best qualified to satisfy all requirements and that investigation and analyses are necessary in order to properly choose a display unit and integrate it with a system. The approach taken in the technology survey is to specify selected, fixed, guidelines relating the IEIS/AIDS parameters and then fully evaluate the contenders against these guidelines. All of the reviewed displays satisfied some of the parameters,

1)	Size of display viewing surface	5"(H)X7"(V)
2)	Maximum display cavity size	12"X8"X8" 3/4 $Ft.^3$
3)	Maximum viewing distance	28"
4)	Minimum viewing distance	12"
5)	Resolution: Must match 320 X 256 screen matrix	
	: 50 to 60 Dots/inch	
	Dot Matrix: Minimum 5 X 7 dot matrix/character	
	Raster Scan: Min. 10 TV lines/character	
6)	Character Size: 3/16" (Height)	
7)	Color: Monochrome If Color: Minimum of 3 colors. (Red, Yellow, Green)	
8)	Grey Scale: None required. (Only normal level and intensify)	
9)	Ambient Light Level: 10,000 Ft.-cdls. Maximum	
10)	Contrast Ratio: 2:1 (Min.) at 10,000 Ft.-cdls.	
11)	Display Brightness: 100 Ft. - Lbts. (Min.)	
12)	MTBF: 3000 Hours	
13)	Power (Average): 100 Watts	

FIGURE 3.6-1 IEIS DISPLAY PARAMETERS

	RELATIVE IES PERFORMANCE VALUE	IES DISPLAY REQUIREMENTS	CRT - MONOCHROME RASTER	CRT - MONOCHROME RANDOM SCAN	CRT - COLOR VOLTAGE PENETRATION	LIGHT EMITTING DIODE	LIQUID CRYSTAL	DIGIPLAY	D.C. PLASMA PANEL	A.C. PLASMA PANEL	UNITS	NOTES:
		H V										
DISPLAY VIEWING SIZE	5	5"×7"	7"×7"	7"×7"	7"×7"	1"×1"	6"×6"	6.5"×6.5"	4"×8"	8.5"×8.5"	--	
DISPLAY BRIGHTNESS - (AVERAGE)	2	~300	1400	<1400	7 Red 50 Green	50	Reflective	15/30	200	50	Ft-lits	
CONTRAST RATIO (W/O SUN)	1	9:1	>10:1	>10:1	Not Available	25:1	>15:1(1) >15:1(2)	20:1	Not Available	25:1	--	(1) Reflective Mode - Viewing Angle Dependent (2) Transmissive Mode
RESOLUTION -												
DOT MATRIX	3	Must Match 320×256 Matrix	250	250	Not Available	70	100	80	30/>80	60	Dots/inch	
RASTER SCAN	3		50/150	50/150	~100	--	30	10	--	--	Lines/inch	
COLOR: (3 COLORS MINIMUM)	4	Mono-chrome	Mono-chrome	Mono-chrome	Yes	Limited	Mono-chrome	Mono-chrome	Mono-chrome	Mono-chrome	--	
UNIFORMITY (BRIGHTNESS)	4	±10-14	Accept-able (3a)	Accept-able (3a)	Worse then Monochrome CRT (3a)	±15-20(3)	±20	±10-20	Non-uniform	Non-uniform	%	(3) Per Array - up to 50% Between Wafers (3a) Data not readily available
BRIGHTNESS CONTROL	3	Yes	Yes	Yes	Yes	Yes	(4)	Yes	No	No	--	(4) Only for transmissive
VECTOR/ALPHANUMERIC DISPLAY	4	Yes	Yes	Yes	Yes	Yes(5)	Yes(5)	Yes	Yes(5)	Yes(5)	--	(5) For a panel designed for I.E.I.S.
SCANNING RATE/REFRESH	3	(6)	30	30-60	100(7)	30-40	2-20	20-30	None	None	Hz	(6) Should not have objectionable flicker or breakup (7) Different scanning rates for red, yellow, and green
EDITING - SELECTIVE	2	(8)	(8)	(8)	(8)	(8)	(8)	(8)	No	No	--	(8) Done with Display Generator
SWITCHING VOLTAGES	3-4	Relates to cost, speed, reliability	0-85(a)	0-85(a)	Hi-V	2-5	20-60	70-150	150-200	150-200	Volts	(9) Video and Magnetic Scan
FIXED SUPPLY VOLTAGES	4	(same as above)	10K-18K CRT	10K-18K CRT	10K-Red 18K-Green	2-5	20-60	10K-20K Phosphor	250 Panel	175	Volts	
POWER:	4											
AVERAGE CONSUMPTION		<100	<15	<15	<15	>1K	~2-10	400	~2	<200	Watts	
PEAK CONSUMPTION		<1K	<150	<150	<150	>1K	~100-200	Not Available	~2	<250	Watts	
CIRCUIT COMPLEXITY:	3											
a) SCAN AND DRIVE		Relates to cost, speed, reliability	Simple	Less Simple(10)	Less Simple(10)	Complex	Extremely Complex for Matrix	Moderate	Simple(11)	Moderate	--	(10) Linear Sweeps (11) No Multiplex
b) DISPLAY GENERATOR			Simple	Simple	Simple(12)	Complex	Complex	Moderate	Moderate	Moderate	--	(12) Must switch Hi-Voltage
MTBF (DISPLAY)	4	>1K	HIGH	HIGH	HIGH(13)	>10K	1K	6K	Not Available	Not Available	Hours	(13) MTBF much less due to Hi-Voltage Switching Derating Hi-Voltage Components of Power Supply
VOLUME:	4											
a) DISPLAY		~3/4	~3/4	~3/4	~3/4	~1	~1½	~3/4	<1	~2	$R.^3$	
b) DISPLAY/SYMBOL GENERATOR		~1½	~1½	~1½	~2	~1½	~2	~2	~2	~2	$R.^3$	
MIL SPEC/RUGGEDIZED	2	Yes	Ruggedized	Ruggedized	Ruggedized	Limited MIL SPEC	No (14)	(15)	No	(16)	--	(14) Limited by temperature Range (15) MIL SPEC only for Vibration and Shock (16) Militarized Smaller size shown
PRODUCTION FEASIBILITY (DISPLAY)	1	--	Yes	Yes	Limited	Uncertain	Limited (17)	Uncertain	Lab	Limited	--	(17) Size - Lab prototype
COST (DISPLAY)	1	--	Low	Low	Medium	High	High	High	High	Med/High	--	

