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GMA200 ATEGG DIGITAL CONTROLS DEMONSTRATION

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Detroit Diesel Allison
Division of General Motors Corporation
P.O. Box 894
Indianapolis, Indiana 46206

December 1978

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Final Report for Period January 1977 - September 1978

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

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This report describes the results of the closed-loop, on engine test of the Bendix EH-K1 digital controller on Build 5 of the Advanced Technology Engine Gas Generator (ATEGG). Control modes are described with emphasis on changes to be incorporated on ATEGG Build 6. The control mode changes include simplification of the fuel governor structure, modification of the fuel splitter logic to aid main fuel system light-off, and modification

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ABSTRACT (Cont'd.)

of the fuel limiting logic to prevent transient overshoots of critical engine parameters. Off-engine testing of the controller with the ATEGG fuel system is discussed. Fuel system characteristics were analyzed and adjusted to yield tighter control of engine fuel flow. The Build 5 test stand set-up and instrumentation are described, along with testing accomplished and data correlation. The open loop operation of the controller was successfully demonstrated, and data correlation with test stand values was satisfactory. Successful closed loop digital control operation was exercised at the end of Build 5 engine testing.

FOREWORD

This test report was prepared by Detroit Diesel Allison, Division of General Motors Corporation with Bendix, Energy Controls Division, as a major subcontractor. The effort was sponsored by the Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Contract F33657-76-C-0021, P00006, for the period January, 1977 to September, 1978. The work herein was accomplished under Project 668A, Task 02, Work Unit 30 with Mr. Marvin P. Wannemacher, AFAPL/TBP, as Air Force Program Manager. Mr. Lester L. Small, AFAPL/TBC, technically directed the work. Mr. John A. Weber of Allison was technically responsible for the work. Other contributing Allison personnel were D. E. Warner and K. A. Pieper. F. J. O'Keefe of Bendix aided in portions of the fuel system analysis. The final submission of this report was made on October 15, 1979.

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GLOSSARY OF TERMS

A/D	Analog to Digital Conversion
AFAPL	Air Force Aero-Propulsion Laboratory
ATEGG	Advanced Turbine Engine Gas Generator
A8	Variable Area Exhaust Nozzle
A8FB	Variable Area Exhaust Nozzle Position Feedback
BOT	Burner Outlet Temperature
BU X	Buildup Number X
CDP	Compressor Discharge Pressure
CJ	Cold Junction
CPU	Central Processing Unit
CRT	Cathode Ray Tube
D/A	Digital to Analog Conversion
DAC	Digital to Analog Converter
DDA	Detroit Diesel Allison
EDR	Engineering Design Report
EHSV	Electro-Hydraulic Servo Valve
F/B	Feedback
F_N	Net Thrust
GMC	General Motors Corporation
HP	High Pressure
HPC	High Pressure Compressor
HPC1	High Pressure Compressor Airflow Control Signal
HPC1FB	High Pressure Compressor Airflow Control Position Feedback
HPC2	High Pressure Compressor Surge Avoidance Control Signal
HPC2FB	High Pressure Compressor Surge Avoidance Control Position Feedback

HPT	High Pressure Turbine
HPTFB	High Pressure Turbine Control Position Feedback
I/O	Input/Output
IR&D	Independent Research and Development
JTDE	Joint Technology Demonstrator Engine
K	Gain
K_I	Integral Gain
K_P	Proportional Gain
LVDT	Linear Variable Differential Transformer
MUX	Multiplexer
N_H	High Pressure Rotor Speed
NHA	High Pressure Rotor Speed - Channel A
NHB	High Pressure Rotor Speed - Channel B
NHC	High Pressure Rotor Speed corrected to Rotor inlet
OGV	Outlet Guide Vanes
OPA8	Operator Request for Exhaust Nozzle Area Position
OPHPC2	Operator Request for Compressor Variable Stator Position
OPHPT	Operator Request for Turbine Variable Vane Position
OPWFA	Operator Request for Fuel Flow through Channel A
OPWFB	Operator Request for Fuel Flow through Channel B
P	Pressure
P+I	Proportional plus Integral
PLA	Power Lever Angle
PXS	Static Pressure at Station Location X
PXT	Total Pressure at Station Location X

RAM	Random Access Memory
REF	Reference Value
REQ	Requested Value
RIT	Rotor Inlet Temperature
RPR	Ram Pressure Ratio
s	Laplace Operator
SEL	Scientific Engineering Laboratory
T	Temperature
TBT	Turbine Blade Temperature
TBT_{AVG}	Average Turbine Blade Temperature
TBT_{Peak}	Peak Turbine Blade Temperature
T/C	Thermocouple
T_E	Temperature as measured by Engelhard probe
Ti	Titanium
T/M	Torque Motor
TOT	Turbine Outlet Temperature
TX	Temperature at Station Location X
UTC	Universal Test Console
VCE	Variable Cycle Engine
VG	Variable Geometry
W	Flow
WA	Airflow
WAC	Airflow Corrected to Rotor Inlet
WF	Fuel Flow
WFA	Fuel Flow through Channel A
WF_{ACCEL}	Acceleration Logic Fuel Flow Request
WFAFB	Feedback of Fuel Flow through Channel A
WFB	Fuel Flow through Channel B
WFBFB	Feedback of Fuel Flow through Channel B
WF_{DECEL}	Deceleration Logic Fuel Flow Request

WF_E	Engine Fuel Flow
WF_{GOV}	Governor Logic Fuel Flow Request
WF_{Main}	Fuel Flow through Main Fuel System
WF_{Pilot}	Fuel Flow through Pilot Fuel System
WX	Airflow at Station Location X
W4B	Compressor 4th Stage Bleed Airflow
W6B	Compressor 6th Stage Bleed Airflow
	Differential
	Correction Factor for Standard Pressure
	Error
	Correction Factor for Standard Temperature
	Time Constant

SECTION I
INTRODUCTION

Detroit Diesel Allison (DDA) Division of GMC has ongoing Advanced Turbine Engine Gas Generator (ATEGG) and Joint Technology Demonstrator (JTD) programs which require a flexible engine controller to perform planned transient tests. The JTD Gas Generator Full Authority Digital Controller Feasibility Study, an addition to Contract F33657-76-C-0021, previously had investigated the feasibility of controlling the gas generator, providing self-checks and incorporating fail-safe operation using the Bendix EH-K1 engine-mounted digital controller. The purpose of this effort was to demonstrate, via actual engine test, the use of the Bendix EH-K1 digital controller for control of the JTD gas generator.

