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PROPULSION INTERFACE UNIT (PIU) CONTROLLER ON PW1120/DEEC RE-ENGINED F4 AIRCRAFT

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Abstract

The re-engining of the F-4 Phantom with PW1120 power plants required an intelligent interface subsystem. This paper briefly describes the design, production, testing, and performance of the Propulsion Interface Unit (PIU), developed to perform this function. The PIU is discussed in terms of its electronics, software, and functional verification. The F-4/PIU flight test and Paris Air Show performance is reviewed and briefly critiqued. A possible production version is discussed in terms of architecture and fabrication methods. Aircraft modernization methodology is discussed utilizing PIU type systems as an integration element.

I. Introduction

To improve the thrust to weight ratio of an engine in an operational fighter by 50% can result in substantial performance increase and economic opportunities. The PW1120 offers this opportunity. A derivative of the F100, the PW1120 represents state of the art in materials and advances in aerodynamic components. Studies of the F-4 re-engined with two PW1120's indicated an increase of 5400 pounds of takeoff thrust with a corresponding reduction in aircraft operating empty weight of 1600 pounds.

The option of re-engining the F-4 with two PW1120 engines was exercised by IAI. Thus the demonstration program of the F-4 with PW1120 engines was launched. The re-engining of the F-4 can be separated into two major categories; 1) the PW1120 installation and 2) subsystem integration. Figure 1 illustrates installation of the PW1120 in the F-4 engine bay. Installation of the PW1120 is characterized by:(1)

- minimal aircraft structural modifications
- minimal engine modifications
- improved aircraft Cg
- Reduced base drag

Subsystem integration requirements came partially as a consequence of the DEEC (Digital Electronic Engine Controller). In addition, various electronic interfaces became necessary to support the modernized propulsion system.

The digitally controlled PW1120 required an intelligent electronic interface for proper integration into the F-4 environment. Figure 2 then became a baseline definition for an intelligent electronic integration device required for incorporation of the PW1120 into the F-4. This device became known as the PIU (Propulsion Interface Unit).

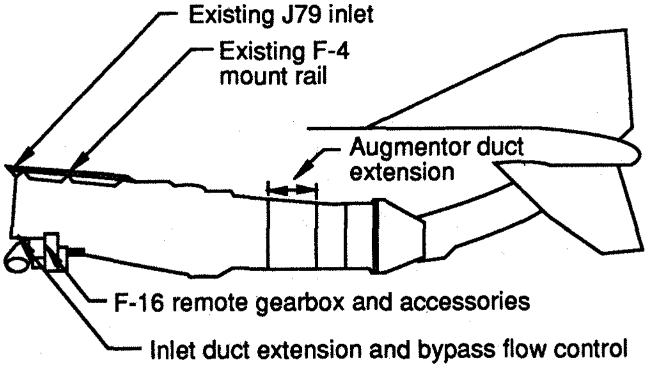

Figure 1. PW1120 Installation in the F-4 Engine Bay

II. PIU Development

A. Overall Requirements and Functional Descriptions

The system integration tasks arising from insertion of PW1120 engines into the F-4 airframe are represented by Figure 3. It is apparent that the major function of the PIU in the re-engining of the F-4 is System Integration. Figure 4 is a full functional block diagram of the PIU integrated PW1120/F-4 system.

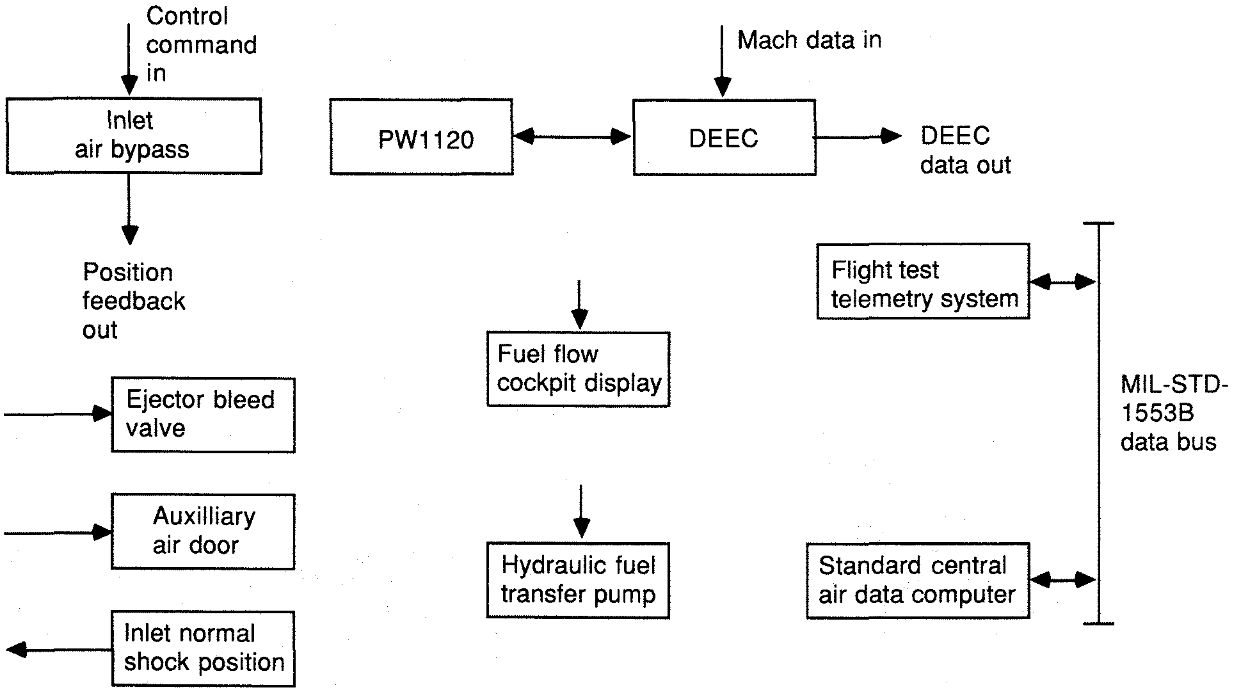

Figure 2. PW1120 Requirements/Opportunities in the J79 Based F4 System Environment

A mission critical requirement of the PIU is the control of the IEDABV (Inlet Extension Duct Air Bypass Valve). Figure 5 is an illustration of the control logic for this function. The objective of the IEDABV control is to maintain a constant Mach number (0.78) at the inlet throat. The IEDABV control operates in two modes. The first mode is based on position feedback, the other is based on pressure feedback. The operating mode is established by the freestream Mach number and the Calibrated Air Speed (CAS).