Figure 3.6-2 Display Matrix Table

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permit fully legible reproduction

but did not fully measure up to the guidelines. The more times a display falls below the set requirements, the more the display will have to be individually tailored to meet the IEIS/AIDS parameters.

The key problem areas associated with the display media are discussed below. For a complete discussion of the characteristics of each media, refer to the Phase IV Final Report, Sections 3.2.2 through 3.2.6.

Large, light emitting diode displays continue to have many problem areas. Wafers of the size necessary for large displays are not available as single crystals. Piecing together small (1" x 1") wafers creates the problem of electrically accessing all of the diodes. High power consumption in the display and drive circuits cause further problems. Also, brightness levels are often inadequate. Work is necessary in the area of reducing drive current requirements while at the same time increasing brightness levels.

The liquid crystal display has certain key problem areas. The scan and drive circuitry required to accomplish the IEIS's requirements is extremely complex in nature. The temperature "window" in which the device must operate is a limiting condition. The future of military spec'd liquid crystal displays are highly uncertain, due to this temperature "window". Brightness and/or contrast is greatly dependent on the viewing angle in the reflective mode. In the transmissive mode, high ambient levels will greatly effect the contrast ratio.

The future of the Digisplay panel is very unclear. Release as a commercial product and not as an avionic display is likely in the future. The low brightness level of the Digisplay panel is also an area of prime concern, as well as its high power consumption levels. The size of a display generator to drive the Digisplay in the IEIS "mode" would be another sensitive region.

The AC plasma panel suffers from a serious brightness problem, lack of adjustment of the brightness level, poor contrast ratio, and lack of selective editing, which for IEIS is important. The size requirements of a total AC plasma panel and display generator exceeds the IEIS specs. Similarly, the DC plasma panel is greatly hampered in many of the same areas as the AC plasma panel. But, the brightness and contrast ratio is better than the AC panel, while the uniformity of brightness across the panel is poor. The chances of mil spec units are poor.

The voltage penetration CRT's have problems with the brightness and the contrast ratio. The efficiency of the red phosphor is much below that of the green phosphor, causing the need for complex circuit design to compensate for this discrepency. High switching voltages required to produce red, yellow and green displays, one color at a time, also requires a higher order of circuit design. The high voltage components of the power supply are greatly effected by this high-voltage switching, causing the shortening of their useful life and reduction of the MBTF. A prominent manufacturer of cathode ray tubes dropped the development of the voltage penetration tube for avionic application primarily because of the phosphor, switching, and brightness problems described above. They still produce voltage penetration tubes, but mainly for computer display applications. Of all the display media reviewed, only this one has color capability.

The monochrome cathode ray tube has had the highest level of development, and the greatest financial outlay for its research and development, of any display covered by this report. This situation exists because the CRT has been on the scene for more than fifty years, and technical understanding has reached a level not approached by the other listed displays. Most of the IEIS/AIDS parameters can be met and in many cases exceeded by the CRT. The weak areas are the contrast ratio in sunlight and the fixed supply voltages. The monochrome cathode ray tube in either the raster scan mode or random scan mode are almost identical to each other when mirrored against the IEIS/AIDS parameters, save for two exceptions. First the linear sweeping circuits are more involved in the random scan mode. Second, the raster scan display generator circuitry is not as simple as the display generator for the random scan. Solid state memory technology advances are improving the latter problem.