Task I of the Demonstration program updated the control system developed in the Feasibility Study. DDA revised engine schedule values to reflect the latest engine test data and GMA 200 ATEGG cyclic endurance test requirements. Bendix fabricated and checked out computer support hardware consisting of a test console and an off-engine mounted core memory module. Bendix then coded the revised software and tested it on the EH-K1 controller. The controller was then mated to the ATEGG fuel system, cabling, and actuator simulator circuits and extensive fuel system testing was done.

Task II of the program performed an open-loop piggyback test of the control system. The control was mounted on the engine and tested with all engine geometry actuators. The control was then monitored during engine testing for correspondence of converted inputs, polarity of actuator and feedback signals, and correct indication of signal and self-check features.

Task III updated the control logic based on information gained during Task II, exercised the revised logic with an analog engine model, performed in an open-loop piggyback fashion during the initial part of B.U. 5 testing, and finally demonstrated closed loop control of ATEGG.

SECTION II
SUMMARY

The purpose of the GMA200 ATEGG Digital Control Demonstration was the performance of an open loop piggyback test of the control system followed by a demonstration of closed loop control of ATEGG by the Bendix EH-K1 Digital Controller. Preparation for this testing included interfacing the EH-K1 with an analog model of ATEGG and also interfacing with the GMA200 fuel system in an off-engine configuration to verify the controller software. The piggyback testing during actual engine operation permitted data to be correlated. The closed loop operation was preceded by open-loop exercising of the engine geometry actuators. Finally the EH-K1 demonstrated closed loop control of the engine.

A digital controller Model No. EH-K1 was provided by Bendix Energy Controls Division. It is the task of the controller and its software to execute the control functions of ATEGG. The primary function is to accomplish the control mode computation. Other functions include input and output signal processing, diagnostic checks, and real-time interactive capabilities.

In the control mode, fuel is controlled to achieve successful engine starting, safe transient excursions, and speed governing during steady state operation. Engine starting fuel flow is modulated in a "hand valve" fashion with Power Lever Angle (PLA) movement. Transient excursions are handled by acceleration and deceleration fuel flow schedules as a function of corrected compressor speed (NHC) and compressor discharge pressure (P3). In steady state operation, fuel flow is modulated to govern to a particular NHC. Critical engine limits are maintained by a fuel flow request. The remainder of the ATEGG Control Mode controls three variable geometry components: variable compressor stators, variable turbine stators, and a variable area exhaust nozzle. The variable stators of the compressor provide maximum surge protection as well as variable flow capacity. Presently no actuation system exists to move the variable flow mechanism during engine operation, but the surge avoidance mechanism is active. The variable turbine geometry control mode moves vanes to achieve a desired, scheduled relationship of Turbine

Outlet Temperature versus PLA. Maintaining this closed loop control of an engine parameter with the HPT vanes permits self-trimming engine operation. The variable area exhaust nozzle is presently tied to PLA. Coordination of movement with the nozzle, turbine, and fuel flow provides for efficient engine operation over a wide range of test conditions.

Also in the control section of the EH-K1 software is logic which synthesizes turbine rotor inlet temperature (RIT). Compressor discharge airflow (W3) is reproduced through measurement of pressures and temperatures and knowledge of a physical area at the compressor discharge. Synthesis of RIT uses this compressor discharge airflow value, other compressor discharge measured parameters, and fuel flow request from the control mode logic.

Any signal appearing in the control logic which is fed back from the engine or control interface hardware is processed through the Input/Output Processing section of the software. In addition to checking for signal reasonableness through range and rate checks, static compensation is added to remove unwanted biases and dynamic compensation is added for purposes of stability.

Diagnostic checks insure that the computer is performing properly. Self checks of the CPU and the memory monitor computer health.

The interactive module of the EH-K1 software provides a real time communication link to the software. Interaction through a CRT allows selection of operation mode, display of control logic parameters, alteration of the control mode software, and plotting capabilities.

The EH-K1 software was verified in two phases prior to B.U. 4 and B.U. 5 testing of ATEGG. The first phase was verification with a nonlinear real-time, analog engine model. The second phase included interfacing the EH-K1 with the ATEGG fuel system and verifying proper operation with the actual hardware components.

A simplified simulation of the ATEGG engine was programmed on the Bendix hybrid computer to examine the engine's behavior with the programmed control mode. Loop stability was examined, and control gains were modified for the characteristics of the B.U. 5 operating line. Extended transients and parameter pulldowns were run to examine particular areas of the control mode including the fuel governor, the fuel acceleration logic, the fuel deceleration logic, the fuel limiter loops, and the signal synthesis logic. The fuel governor gains, as sized, yielded stable engine operation at all anticipated operating points. Safe transient behavior was observed as regulated by the fuel acceleration/deceleration logic. The fuel limiter logic functioned correctly with the B.U. 5 test characteristics. Finally the signal synthesis logic, synthesizing inlet airflow and rotor inlet temperature, was exercised and modified in an attempt to improve performance on B.U. 5 relative to B.U. 4.

Fuel system testing was also performed prior to B.U. 4 and B.U. 5 engine testing. The EH-K1 was interfaced with the GMA200 fuel system to accomplish phase II of the software verification. During this stage of the verification the pilot fuel system exhibited responsive behavior to stepped requests, but noisy about-a-point fuel modulation. This noise was reduced by redistributing the gain in the fuel valve positional loop.

While still interfaced with the fuel system, a simplified engine model, represented by a gain and a simple lag, was mechanized. This model made it possible to close the governor loop and to activate the fuel control portion of the EH-K1 software. Stability of the governor loop was verified for various engine lags and inlet conditions. Extended transient excursions were used to examine transient fuel flow metering characteristics. Proper implementation of the fuel valve splitter logic was also exhibited with this model.

After concluding the off-engine fuel system testing, the EH-K1 was mounted on ATEGG for piggyback operation during B.U. 5 engine testing. Test data was accumulated from the engine measurement instrumentation interfacing with the EH-K1, and this data was correlated with engine data processed through the System's Engineering Laboratory (SEL) data acquisition system. Satisfactory correlation was indicated with all points compared.

Closed loop testing of the EH-K1 with ATEGG was accomplished with two successful starts and power calibration running up to 85% NHC. The EH-K1 behaved satisfactorily, but the testing allowed insight into necessary modifications to the start logic and the fuel splitter logic within the control mode.

This program evaluated and demonstrated the feasibility of controlling a variable cycle engine with an engine mounted digital controller. A set of VCE control logic was synthesized that featured closed loop (i.e. trim free) control of fuel and turbine area. Logic synthesis via a detailed, non-real-time engine model as well as software checkout techniques using real-time non-linear models derived from the detailed model were proven. Modular programming of the EH-K1 made it relatively easy to incorporate and checkout software changes between builds.