The DEEC requires current aircraft Mach number to perform its functions, necessitating several integrational functions on the part of the PIU. The DEEC is required to receive Mach information over a nonstandard serial synchronous interface. The aircraft Mach number data was available from the SCADC (Standard Central Air Data Computer) over the MIL-STD-1553B bus. The SCADC is a MIL-STD-1553B Remote Terminal (RT). To meet DEEC requirements, a MIL-STD-1553B Bus Control function was required to transfer air data from the SCADC to the PIU and retransmit to the DEEC. Since the requirement for this function was a simple RT to RT MIL-STD-1553B data transfer, it was possible to design a simplified Bus Controller. Figure 6 illustrates the basic block diagram of this interface.

An important requirement for this project was also the acquisition of flight test data. An FTTS (Flight Test Telemetry System) was installed on the F-4 to provide this function. The flight telemetry unit, similar to the SCADC, is a MIL-STD-1553B RT. The DEEC engine data, available over an RS422 serial interface, was required to be sent to the FTTS, a MIL-STD-1553B device. A special hardware/software interface had to be designed into the PIU to accept the data from the DEEC. The Bus Control function of the PIU was then utilized to transfer DEEC data to the FTTS. Requirement of the engine's oil pressure data for the FTTS was handled similarly. The oil pressure signal, a synchro output, was processed by a PIU synchro to digital interface and transfered to the FTTS over the MIL-STD-1553B bus.

Display of fuel flow in the cockpit was an additional support requirement. Analysis showed that based on information in the DEEC data stream (fuel flow valve position) fuel flow could be computed (Figure 7). This function was incorporated by the PIU, providing an option to hardware metering.