In conclusion the recommendations are twofold. One, the immediate choice for an IEIS display is a cathode ray tube. Two, carefully monitor other technologies to consider them for implementation into AIDS when their deficiencies are sufficiently reduced.

3.7 Keyboard

The method by which the flight crew interrogates the IEIS will be a part of an integrated "keyboard" which will service all AIDS functions. Furthermore an advanced technology approach resulting in programmable push buttons will be implemented. The keyboard described below is the approach taken for the IEIS Display System Evaluation Equipment which allowed interactive evaluations to be performed. Although this equipment was fabricated in 1971 and does not presently represent the state-of-the-art, some insight into IEIS input requirements can be obtained.

The keyboard used in the Display System Evaluation Equipment is shown in Figure 3.7-1. This keyboard provides the means for the pilot to interact with the display and it also serves as a display. Whenever a function is selected, the legend cap of the push-button switch for that particular function will light. In this way, the keyboard serves as an indicator as to what modes are currently being displayed.

A brief description of the keyboard functions defined for the evaluation equipment is given below.

1. Parameter Display

This group of seven (7) switches perform the following functions:

- Main Eng., Fuel/Cont., Lub., Elec., and Mech. - Five individual switches each representing a sub-group, used to select the parameters within their respective subgroups for display in the parameter display area of the IEIS display.
- Prime Parameter - A single switch used to select the "Prime Parameter" display for display in the parameter display area.
- Vertical Format - A single switch used to select Engine Performance Factor or the four eligible parameters for vertical display in the engine performance factor display area. This switch is cycled to get the desired display, that is, the pilot would depress it each time he wanted the display to change. His indication of the position of the switch would be by the title of the display in the engine performance factor area. The switch will require the following (6) positions: Off; Engine Performance Factor; and four parameter positions.

FIGURE 3.7-1 IEIS DISPLAY SYSTEM EVALUATION EQUIPMENT KEYBOARD

2. Energy Management Display

A group of five (5) switches are used for the following functions:

- Take Off - used to select the takeoff display.
- Time Climb - used to select the time climb energy management display.
- Fuel Climb - used to select the fuel climb energy management display.
- Range Cruise - used to select the range cruise energy management display.
- Endurance Cruise - used to select the endurance cruise energy management display.

The pilot selects the desired mode by depressing the appropriate switch. Only one mode can be selected at a time with the exception of the "Climb" modes. The climb modes can be selected while the takeoff mode is being displayed. The display will not change to the appropriate climb display until the aircraft is off the ground and the wheels are stowed. To remove a mode that is currently being displayed, the appropriate switch is depressed again.

3. Aircraft (A/C) Performance

These two switches are used to select for display, either the A/C performance plot without afterburner (W/O A/B) or the A/C performance plot with dropped stores (DROPPED STORES).

To select for display the desired switch is depressed; to remove, the same switch is depressed again.

4. Manual

These three pushbutton switches and one toggle switch are used by the pilot to manually enter altitude, mach, or time information into the energy management program. This feature allows the pilot to select altitude, mach., or time values, enter the values into the computer and observe on the display what "Margins" (miles and time) he will have, based on these inputted values. It allows the pilot to know, beforehand, what his margins would be if he flew at a non-optimum cruise path.

To enter altitude, the "ALT" button is depressed which indicates a manual altitude entry is going to be made and a readout of altitude appears in the data block of the energy management display.

The count button is set to "up", which causes the altitude readout to start counting upward in increments of 100 feet. A two-speed position switch commands a slow count rate or a fast count rate. The pilot watches the readout on the display; when the desired altitude is shown on the readout, he stops the counter (sets "COUNT" at center position) and enters the data into the program by pressing the "ALT" button again.

To enter mach. or time, the same procedure is followed, except the "Mach" or "Time" button is used and the counter counts in increments of .1 Mach for mach and 1 second for time. The "Down" count position causes the counter to reverse and has two-speeds, the same as "up".

4.0 DISPLAY ENGINEERING/HUMAN FACTORS

4.1 INTRODUCTION

The display engineering/human factors efforts, for the IEIS Program, have been concerned with defining the pilots information requirements and the formulation of these information needs into usable display formats. To accomplish these tasks the human factors efforts during the earlier phases of the program were concerned with information analysis and display formatting, while the later phases have been concerned with format modification and evaluation. This human factors effort has been an iterative process with each succeeding phase modifying the results of the previous phase.

4.2 DISPLAY ENGINEERING

The human factors efforts initially were concerned with information analysis, display concept formulation and initial display format definition.

A display philosophy was established which consisted of the following criteria:

- An integrated display is desirable wherever possible.
- Display only that information which is necessary for that particular phase of the mission.
- That information which is not necessary for that particular phase of the mission should be available upon the request of the pilot.
- Emergency information should be displayed automatically.
- Pilot interpretation should be avoided whenever possible.
- Good human factors engineering display criteria will be applied.