The success of the digital controller on B.U. 5 has convinced the DDA ATEGG project group of the controller's safety and reliability. Follow-on control efforts will be carried under ATEGG funding for all three builds in the ATEGG XII program.

SECTION III
ENGINE AND ASSOCIATED HARDWARE

1. Engine Components

The Air Force originated the technique of developing advanced gas generator components in the Advanced Turbine Engine Gas Generator (ATEGG) program. The GMA200 gas generator (Figure 1) is adaptable to a wide range of transonic/supersonic applications. It incorporates a six stage, variable flow compressor; a staged high heat release, annular combustion system; and a variable area, transpiration-cooled, high work turbine capable of operating near stoichiometric temperatures. The gas generator is flightweight from the front compressor flange to the aft turbine flange and incorporates a test equipment-type front support, to simulate the flow path between a fan and the compressor inlet, and a test equipment-type variable exhaust nozzle and rear bearing support.

Mission analysis indicated that the GMA200 should incorporate variable geometry capabilities in all of the major engine components. This flexibility can be used to match the various components at widely variable operational conditions and to match the engine characteristics to the inlet and exhaust system to obtain the best possible total system performance. Flexibility is achieved by the use of variable geometry designed into the variable-flow compressor and the variable-area, air cooled turbine components. Exit area variability is provided by a test equipment, variable exhaust nozzle.

a. Inlet

A reinforced plastic air inlet housing is part of test equipment. It simulates the fan-to-compressor transition flow path of a turbofan engine.

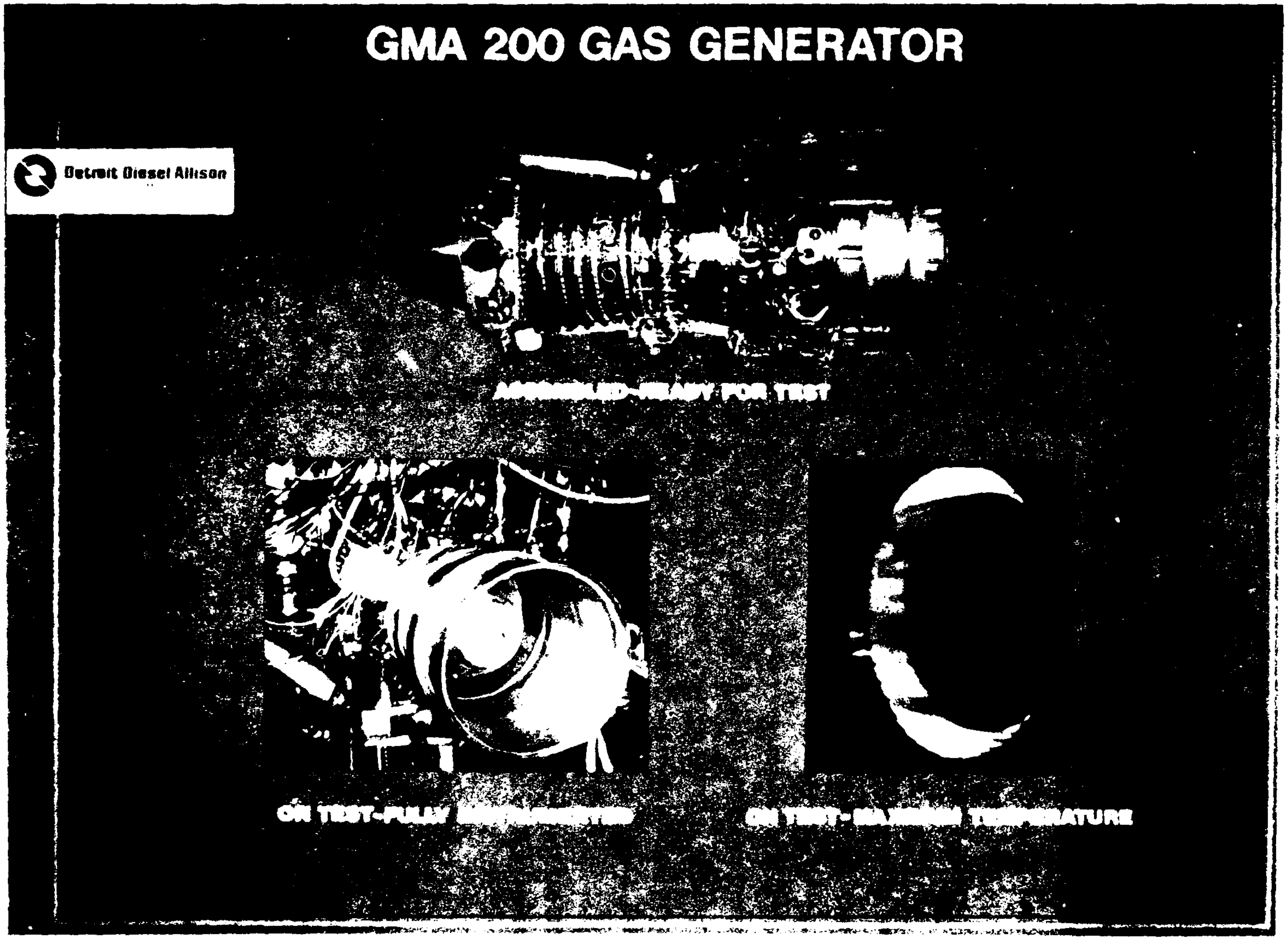


Figure 1. GMA 200 Gas Generator

b. Compressor

A six-stage axial flow compressor assembly consists of subassemblies of the rotor, the case and variable vanes, and the front bearing support and sump. The compressor rotor is an integral, electron beam welded titanium drum with bolted on first and sixth stage Ti wheels. This rotor construction results in a simple, lightweight structure using optimum materials selected to match the design requirements imposed by the varying temperature and stress conditions through the compressor.

The case and vane assembly is a horizontally separable, titanium case which supports all six stages of variable vanes. The first-stage vanes are tied together at the hub end by a segmented inner ring. The remaining five variable vane stages are cantilevered from the compressor case. All stationary vane rows except the outlet guide vanes have the capability for variable setting angle. This feature promotes maximum variability in airflow capacity and a flow-speed relationship suitable for supersonic flight. It also allows surge relief at low compressor speeds.

The sump and support assembly houses the rotor thrust bearing and transmits radial and axial loads into the air inlet housing and forward frame.

c. Combustor/Diffuser

The GMA200 combustor/diffuser section consists of an annular combustion liner and a strutless diffuser. It is a triple passage, diffusion system with inner and outer boundary layer slots added to produce a diffusion system insensitive to compressor discharge profile variation.

The combustion liner uses a combination of convection and film cooling. This design provides the capability to operate at extremely high temperatures with minimum cooling airflow, thus permitting a larger percentage of total airflow to be used to tailor the temperature pattern.