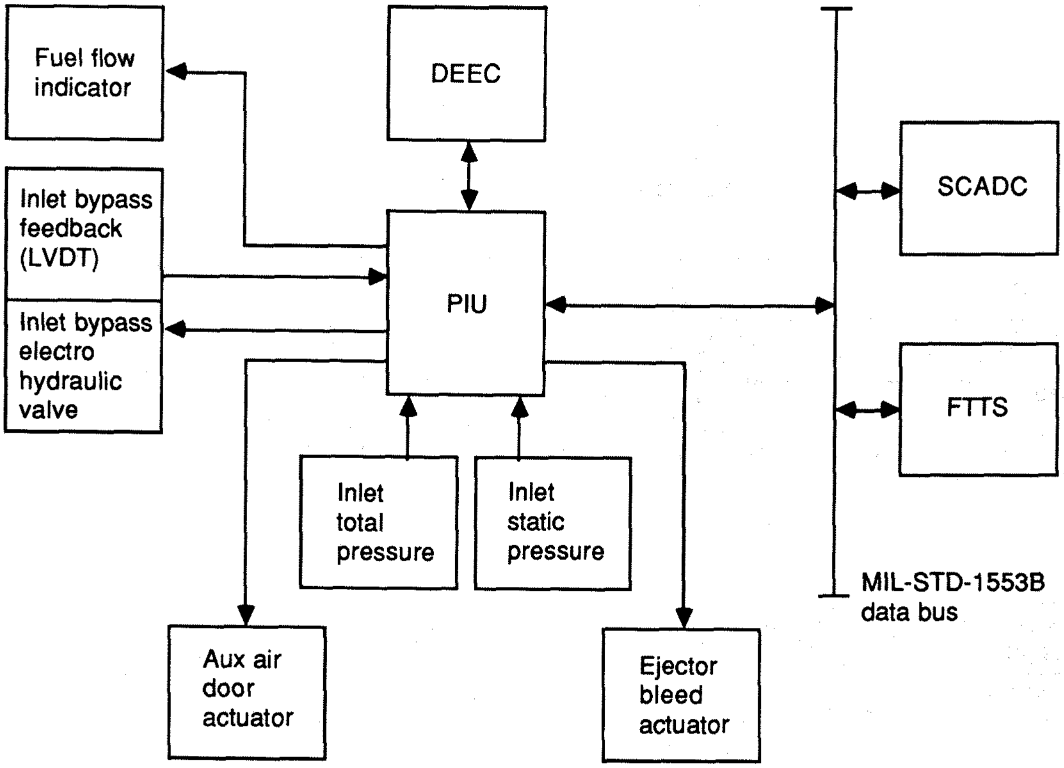

Figure 3. F-4/PIU System Integration

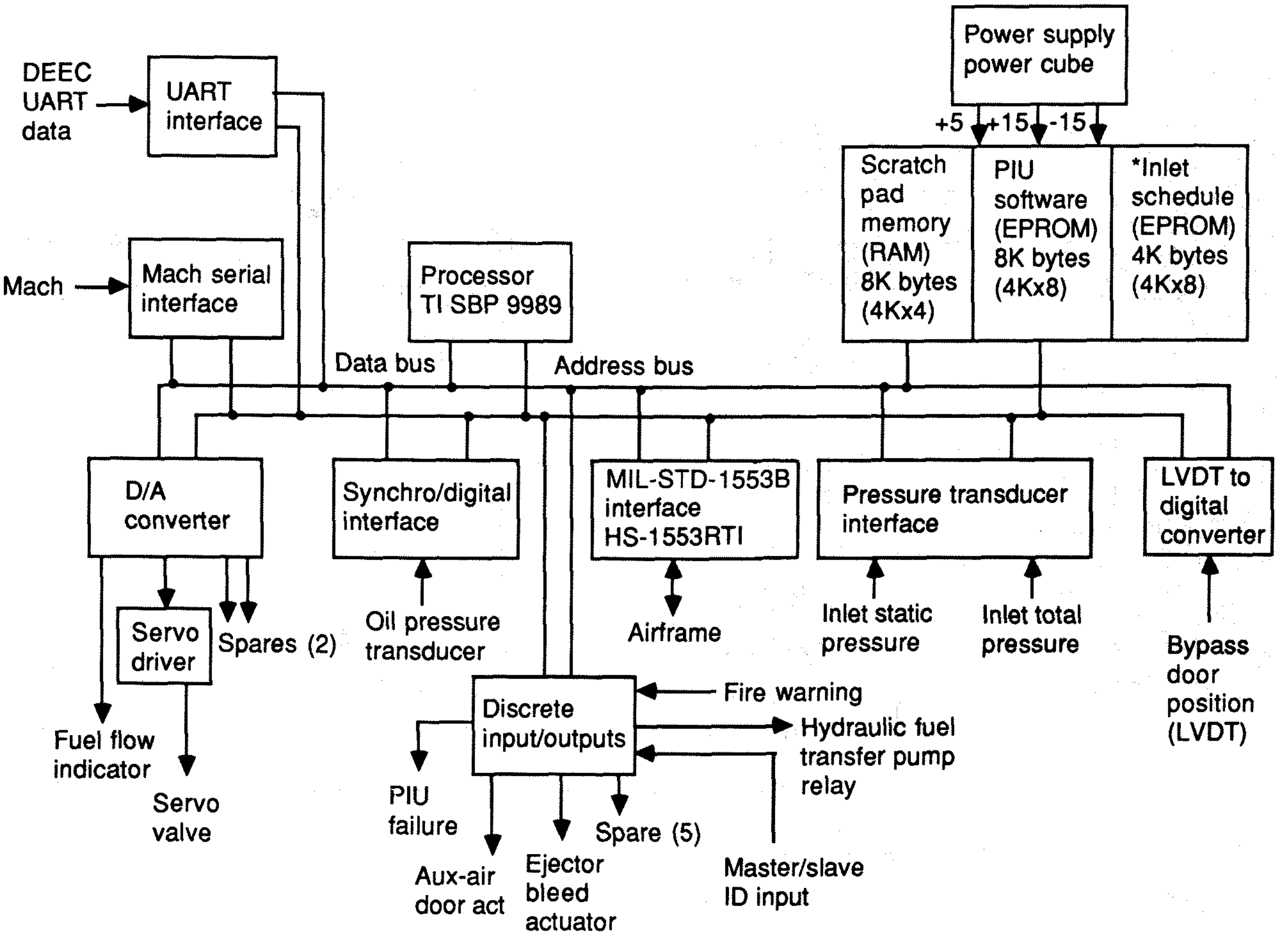

Figure 4. PIU Functional Block Diagram

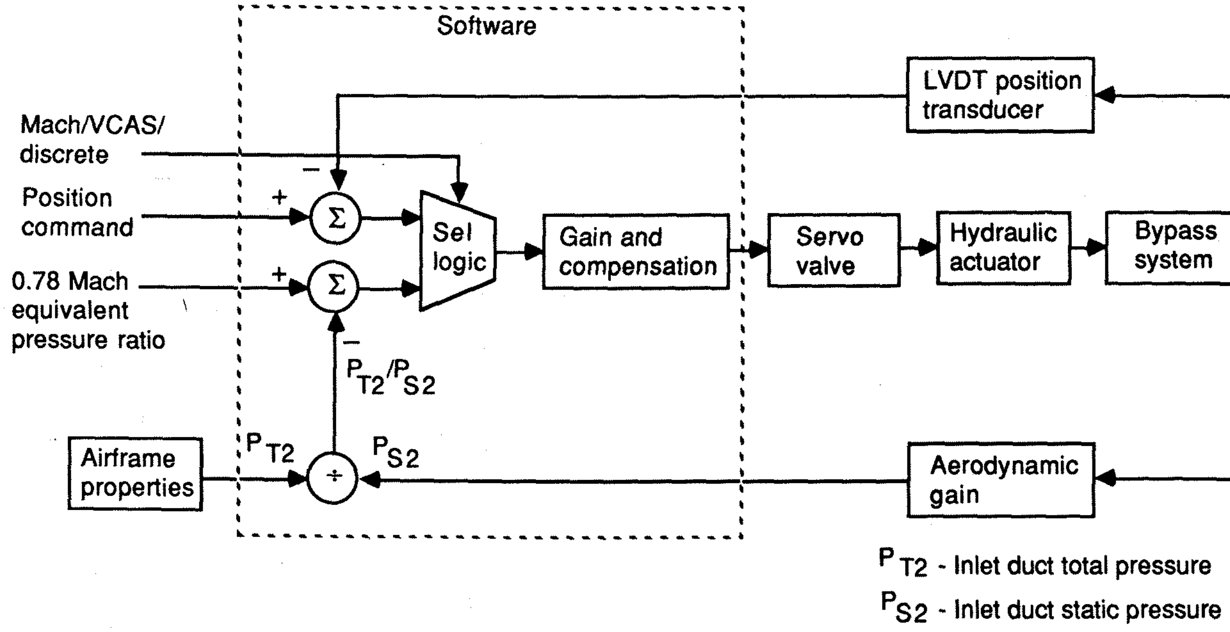

Figure 5. Inlet Extension Duct Air Bypass Valve, (IEDABV) Control Logic

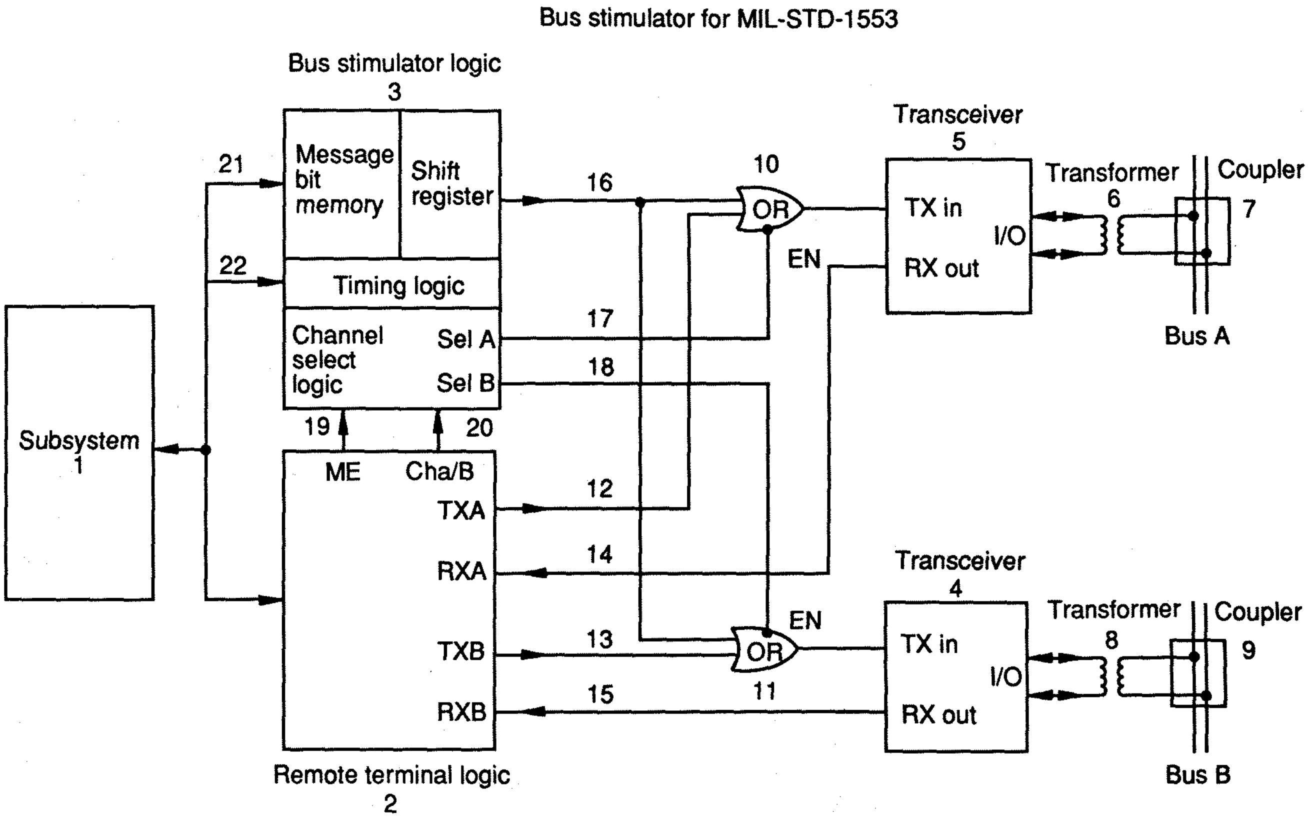

Figure 6. MIL-STD-1553B Bus Stimulator

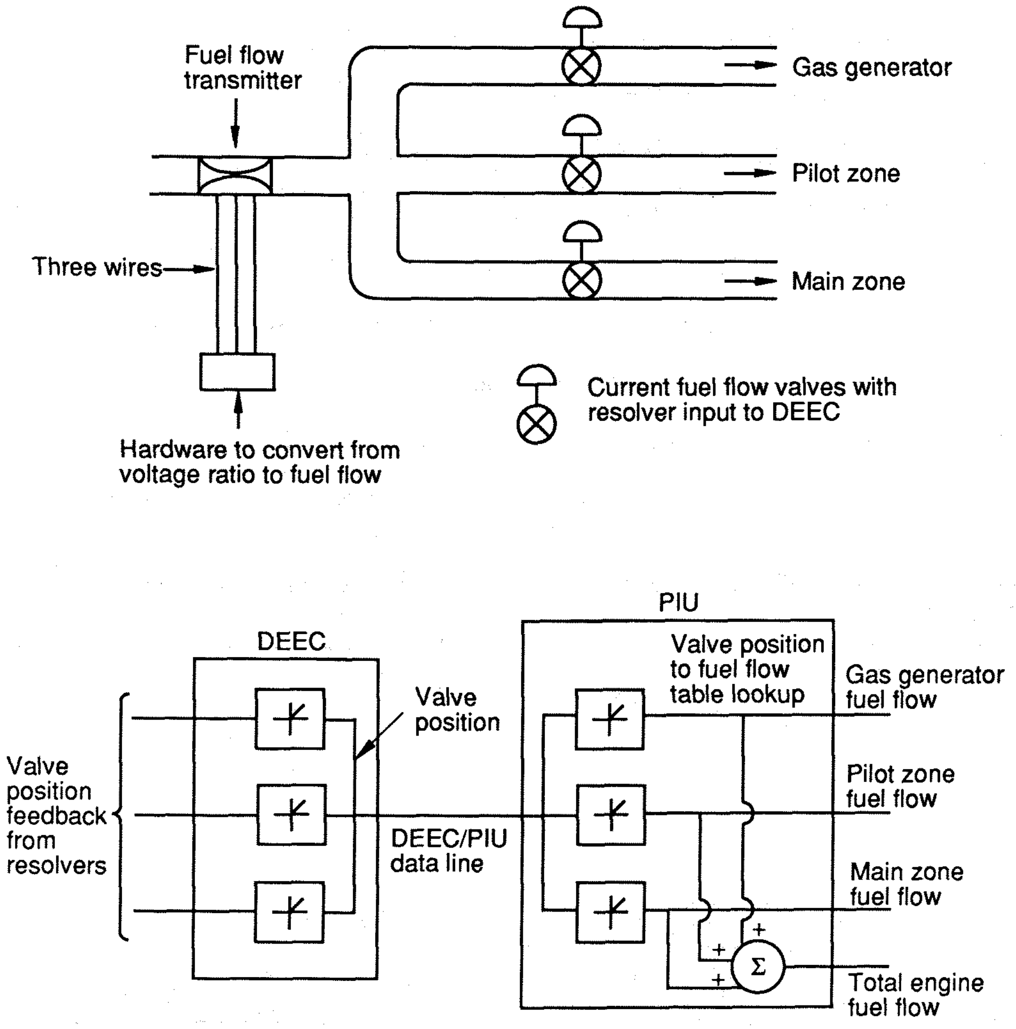

Figure 7. Fuel Flow Computation

Other functions provided by the PIU were the control of the Auxilliary Air Door and the Ejector Bleed Valve. These control functions were based on current Mach number, calibrated airspeed and the fire suppression discrete. The Mach number and the calibrated airspeed information was available from the SCADC data as discussed above. Fire suppression input, provided by a pilot operated cockpit switch, was required for these functions. A discrete input was utilized to sense the state of this switch.

Availability of Power Lever Angle in the DEEC data stream to the PIU made it a convenient point for controlling the HFTP (Hydraulic Fuel Transfer Pump). Pump operation was based on energizing of the HFTP relay as a function of the PLA angle. A major function within the PIU was the Built In Test capability, determining functional state of the PIU and its mission critical interfaces. In the event of a detected PIU failure, a Caution Light on the Control Panel was activated. Table 1 is a summary of PIU functions.