An information analysis was conducted using Decision-Action-Diagramming as the analytical tool. This program identified the pilots informational needs for the different mission segments and the display frequency for this information.

The information analysis provided inputs for the display format effort. However to effectively design a group of display formats that would present all the required information in a usable form, using sound human engineering principles, and be compatible with physical constraints required information from many sources. Figure 4.2-1 is a tree chart of the various inputs that were used in the design of these formats.

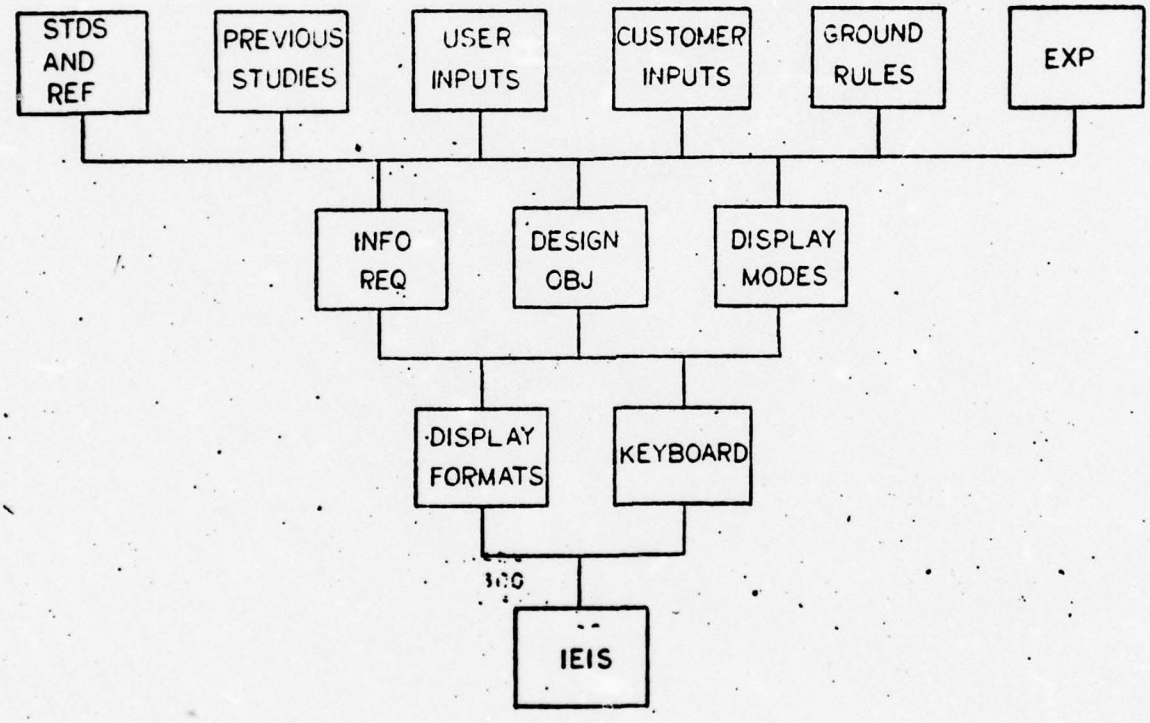


FIGURE 4.2-1 Design Information Flow-IEIS Display

A major input was, of course, the engine parameters that were monitored by the diagnostic system. These parameters were weighted to determine which should be available for display to the pilot. This basis for weighting parameters was provided by pilot ranking of the informational content of each parameter. The parameter list and the sub-grouping of these parameters are shown in Table 4.2-1.

The informational analysis determined that the IEIS display should have the following three (3) informational modes:

Continuous - information that is displayed during all mission segments

On Demand - information that is displayed upon pilot request

Automatic - information that is displayed automatically as needed, based on mission segment, or in case of an emergency (malfunction).

At the conclusion of the Phase IV effort the recommended IEIS display concept consisted of these three informational modes, with each presenting specific information, as follows:

- Continuous Data Display
  - Status Bar
  - RPM Vertical Scale
  - THRUST Vertical Scale
- Automatic Data Display
  - Marginal Malfunction
  - Critical Malfunction
  - Self Test
  - Start
- Manual Data Display
  - Energy Management Mode
  - Normal Parameter
  - Special (Air Start, Data Entry, etc.)

PARAMETER LIST WITH ABBREVIATIONS

MAIN ENGINE

Low Pressure Compressor Rotor Speed	N1 RPM
High Pressure Turbine Blade Temperature	TBT
Core Engine Rotor Speed	N2 RPM
Main Fuel Flow	FF
Stall Margin	STALL
High Pressure Compressor Internal Bleed Flow	INTFLW
High Pressure Compressor Discharge Bleed Flow	DISFLW
Airflow Limit Switch	AIRFLW

FUEL/CONTROL

Afterburner Fuel Flow	A/B FF
Fan Inlet Guide Vane Position	IGV
Core Variable Stator Position	CVS
Jet Nozzle Throat Area	A8