Staged combustion provides efficient and stable operation over a very broad range of outlet temperatures. Two combustion reaction zones are provided, the pilot and the main. The initial or pilot zone is optimized for operation in the lower temperature range, and the second or main zone is optimized for operation at the maximum temperature.

The combustor uses 36 air blast fuel nozzles, 18 of which have a spray cone angle set to deliver primary zone fuel and 18 of which have a spray cone angle designed to introduce fuel into the secondary combustion zone.

d. Turbine

The GMA200 gas generator features a variable-capacity single-stage turbine with mechanically variable nozzle guide vanes and transpiration-cooled airfoils. The first-stage vane is supported by high temperature spherical bearings at both the hub and tip and is designed to provide a 23% variation in inlet nozzle area. The turbine wheel and rotating seals are fabricated of advanced materials which permit significant weight savings in the highly loaded, high speed unit. The blade is cooled by the application of a variety of cooling techniques including a film-cooled leading edge and transpiration-cooled airfoil walls with convection cooling on the trailing edge of the walls.

e. Turbine Rear Bearing Support

The GMA200 gas generator uses a test equipment type turbine rear bearing support and variable area jet nozzle for demonstration testing. The support and nozzle is designed to withstand loads from blade-off condition (unbalance due to loss of blade), pressure, and aerodynamic forces. The support, a fabricated welded structure that attaches to the turbine vane case, has four functions:

- To house the turbine rear roller bearing
- To provide a gas path from the turbine exit to the convergent variable area nozzle

- To provide mounting and support for the variable area exhaust nozzle and actuation system
- To provide mounting attachments at the rear of the gas generator

Cooling of the support and nozzle assembly is accomplished by introducing facilities air into an annulus formed by the outer wall of the support and the outer gas-path wall. Some of this air is transferred through hollow struts into an inner annulus formed by the inner gas path wall and the inner support wall. Cooling air is bled from these two chambers to cool the various elements of the support and nozzle assembly.

f. Exhaust Nozzle

The convergent, variable area nozzle is a hydraulically actuated leaf type with cam followers, and attaches to the turbine rear bearing support. The nozzle leaves are film cooled by means of air bled from the outer chamber of the turbine rear bearing support.

2. Control Hardware Interface

Figure 2 shows the Bendix EH-K1 Digital Controller/ATEGG interface necessary to control fuel flow, compressor vanes, turbine vanes, and exhaust nozzle. The "ACTUATORS" box represents electro-hydraulic and electro-pneumatic devices which convert digital controller commands into ATEGG control inputs. Feedback signals are returned to the controller through the "POSITION SENSORS" box indicating the sensed positions of the control inputs.

a. Fuel Flow Interface

The ATEGG fuel system is two identical fuel systems identified as the pilot fuel system which supplies the pilot nozzles and the main fuel system which supplies the main fuel nozzles (see Figure 3). For each system an electrically driven, variable displacement TF41 pump maintains a constant pressure drop across a Pegasus fuel metering valve. The Pegasus receives an electrical signal from the EH-K1 through a torquemotor which positions the

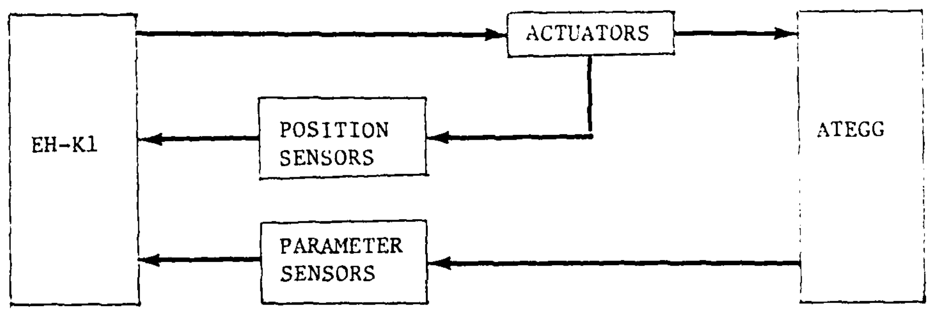


Figure 2. EH-K1/ATEGG Interface

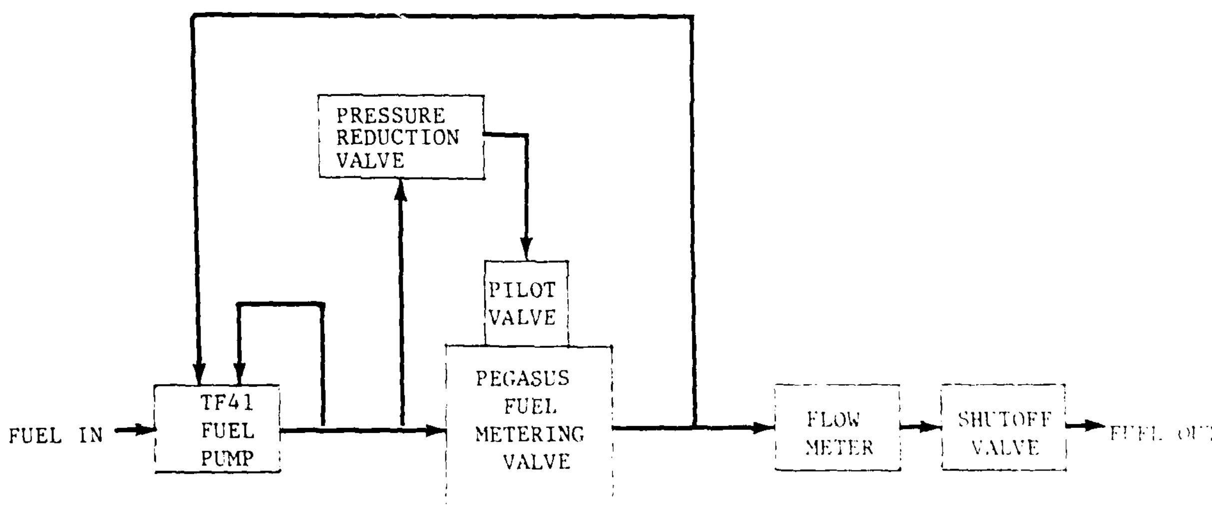


Figure 3. GMA200 Fuel System

pilot stage of the valve. This drives the main stage whose position is sensed by the EH-K1 via an LVDT. Fuel flow is a function of main stage valve position and is compared to desired fuel flow to effect closed loop control. A shutoff valve is in series with each fuel valve.