B. PIU Electronic Design

Electronically, the PIU is a digital controller based on a Texas Instruments TI9989 microprocessor. The TI9989 is a 16 bit Current Inject Logic full MIL-STD-883B device. Its main characteristics are;(2)

- memory to memory architecture
- 73 basic instructions including Signed Multiply and Signed Divide
- User extension to the basic instruction
- direct access to 128K BYTES of memory
- Multiprocessor system features

1. Provide aircraft Mach number to the Digital Electronic Engine Controller (DEEC)
2. Control aircraft Inlet Extension Duct Air Bypass Valve (IEDABV)
3. Provide Control for the aircraft Ejector Bleed Actuator (EBA)
4. Provide Control of the aircraft Auxiliary Air Door Actuator (AADA)
5. Place DEEC serial data stream on the MIL-STD-1553B data bus
6. Control the aircraft Hydraulic Fuel Transfer Pump (HFTP)
7. Convert synchro oil pressure signal to digital form and place it on the MIL-STD-1553B data bus
8. Drive the fuel flow display in the cockpit based on fuel flow resolver data from the DEEC
9. Transfer internal PIU data to flight test telemetry over the MIL-STD-1553B data bus
10. Transfer Standard Central Air Data Computer (SCADC) data to flight test telemetry over the MIL-STD-1553B data bus
11. Perform Built In Test (BIT) and control a PIU fault light in the cockpit based on PIU or mission critical PIU peripheral fault

Table 1. PIU Functions

Figure 4 illustrates hardware block diagram of the PIU. System memory consists of 4K words of static ram and 8K words of EPROM's. The EPROM's are divided into two segments. The First segment is used for executable code. The other is utilized to hold system data and field reprogrammable data for control system tuning.

C. Software

Operationally, the PIU software can be grouped into three functions; Real Time operation, task execution, and Failure Detection. Combined, these categories provide the PIU with capability to operate as a stand-alone unit within the environment it was designed for, the F-4 Phantom.

The Real Time operation structure is based on the task scheduler. The logic of the task scheduler is illustrated in Figure 8. Driving this logic is a high level 12.5 ms hardware interrupt. The failure detection consisted of verifying internal system integrity and validity of the data acquired from its interfaces. Internal state was monitored by verification of the entire microprocessor instruction set and performance of a complete memory check. External data acquired over the interfaces was checked for upper and lower limits where appropriate. A watch dog timer circuit was continuously strobed as an indication of normal operation. Failure to provide this input resulted in PIU failure to be activated on the Master Caution Panel in the cockpit.

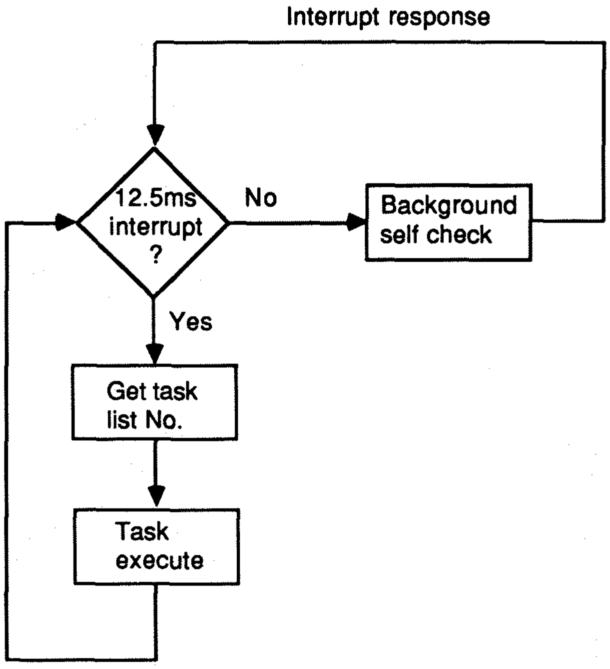

Figure 8. PIU Task Scheduler

A major function of the PIU, illustrating its requirement in the F-4 Phantom, is the control of inlet bypass air. Figure 5 is a block diagram of the IEDABV control system. The inputs to this function are freestream Mach number and Calibrated Air Speed from the SCADC, the total and static pressure values from the inlet pressure transducers, and the fire suppression discrete.

The IEDABV control operates in two modes, position feedback or pressure feedback. The operating mode is established by transitioning of the Mach number and the calibrated airspeed acroBs predetermined limits. This is equivalent to maintaining a pressure ratio (Pt2/Ps2) as derived from the following equation:

$$\frac{P_{t2}}{P_{s2}} = (1 + \frac{\gamma-1}{2} M^2) \frac{\gamma}{\gamma-1}$$

where γ is equal to 1.4.

The controlled pressure ratio is scheduled as a function of aircraft Mach number. When the function is in the position feedback mode, it positions the IEDABV to a fixed position. Position is determined as a function of aircraft Mach number. Typically the IEDABV is positioned to a fixed minimum area. The select logic monitors Mach number, calibrated airspeed, and the fire suppression discrete. Mode selection is based on the status of these inputs. The output of the IEDABV control function is transferred to a Voltage to Current circuit to drive the electro hydraulic valve.

The software function of the PIU is summarized by the software module list in Table 2. A more detailed description of these functions can be found in the Boeing PIU document.

D. Fabrication

The PIU design and fabrication was performed to meet the requirements for flight test of a demonstrator. Only three units were contracted for construction. The following is a brief description of the fabrication of the three units.

Appendix A lists environmental requirements which were met in fabrication of the three PIU's. All integrated circuits and electronic components used in the design were "off the shelf" items in order to simplify parts acquisition.

The digital and analog circuitry comprising the PIU logic are typically made up of the dual in line package type, meeting the MIL-STD-883B. The logic was assembled on MUPAC wire wrap boards. These boards are ideal for implementing prototype designs while conforming to specifications to allow implementation of high reliability analog and digital circuitry. Figure 9 illustrates the CPU board component side. A power supply was selected for its minimal weight and conformance to all applicable MIL-STD's. An off the shelf enclosure was selected primarily for its low weight and conformance to EMI (Electro Magnetic Interference) requirement. All connectors on the PIU conformed to the required MIL-STD's for aircraft use in addition to EMI specification. Figure 10 is an illustration of the completed PIU.