LUBRICATION

Oil Level	LEVEL
Oil Pressure	PRESS
Oil Temperature	TEMP
Oil Quality	QLTY
Lube Oil Flow	FLOW

MECHANICAL

Foreign Object Detector Flag #1	FOD 1
Foreign Object Detector Flag #2	FOD 2
Thrust Bearing #1 Condition	BRNG 1
Thrust Bearing #2 Condition	BRNG 2
Mass Unbalance Monitor #1	MUM 1
Mass Unbalance Monitor #2	MUM 2
Bearing Race Temperature #1	TEMP 1
Bearing Race Temperature #2	TEMP 2

TABLE 4.2-1

A set of display formats were generated, based on the informational analysis and display philosophy. These formats were iterated through each phase of the program, with Figure 4.2-2 depicting a composite format sketch based on Phase IV results. The following are the definitions of the numeric callouts:

1- Warning Message Area - used to display a summary flashing warning message and the time, in seconds, of how long the particular situation has existed

2- Status Bar - constant indication of engine status (normal, marginal, critical); summarized into 4 sub-groups including all of the monitored engine parameters

3- Critical Bar Graph Display - bar graph presentation of parameters which have exceeded critical limits; automatically displayed, provides actual numerical value limit value for the parameter

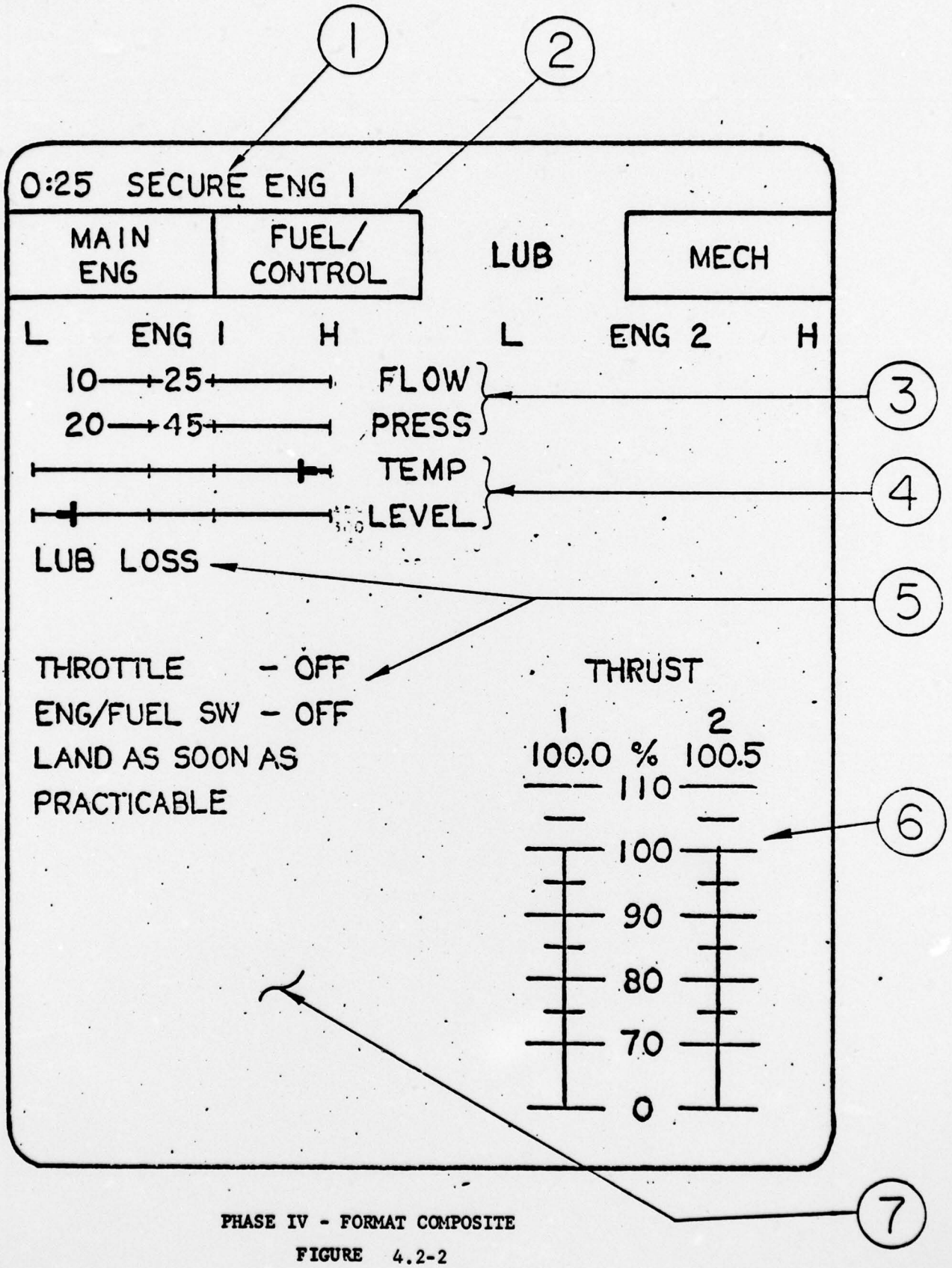
4- Marginal Bar Graph Display - bar graph presentation of parameters which have exceeded marginal limits; automatically displays and provides trend information regarding the malfunctioning parameter