b. Compressor Geometry Interface

The hydraulic vane actuation system is controlled on corrected speed by the digital controller through an Electro-Hydraulic Servo Valve (EHSV) and a position transducer. A pair of hydraulic cylinders actuate two translating cam plates. Bushed rod and roller assemblies transmit desired motion established by contoured slots in the cam plates through a turnbuckle linkage to each of seven vane actuation rings, one per stage of variable vanes. Linear potentiometers sense cam travel and provide position feedback to the controller. With this type of actuation system, only one of the two digital controller compressor control functions, surge avoidance (HPC2), is actively controlling. This mode schedules actuator piston travel (cam travel) vs. corrected speed. The flow control (HPC1) is a function of the cam plate contour and changes only when the cam plate itself is changed.

c. Turbine Geometry Interface

The flow capacity of the turbine is varied mechanically by the angle of the nozzle guide vanes. The turbine actuation system, shown in Figure 4, has a pneumatic motor which drives multiple planocentric actuators located around the periphery of the engine by means of a high speed flexible drive cable system. The actuators in turn position a synch ring. An electrical signal from the digital controller modulates the air supply to the motor to control the synch ring rotational rate and direction. Linear potentiometers provide position feedback to the controller. This system was developed on IR&D and is a prototype of a high temperature actuation system.

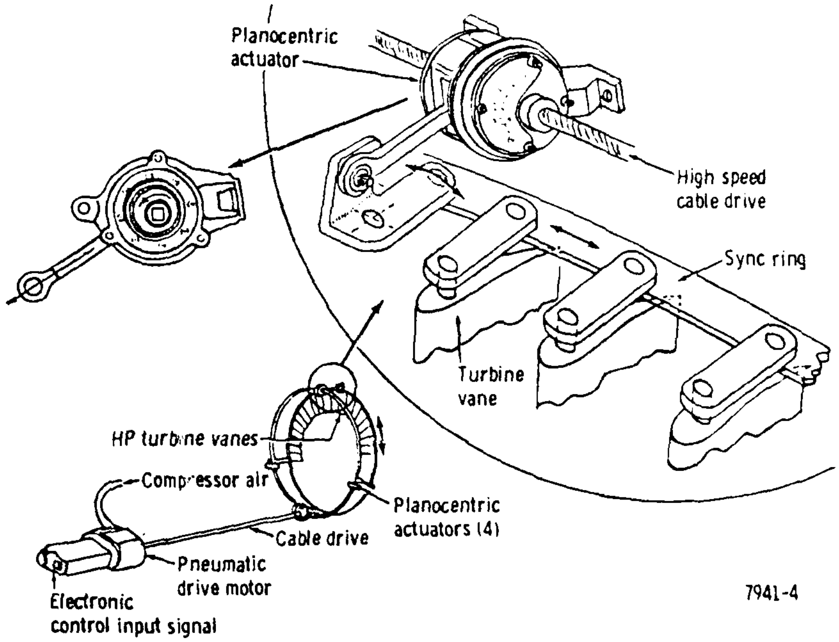


Figure 4. HP turbine vane actuation system.

d. Exhaust Nozzle Interface

The exhaust nozzle is hydraulically actuated. The digital controller effects position control via an EHSV and position transducers.

e. Engine Sensors

In addition to the sensors used for position feedback of the controlled variables, the EH-K1 is also connected to a tachometer, pressure probes, thermocouples, and an optical pyrometer to sense speed, pressures, and temperatures as indicated by the signal flow through the "PARAMETER SENSORS" box of Figure 2. Table 1 summarizes the sensed variables in ATEGG and the means of transmitting these variables to the digital controller

Table 1. ATEGG sensors and accuracies

Variable	Symbol	Type of Probe	Range	Conversion Circuitry	System Accuracy
Compressor Inlet Total Pressure	$P_{T2.1}$	Multiple Rakes-Manifolded	2 to 76 psia	Paroscientific Digital Quartz Transducer in EH-K1	0.05% F.S.
Compressor Discharge Total Pressure	P_{T3}	Multiple Rakes-Manifolded	10 to 300 psia	Paroscientific Digital Quartz Transducer in EH-K1	0.05% F.S.
Compressor Discharge Static Pressure	P_{S3}	Multiple Rakes-Manifolded	10 to 300 psia	Paroscientific Digital Quartz Transducer in EH-K1	0.05% F.S.
Turbine Discharge Total Pressure	$P_{T4.1}$	Multiple Rakes-Manifolded	10 to 125 psi	Paroscientific Digital Quartz Transducer in EH-K1	0.05% F.S.
Rotor Speed No. 1	NHA	Berkley Model 466-120 Tachometer	934 to 9815 Hz	Digital Pulse Counters in EH-K1	0.2% of point
Rotor Speed No. 2	NHB	Berkley Model 466-120	934 to 9815 Hz	Digital Pulse Counters in EH-K1	0.2% of point
Compressor Inlet Temperature	$T_{2.1}$	Chromel/Alumel T/C - Multiple Parallel Elements	349 to 990°R	Amplifier in EH-K1	±9°R
Compressor Discharge Temperature	T_3	Chromel/Alumel T/C - Multiple Parallel Elements	320 to 1750°R	Amplifier in EH-K1	±9°R
High Pressure Turbine Exit Temperature	$T_{4.1}$	Thoriated Platinum/Platinum -40% Rhodium-Single Element	402 to 3462°R	Amplifier in EH-K1	±9°R
Turbine Blade Metal Temperature	TBT	Optical Pyrometer	1700 to 2300°R	Amplifier Circuitry External to EH-K1	±0.1% F.S.

As indicated the pressures are transmitted as manifolded air signals to Paroscientific Digital Quartz transducers in the EH-K1. These transducers produce a frequency which varies with pressure. This frequency is converted to a digital word by counter circuits.

The rotor speed is sensed through redundant channels (NHA, NHB) from a tachometer. The redundant channel feature allows for failure of a speed transducer to a failed-operate condition.

Chromel/alumel thermocouple clusters are used to sense temperatures at the compressor inlet and compressor discharge, turbine inlet temperature is sensed by a single Engelhard thoriated platinum/platinum-40% rhodium thermocouple developed on AFAPL Contract F33615-74-C-1069. Turbine blade temperature is sensed by a Solar optical pyrometer.