Module Name
Reset Initialization
Task Scheduler Interrupt Service
DEEC Data Interrupt Service
Watchdog Timer Interrupt Service
Bus Activity Done Interrupt Service
Microprocessor Failed Interrupt Service
DEEC Data Verify and Transmission
SCADC to PIU No. 1 Data Transfer and Verify
PIU No. 1 and No. 2 Internal Data to FTTS
Poll PIU No. 2 for Data Requests
Oil Pressure Conversion
Send Converted Mach Number to DEEC
Read and Restart the Paros Converters
Inlet Extension Air Bypass Valve Control Function
Lead-Lag Compensation Routine
Fuel Flow Display Function
Ejector Bleed Valve Control Function
Auxiliary Air Door Control Function
Hydraulic Fuel Transfer Pump Control Function
Fire Suppression Discrete Validation
Real Time Portion of Self Test
Non Real Time Portion of Self Test
Univariate Table Lookup
Bus Activity Generator Subroutine

Table 2. PIU Executable Software Modules

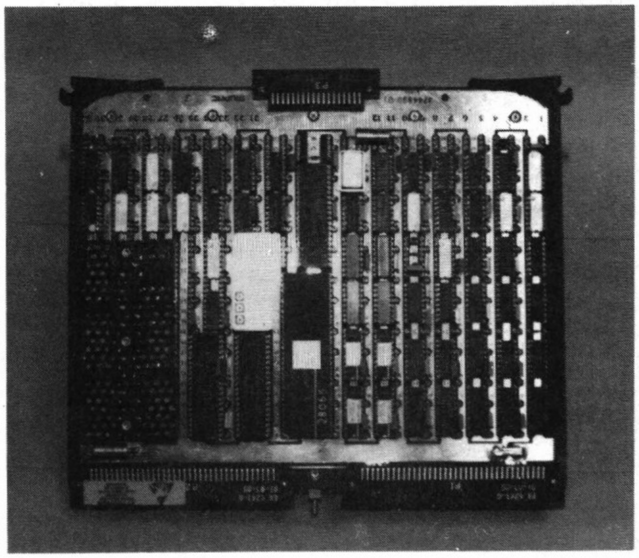

Figure 9. CPU Board

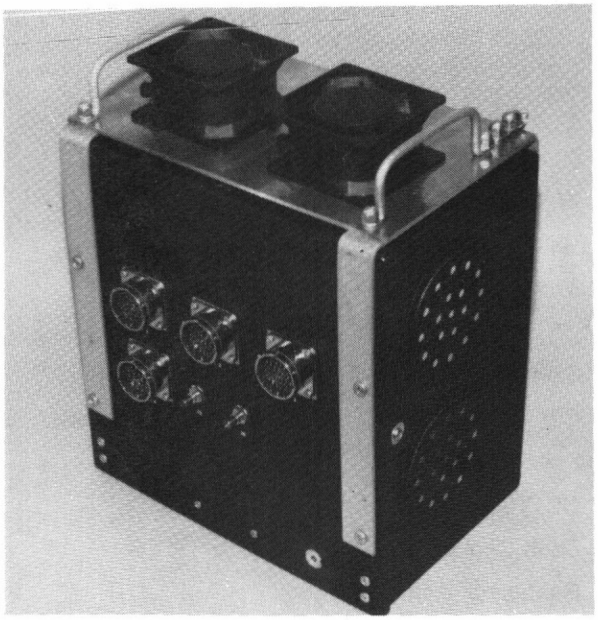

Figure 10. Installation Ready PIU

E. Testing and Validation

A critical aspect of producing flight qualified electronic equipment is testing and validation. All PIU test and validation activities were performed under full supervision of the Boeing Quality Assurance Program. The Test results have been documented and archived by the Boeing Advanced Systems.

The PIU qualification consisted of the Acceptance Test and Flight Clearance Test for the first PIU unit. Subsequent units were subjected to the Acceptance Test. The Acceptance Test consisted of Functional Testing, Burn-In, and Weight testing. The Flight Clearance Test consisted of Functional, Vibration, Combined Altitude Temperature, and repetition of Functional testing.

The Acceptance Test was designed such that the PIU was required to operate in conditions similar to its operating environment, the F-4 aircraft. Figure 11, illustrating the Test Setup, functionally provides the F-4 environment. From the Test Setup it can be seen that every PIU interface is being exercised and tested. For purpose of test validity, real equipment was provided whenever possible.

The test set up clearly indicates that every effort was made to insure fault free operation upon installation in the aircraft. Minor difficulties surfaced and were easily corrected on site upon installation. Overall, the test and qualification proved to be a valid process resulting in delivery of a product operational per design specifications.

III. PW1120 Installation

The F-4 B/C/D/E/J aircraft were designed for compatability with the GE J-79 engine in mind. Structural and system modifications were necessary to accomodate the PW1120 engine. Differences in length between the forward mount, thrust mount and the nozzle exhaust plane of each engine required aircraft internal structure modification. The PW1120 engine's lower contour interferes with the inside contour of the existing engine bay door. New doors were designed which minimized external contour changes but which provided the requisite engine clearance.

The J-79 nozzle control actuators are powered by high pressure fuel and do not require external ports. The Super Phantom configured with PW1120 incorporates nozzle control powered by a high-pressure high-temperature air turbine. The hot turbine exhaust air is ducted through the engine bay doors.

The PW1120 engine requires an airframe-mounted accessary drive system (AMAD). The AMAD is powered by the engine gear box through a removable high speed drive shaft. The integrated drive generator (IDG), two hydraulic system pumps, and the engine start system are mounted on appropriate pads of the AMAD. The AMAD is supported from an extension to the engine inlet duct and by the aircraft lower structure. In turn, the inlet extension duct (IED) is supported by the existing inlet duct at the main spar bulkhead and by the aircraft keel beam and side wall.

The aircraft structure in the vicinity of the engine cannot exceed a maximum allowable temperature of 715°F. J-79 installation requires inlet cooling air bypassed into the engine bay and out through the engine nozzle. The PW1120 outer case maximum temperature does not exceed 560°F and therefore, does not require cooling air. Control of the bypass airflow for the PW1120 installation is enabled by the PIU.

Engine bay ventilation flow is necessary, above Mach 1.2. This is provided by the inlet bypass air flow. For flight conditions less then Mach 1.2 external inlet scoops were installed on the aircraft side walls and engine removal doors to provide engine bay ventilation flow. The inlet bypass air flow exits through an annular space around the PW1120 nozzle.