5- Computer Recommendations - provides pilot with computer diagnosis of the problem and a step by step procedure for corrective action

6- Vertical Scale Display - vertical scale presentation of "RPM" or "THRUST"; continuously displayed with scale differentiation to denote which parameter is being displayed, and a set of indicii and acceptable range markers

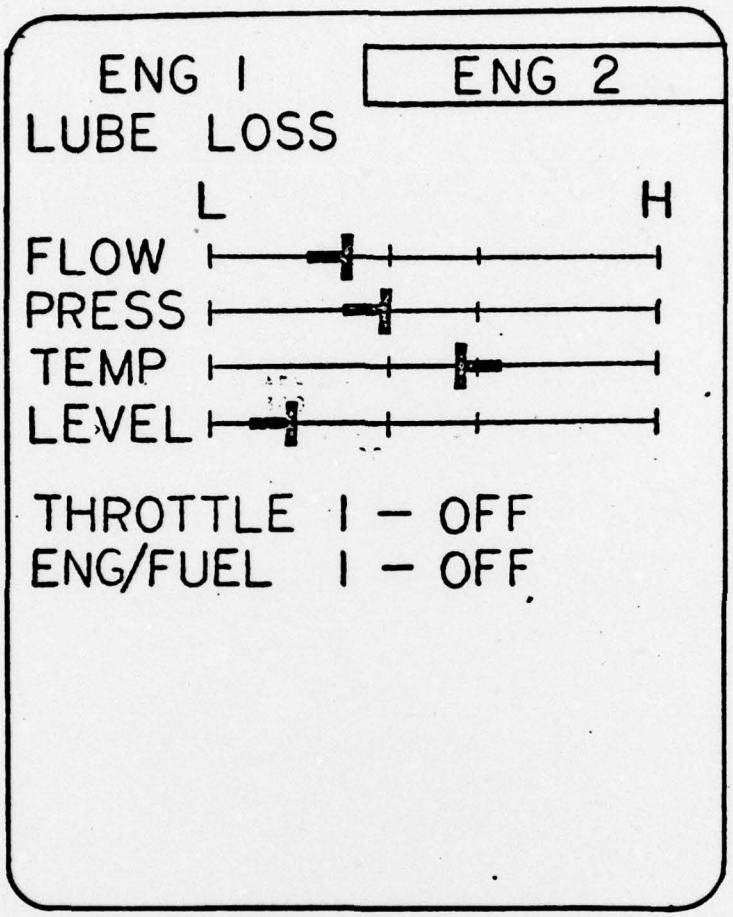
7- Energy Management Display - (not shown) summary profiles for climb and cruise were presented in the lower left quandrant of the display; deleted whenever a malfunction display appeared

A major display change occurred at the beginning of the Phase V effort. This change was due to the display size change from 8" x 10" to 4" x 5". The basic display characteristics STATUS BAR, HORIZONTAL BAR GRAPHS, etc., did not change. However, the amount of information presented on an individual format was reduced. Figure 4.2-3 is a typical format representation used during the Phase V effort and indicative of future formats of this display size.



PHASE IV - FORMAT COMPOSITE

FIGURE 4.2-2



TYPICAL PHASE V FORMAT

FIGURE 4.2-3

Also the Phase V effort did some initial formatting of pictorial displays as shown in Figure 4.2-4. A comparative evaluation was conducted of the pictorial versus the present presentation