SECTION IV

EH-K1 CONTROLLER

1. Hardware Description

A digital controller Model No. EH-K1 (Figure 5) has been provided by Bendix Energy Controls Division for use during ATEGG testing. The EH-K1 contains a Bendix BDX-920 series CPU which uses low-power SCHOTTKY T^2L digital logic and has a 1.3 microsecond cycle time. The controller arithmetic features binary, fixed-point operations on 16 bit data words and represents negative numbers in two's complement form. Typical execution times are 2.6 microseconds for an add, 7.8 microseconds for a multiply, and 16.9 microseconds for a divide. The CPU can interface to core or semiconductor memory modules and can address 32K of memory. For ATEGG purposes, core memory has been used to allow maximum flexibility. All software was partitioned into 8K of the available 32K memory locations. The

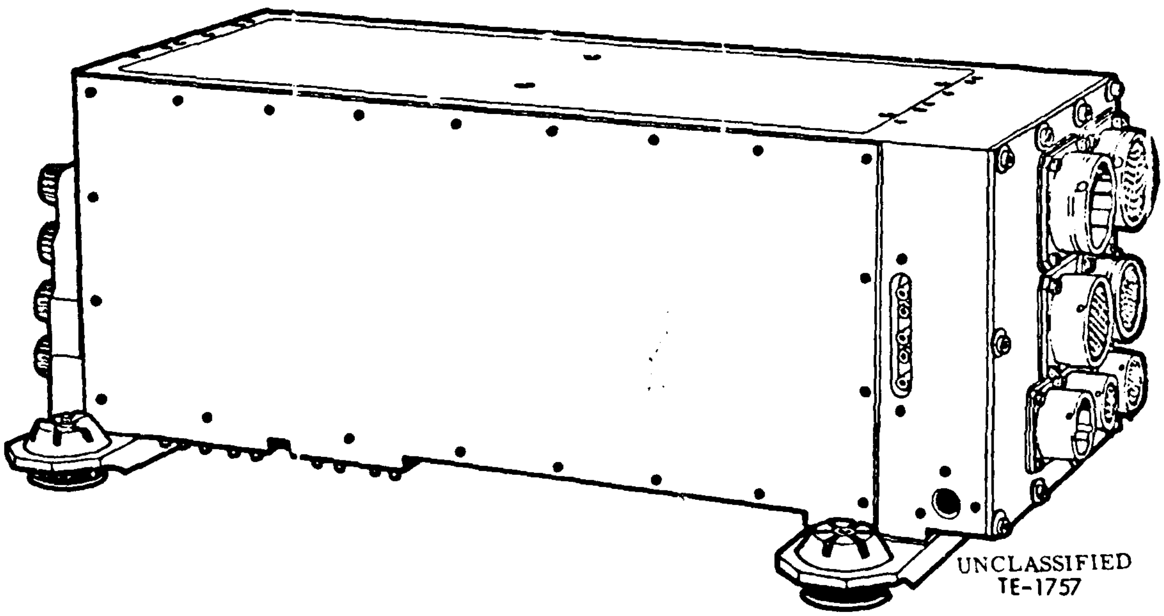


Figure 5. Programmable Digital Electronic Control

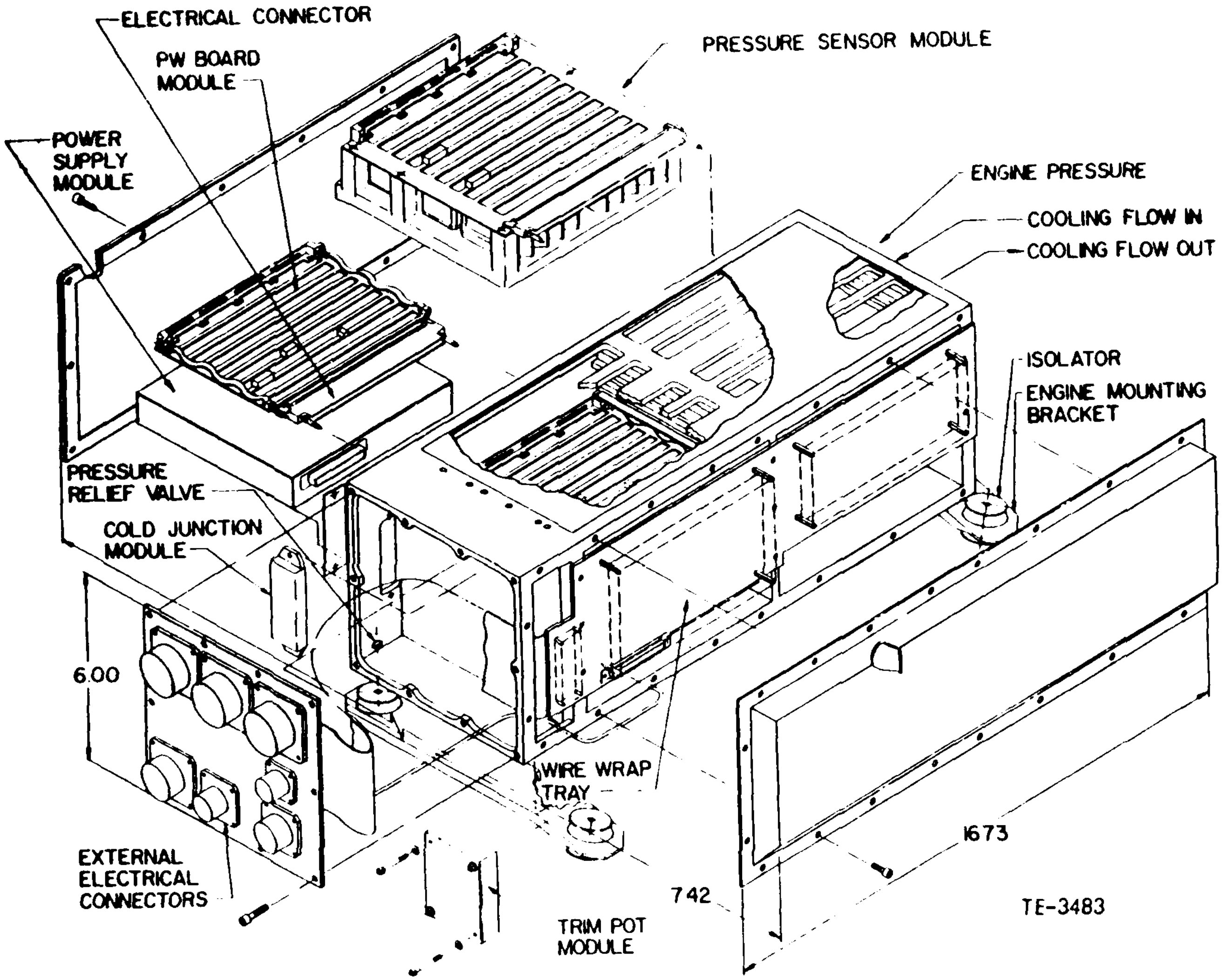
CPU is microprogrammable and can directly address 512 words of memory. Indexed addressing and multilevel indirect addressing modes are also available. Program interrupt capability is expandable to 256 priority levels and power-fail and power-restore interrupts are available. The power consumption of the CPU excluding memory is less than 22 watts.