IV. F-4/PIU Performance

The performance of the PIU is tightly coupled with the performance of the re-engined F-4 Phantom. Several landmarks in the completion of this effort should be mentioned to fully illustrate the coupling of the electronics with the airframe. The re-engining of the F-4 consisted of first evaluating the airframe with one PW1120 and one J79. The next stage consisted of twin PW1120 operation. This period consisted of extensive ground and flight testing.

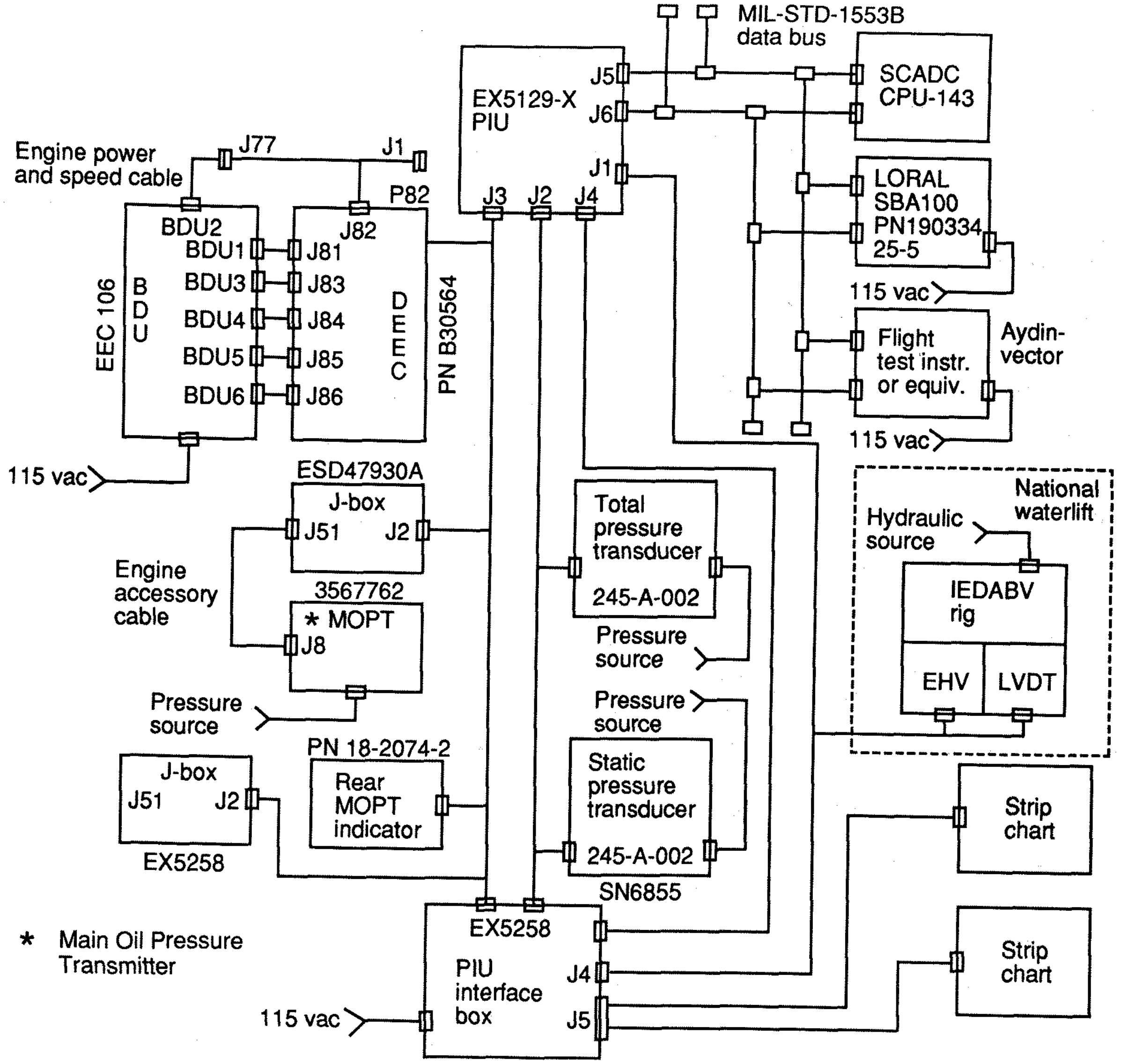

Figure 11. Test Set-Up Schematic

The final landmark in this project was a flight demonstration of the reengined F-4 Phantom at the 1987 Paris Air Show. Though not as publicised, an additional performance test of the re-engined F-4 Phantom occured in a "fly off" with an F- 15 sometime following the Paris Air Show.

The first phase of re-engining consisted of operation with one PW1120 and one J79 engine. Prior to PIU installation, airframe configuration and wiring was verified to assure proper operating environment. Following this procedure, the Field programmable EPROMS were changed to accomodate specific LVDT and pressure transducer calibration. At completion of installation and callibration, the PIU was tested for communication with the DEEC, the SCADC and the FTTS. Supporting this effort were two Boeing engineers using most of the test instrumentation set up from the validation testing. With the PIU operation confirmed, the F-4 Phantom continued to complete appropriate ground testing. On July 30, 1986 the mixed engine F-4 Phantom made its first flight. Flight telemetry data indicated normal PIU operation. With the completion of this phase, efforts were immediately initiated to install the second engine to be ready for the Paris Air Show.

The two engine two PIU operation and support was relatively simple. The major portion of the work was completed during installation of the first unit. The two PIU operation ran into minor difficulties which were easily resolved on site. Following full ground testing, the F-4 Phantom fully re-engined with the PW1120 engines took off in April of 1987. FTTS data indicated normal PIU operation. The F-4 was now ready for the Paris Air Show.

The Paris Air Show demonstrated the quality of the work performed on the aircraft. The 4 minute demonstration sequences flown were flawless. Following a short takeoff, the F-4 rotated to full vertical attitude in its climb to demonstration altitude, demonstrating its thrust to weight characteristics.