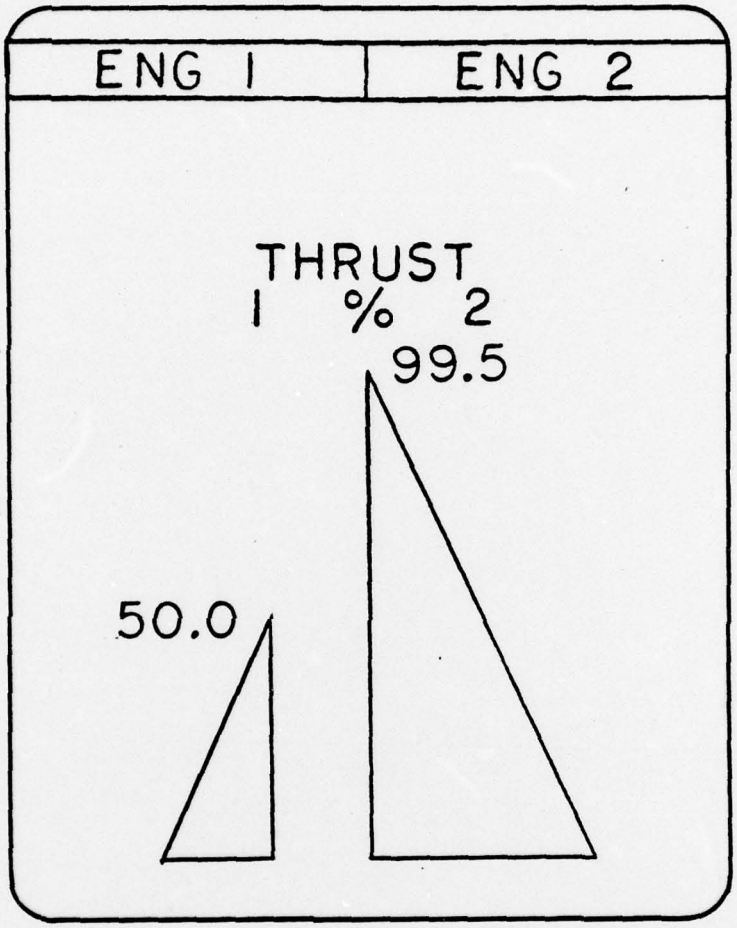
4.3 EVALUATION

The previous discussion addressed the information analysis and format generation that occurred during the five phases of the IEIS Program. The other major task area of concern to human engineering was that of display evaluation. This effort was directed toward the evaluation of the IEIS concept and associated display formats by current Navy pilots.

Initially it was decided to conduct two evaluation procedures. One was a Dynamic evaluation, using the IEIS demonstration hardware to present the scenario in a dynamic mode. The other a Static Evaluation with the scenario presented by means of Vu-graphs. In both cases the pilot subjects were observers only and their opinions and preferences were gathered by means of a questionnaire. The questionnaire addressed the following display considerations:

- Display characteristics (size, arrangement, content, etc.)
- Status Bar concept
- Manual parameter call up
- Automatic fault indication
- Quantitative versus Qualitative information
- Energy Management Concept
- Vertical Formats

Both evaluation procedures were run with the Dynamic Evaluation conducted at the Naval Air Development Center at Warminster, Pennsylvania, and the Static Evaluation at the Naval Air Test Center, Patuxent River, Maryland and at Oceana Naval Air Station, Virginia. A total of 43 pilots participated in the evaluation exercise and 24 of them completed questionnaires.



PICTORIAL FORMAT

FIGURE 4.2-4

The second evaluation effort, conducted during Phase IV, was a "dynamic" evaluation using the IEIS demonstration hardware to present the display formats and a prepared questionnaire to record pilot opinion and preference. This evaluation exercise was conducted at the Naval Air Test Center, Patuxent River, Maryland. Nineteen Navy test pilots participated in the evaluation and sixteen of these pilots completed the questionnaire.

The output of the human factors effort was a set of display format recommendations which were based on the analysis of the questionnaire responses. Generally the basic display formats and the display concept appeared to be satisfactory for presenting engine status information. There were, however, specific recommendations for format modification, they were the following:

- Continuous Data Display - the scales should be modified to differentiate between RPM and THRUST. Also a setting indicator and "range about the setting" should be added to the vertical scale display.

- Checklist and Procedures - checklist data and procedural data display should be a part of the IEIS presentation; especially complete procedural information for corrective actions.

- Energy Management Display - The Phase IV scenario presented the energy management data as summary type information only, not as a "fly-to" display. As a summary display fuel data should be added to the margin information.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The IEIS studies to date have investigated many areas of technology related to the definition of a baseline system. This report reflects the depth of definition of each element of an Integrated Engine Instrument System which will contribute to the overall AIDS requirements.

Specific conclusions and recommendations for IEIS relative to engine condition monitoring, system design, sensors, and displays/display engineering are presented in the following sections.

5.1 Engine Condition Monitoring

- An appropriate approach to engine condition monitoring is to employ a computer model of the engine thermodynamic, lubrication, and mechanical systems.
- A maximum of forty five engine and twenty air data parameters are deemed necessary to adequately monitor the condition and health of each engine.
- Oil quantity and vibration monitoring along with boroscope inspection are found to be three of the most effective techniques presently used for detecting impending engine failure.
- An effective approach to reduce data scatter during engine monitoring is to sample each parameter eight times over a two second period and average the readings to provide a single parameter estimate.
- Specifications and characteristics of software for performing on board engine diagnostics have been generated, including both long term trending and fault isolation.
- Transient condition monitoring is feasible, but extensive development is required in engine modelling and sensor transient response to implement this concept (see Volume II, Appendix A).
- For lubrication/fuel monitoring systems a reduction in size of the Phase V airborne software can be expected using techniques found satisfactory in related condition monitoring programs.

- The Phase III gross thrust meter availability assumption is no longer appropriate since no work has been undertaken to make it realistic. An alternate approach to obtaining this data is required to provide an effective thrust display for IEIS.

- Studies should be undertaken to reduce the size of the necessary airborne aerothermodynamic model significantly below that of the Phase III IEIS study and tailor it to a candidate engine.