The principal components included in the EH-K1 Digital Controller assembly are the printed circuit boards which contain the digital and analog computational and input-output devices, the engine pressure transducers, the voltage regulator for generating the necessary controller voltages, the motherboard which provides the internal electrical power and signal communications, the package housing, the covers and the mounting brackets. A pictorial, exploded-view representation of the design showing the various component parts is shown in Figure 6.

The electronic unit utilizes modular construction and plug-in subassemblies. The controller includes thirteen printed circuit card module assemblies, one pressure transducer assembly, one power supply assembly and an internal wiring and motherboard assembly, each of which is individually removable from the controller housing. A positive method of keying each of the printed circuit board electrical connectors is included to prevent improper interchange of the card modules.

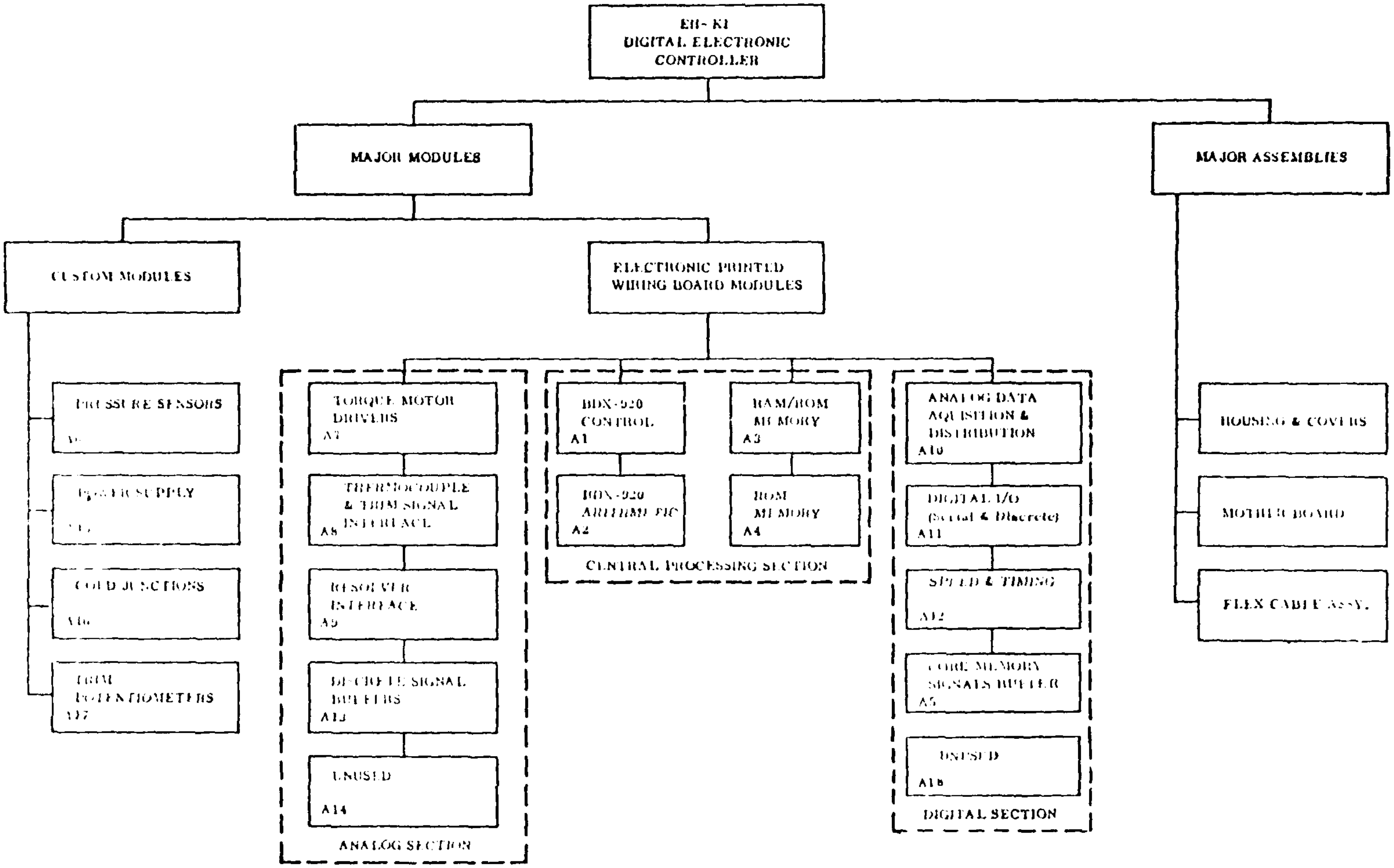
Figure 7 shows the major modules and assemblies in the EH-K1. Among the separate modules is a speed and timing board providing counter circuits for converting up to four speed inputs directly to digital equivalents. A "watchdog" timer which must be reset at a fixed time interval by software to indicate proper execution is also provided.

Six differential thermocouple amplifiers are provided on another board. A separate cold junction temperature module provides a cold junction compensation signal. A resolver interface board provides for up to 12 resolver input demodulators. The amplified thermocouple and resolver signals are converted to digital signals by the analog data acquisition board, which can also input up to 18 other external analog signals.



EH-K1 CONTROL ASSEMBLY

Figure 6. EH-K1 Control Exploded View



TE-3484

MAJOR MODULES & ASSEMBLIES HARDWARE TREE

Figure 7. Major Modules and Assemblies

Buffer circuits and timing logic are provided for up to 16 discrete inputs. Two serial digital input data channels are provided for communication with test equipment or airframe equipment. Five discrete solenoid drivers and three fault indication flag drivers are on the digital I/O board, as is a serial digial output channel. Drivers for up to ten torquemotors are available for controlling actuators.

The pressure sensor board can contain up to 8 Paroscientific pressure transducers. These transducers employ a quartz-crystal oscillating beam whose resonant frequency varies with pressure. The board also contains the electronics to convert the oscillatory output to a digital count. This transducer system gives an overall system accuracy of $\pm 0.05\%$ of full scale.

The power supply for the entire controller is contained in one removable module. The power converter can operate off three-phase power from a permanent magnet generator or from a dc power source.

Provisions are included in the controller test capability to facilitate detection and isolation of faulty operation down to the printed circuit board or subassembly level. Once the malfunctioning subassembly is identified, that device can be quickly and readily removed and replaced with an interchangeable, working spare unit, without need for special adjustment, calibration or selection. Subassemblies which malfunction are capable of being repaired at the appropriate maintenance facility so that they may be restored to service.