The Paris Air Show provided an excellent opportunity to demonstrate the re-engined F-4. However, a true test of a new fighter is a "fly off" against a known factor such as the F-15. Following the Paris Air Show the re-engined F-4 Phantom was evaluated against the F-15. The Phantom was able to out accelerate the F-15 in a straight path. The F-15, however, outperformed the F-4 during turns due to wing loading differences between the aircraft. The "fly off" was not performed to conclusively evaluate detailed differences between the aircraft. In addition, fuel weight was not appropriately considered in the matchup. Furthermore, the production structural changes are expected to result in (F-4 configuration) at least 1000 pounds lighter then the demonstrator. These differences can substantially impact performance of an aircraft.

V. Production PIU & Aircraft Modernization Methodology

In the event of a full modernization of the F-4 Phantom with the PW1120 engines, a production version of the PIU needs to be considered. It is possible to implement current design and fabrication methods to produce additional units. However, this is not a cost effective method for a production run. Weight, fault tolerance, and fabrication methods for production units are therefore expected to be substantially different. Design and functionality are similarly expected to change due to the benefit of the experience gained from the demonstrator.

In considering the Production Unit it is neccessary to address two major categories. The first category is the general architecture of such a unit.

Redundancy, parallelism, throughput requirements, and processor selection are among the major details to be addressed in this area. The second category is fabrication. Design verification, printed circuitry, and packaging for reduced weight are critical in a military aircraft. The architecture and fabrication of a production unit are as critical as its basic function within the aircraft.

Architecturally, the PIU system is a straight forward one PIU per one engine design. There were no provisions for redundancy and fault tolerance. In case of a fault, pilot instructions are to shut down the PIU. This results in a safe, hard wired power down physical system configuration. Though adequate for a test program, such a system can not be utilized in a functional military aircraft. Fault tolerance must be built into modern aircraft electronic controls as well as physical subsystems. A fault tolerant system can dramatically improve the survivability of an aircraft. In addition, it can also enhance its capability to complete its mission. In a combat situation this feature can no longer be considered an option. Fault tolerance is a must in today's sophisticated electronic subsystems.

A possible option for a production PIU CPU board is a system based on three CPU's. The essential part of the system consists of the process control CPU and the I/O CPU. The third CPU is utilized as a backup, performing system checks and possible co-processing in case of such work as model reference control. Redundancy and fault tolerance is incorporated by utilizing Hard Wired Configuration Control Logic (HWCCL). In effect HWCCL is a sophisticated watch-dog timer controlling the entire system interconnection and configuration. The purpose of HWCCL is to isolate a faulted subsystem and to provide a configuration information to the rest of the system. In this manner the backup CPU can assume the role of either the Central Process CPU or an I/O CPU.

Similarly, the HWCCL can be configured such that a single CPU should be capable of performing all required functions. The later could be configured to execute only the more critical functions to maintain system throughput. Sufficiently high throughput processors, such as the Motorola 68030 running at 20 to 30 MHZ, or the newer RISC devices such as the AMD 29000, can be utilized to provide adequate throughput for a single unit to cover dual engine operation and support.

An important feature, often not given adequate importance in the architecure of a system, is maintenance. Difficult to maintain and troubleshoot subsystems result in prolonged grounding of aircraft. In a military environment this is a critical issue that needs to be addressed. A special interface is proposed to be incorporated into a production unit to provide an external device with capability to completely interrogate a downed system. EEPROMS can be utilized to maintain full records of system operation and failures during operation. These can be routinely accessed by regular maintenance, thus improving system reliability and early fault detection.

The fabrication process of a production unit is typically more rigorous then that of a prototype. Conceptually, a prototype is a unit still open to major design changes. The production unit is an implementation of a completed design. Modern Computer Aided Electronic Design (CAED) tools such as the Daisy CAED and Mentor CAED allow for relatively trouble free design of digital and analog systems. These tools allow for accurate system simulation, thus verifying proper logic and system timing. In addition, more sophisticated options, such as Hardware In The Loop, allow for checking of subsystem design with actual hardware interface to simulated logic. The result is a substantial saving in labor, fast turnaround from design to implementation, and a higher quality finished product.

It is apparent that major differences exist between prototype and proposed production units. The discussion above is intended to explore some of the issues and methods of approaching a production program.

VI. Conclusion

The cost of designing and producing a new airframe today makes it apparent that modernization programs should be viewed as an ongoing process for all existing and future airframes. The implication is that airframers must seriously start designing future airframes with maximum capability to incorporate new technology. Increasingly, electronic development is revolutionizing communication, controls, weapons, and detection subsystems. The need to rapidly incorporate new technology into an existing airframe is well illustrated by the F-4 modernization program. The 50's airframe required modification structurally and electronically to incorporate a new propulsion system. The PIU program served to illustrate that the F-4 system was not capable of absorbing new technology on its own. The PIU served as an integration device, providing subsystem communication, pilot interface, instrumentation, and auxilliary control functions. Designing this capability into future systems will result in systems that could be easily updated with new technology. It is suggested that the most expedient method to provide this capability is to incorporate high speed standard optical communication networks into the new airframes. Separate buses for sensors, actuators, and subsystem communication can result in highly reconfigurable and adaptable systems. Standard communication protocols could provide global control and database access to all subsystems. The existence of aging airframes capable of being greatly optimized through modernization programs makes the PIU a viable method of integrating these changes. In the future it is the concept of the PIU that must be incorporated in airframe systems to provide new technology integration capability.

VII. Acknowledgements

Propulsion Controls of the Boeing Advanced System is greatly indebted to several people for their advice and technical assistance in the PIU project. G. Mount, D. Cluett, and J. Gill of P&WA were deeply involved in providing frequent input as well as consultation. A Lavi and A. Edlestein of IAI, A. Kolran of IAF, and E. Zapel of BAS, similarly had great impact on the technical success of the program. Overall, the project success was largely due to the intercompany team spirit born out of the mutual goal to accomplish the work and the opportunity to demonstrate the improved aircraft at the Paris Air Show.

Appendix A
Military Standards
Test Documents Military Standards and Drawings

Boeing Military Airplane Company Documents:

D180-28977-1 Flight Clearance Test by Analysis for Propulsion Interface Unit, May 1985.

D180-29031-1 System Level Bench Test Plan, July 1985

D180-29080-1 PIU Acceptance Test Plan

D180-28961-1 Part I Software Specification

DRAWINGS:

Boeing Drawing EX5236, PIU Interface IAF Drawing 2207-60-004 PIU System

Military Standards:

MIL-STD-810C Method 504-1

Mil-STD-781C

MIL-E-5400T

MIL-STD-883B

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