- Studies should be undertaken to establish the extent to which the lubrication/fuel airborne software size can be reduced and tailored to an IEIS candidate engine.

- Further IEIS studies should include investigation of integration of Digital Electronic Engine Controls and transient condition monitoring.

5.2 System Design

- An overall system concept for IEIS has been defined and is summarized in this report.

- The total IEIS memory requirements, in terms of AADC building blocks, are estimated to be 27.5K words of BORAM and 16.9K words of RAMM. These BORAM requirements amount to approximately 43% of a standard AADC BORAM module. Projected AADC processor utilization time is 1.3%.

- A one million bit data recorder with a five minute loop record capability when an engine fault occurs will be required.

- Analog temperature and vibration processing is not recommended because of the excessive memory size and processing time required to perform these functions digitally.

- The data bus transmission rate is a maximum of 40 KBPS. Because this bus must interface with other A/C systems, it will probably be a MIL-STD-1553 command response type bus.

- Signal conditioning and A/D conversion hardware requirements have been established (see Phase III for details).
- A comparison of computer hardware characteristics has been made.
- A modular approach to signal conditioning circuitry should be investigated so that IEIS hardware would be adaptable to various aircraft applications.
- Defining a baseline IEIS system (taking into account the AIDS impact) is recommended. The system should be based on a specific engine and could be used in a simulator and/or flight evaluation program.

5.3 Sensors

- Pressure sensors currently used are a strain guage and a bourdon type.
- In order to improve pressure sensing accuracy and to provide digital outputs, frequency output devices such as piezo-electric crystals are projected as future pressure sensors.
- Temperature sensors currently used are thermocouples, resistance temperature detectors (RTD), and optical pyrometers.
- Other temperature measuring techniques which should be developed are the following:
    - Wall Mounted (non-immersion)
    - Resonating Quartz Crystal
    - Fiber Optics Harness
    - Improved Optical Pyrometers
- Vibration parameters will continue to be sensed with piezoelectric accelerometers.
- Flow rate measurements are made using fluid drive angular momentum type flow transmitters.
- Future flow devices will employ fluidic principles to obtain volumetric flow rate and utilize a density measurement to calculate mass flow rate.

- Position sensors presently used are the linear variable differential (LVDT) type.

- Projected future position sensors will be magnetic or optical digital position sensors.

- Speed sensors will continue to be the variable reluctance and eddy current types.

- Torque motor current, which is pulse width modulated, will be measured by a timing technique. This technique is the current standard.

- An improved oil quality measurement technique must be developed. The most promising technique is to measure the magnetic debris in the lube oil.

- Thrust is perhaps the most difficult engine performance parameter to measure directly in an airborne situation. The accuracy of indirect measurements, which require sensing nozzle static pressure and throat area, must be improved significantly to obtain desired thrust accuracy.

- A UV tube with an electronic interface system is the accepted standard device for detecting afterburner lightoff. For the future, smaller, more rugged, and higher temperature range UV detectors should be developed.

5.4 Displays/Display Engineering

- A comparison of candidate display devices indicates that a monochrome CRT best meets the requirements of IEIS.

- Significant improvements in brightness problems and circuit complexity problems of penetration type color CRT's must be made before consideration could be given to them for this application.

- A 5" x 7" viewing surface is recommended. However, displays can be adapted to other sizes, for example the 4" x 5" Phase V display.

- Minimum character size is 3/16 inch and minimum resolution is a 256 x 320 dot matrix equivalent.

- Average power is less than 100 watts.
- Brightness is greater than 100 foot lamberts.
- Contrast ratio is 2:1 in 10,000 foot candles ambient.
- MTBF is greater than 3000 hours.
- A slight edge is given to the raster scan mode of display generation due to simple scan and drive circuitry.
- The recommended approach to display generation using AADC modules is to employ a dedicated PMU and TM, which would operate from a coded display list stored in TM.
- For certain parameters human factors display evaluations utilizing pilot subjects have shown that the IEIS display concepts and formats are satisfactory for engine status monitoring.
- Pictorial displays appear to be a possible alternative display technique, however further investigation and evaluation are required.
- The energy management formats have to be modified and expanded to present more "capability" type information, e.g. fuel management.
- The procedure/checklist type information has to be expanded to cover all mission aspects.
- Consideration should be given to the continuous display of additional parameters, especially fuel flow.
- Some recommendations regarding data deletion and reorientation are reflected in the proposed IEIS formats as shown in Appendix D.
- Dynamic evaluations of the IEIS displays should be undertaken. A simplified engine model could be developed for this purpose.
- The IEIS effort to date has not specifically addressed the engine display requirement posed by VSTOL operation. In particular the area of thrust vectoring displays for all flight phases should be investigated.

- Based on the results of the limited Phase V evaluations of color coded displays, which indicated distinct advantages in display interpretations, we recommend that the future human factors activities include more color evaluation.

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