The EH-K1 design includes fuel cooling of the electronic components contained in the controller assembly. To implement the fuel cooling method, cooling fuel is distributed to parallel flow channels in the controller housing walls. The cooling fuel supply line enters an inlet manifold in the control housing that distributes the flow equally. An outlet manifold is included to collect the fuel at the discharge. Conductive metal heat paths are built into each printed circuit card module and into the power supply and pressure transducer assemblies. The heat paths are formed by including an aluminum or a copper grid in each printed circuit card module and by using aluminum mounting frames for the power supply and the pressure transducer assemblies. High power electrical components are mounted in intimate contact with the heat paths. The self-generated heat is conducted away from the components to the fuel cooled walls of the housing assembly.

The housing assembly has been designed to mount to the engine case on vibration dampers. The spring rate of the mounts and the percentage of critical damping have been adjusted to produce the best possible protection for the components of the controller.

A functional system block diagram for the ATEGG application is shown in Figure 8. The controller hardware is shown within the dotted lines.

2. Software Description

The EH-K1 software, in conjunction with the peripheral hardware and interfaces, performs the following functions:

- Control mode computation
- Input and output processing including reasonableness checks and redundant sensor switching.
- Diagnostic checks of reference voltages, I/O interfaces, CPU and memory.
- Real-time interactive capabilities including operator control of geometry actuators and monitoring/modification of selected control variables.

The executive software for the EH-K1 has been set up on a real time interrupt driven basis. The interval timer issues an interrupt request at 1 millisecond intervals of the total 20 millisecond solution interval. Synchronous tasks such as parameter I/O and Serial I/O are provided at the interrupt level. After tasks at the interrupt level are completed, the monitor routine allocates CPU time first to control computations and after these are completed then background tasks in a "round-robin" fashion. Background tasks include CPU self-tests, read only memory sum checks, random access memory pattern

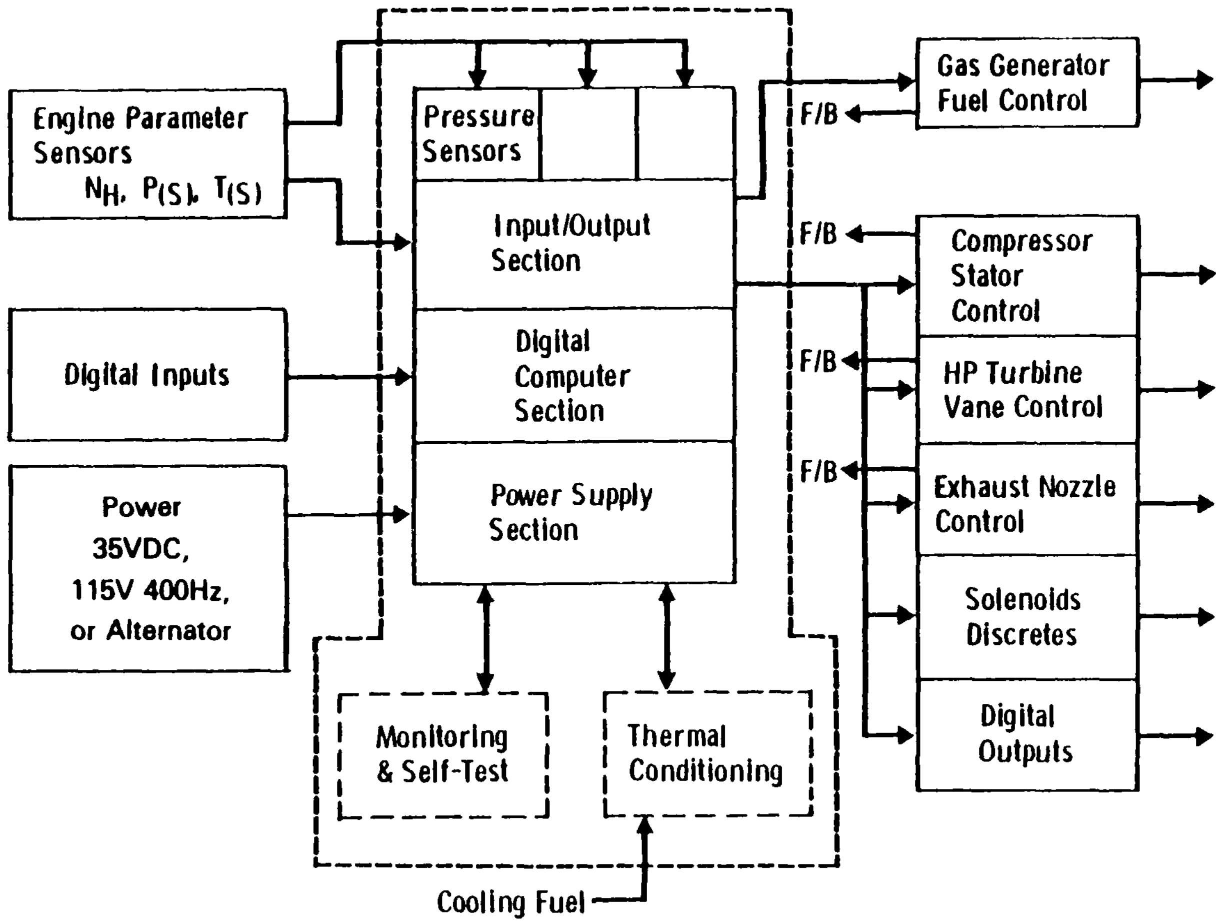


Figure 8. EH-K1 Functional Design

tests, and test console interactive routines. Thus background tasks, which take considerably longer than the 20 millisecond solution time, can be accomplished.

Figure 9 is an example of the sequences of operation during a normal 20 millisecond solution interval.

a. Control Mode

As mentioned above the control mode computation is the priority item in the software. The control logic used during B.U. 5 of ATEGG evolved from a control mode study prior to B.U. 4 (reference AFAPL-TR-77-57), updating of engine characteristics based on B.U. 4 testing (reference DDA EDR 9440), and definition of B.U. 5 operating requirements. Several steps were included in the original control mode study as discussed below.

- o Definition of engine operational envelope - Since ATEGG is a demonstrator engine to be tested in a test cell environment, it is not subjected to the conventional aircraft flight envelope; however conditioned air is provided to the inlet to simulate the ramming effect of the JTDE fan. The control logic was formulated to provide proper engine control and protection for ambient conditions and conditions of elevated inlet pressure and/or temperature.

- o Definition of engine control variables - ATEGG is a variable cycle engine with a multi-input, multi-output structure. The multi-input part of that structure consists of four control variables: fuel flow, compressor variable vanes, turbine variable vanes, and exhaust nozzle area.

- o Definition of sensed engine parameters to be used for control purposes - Even though the testing of a demonstrator engine such as ATEGG

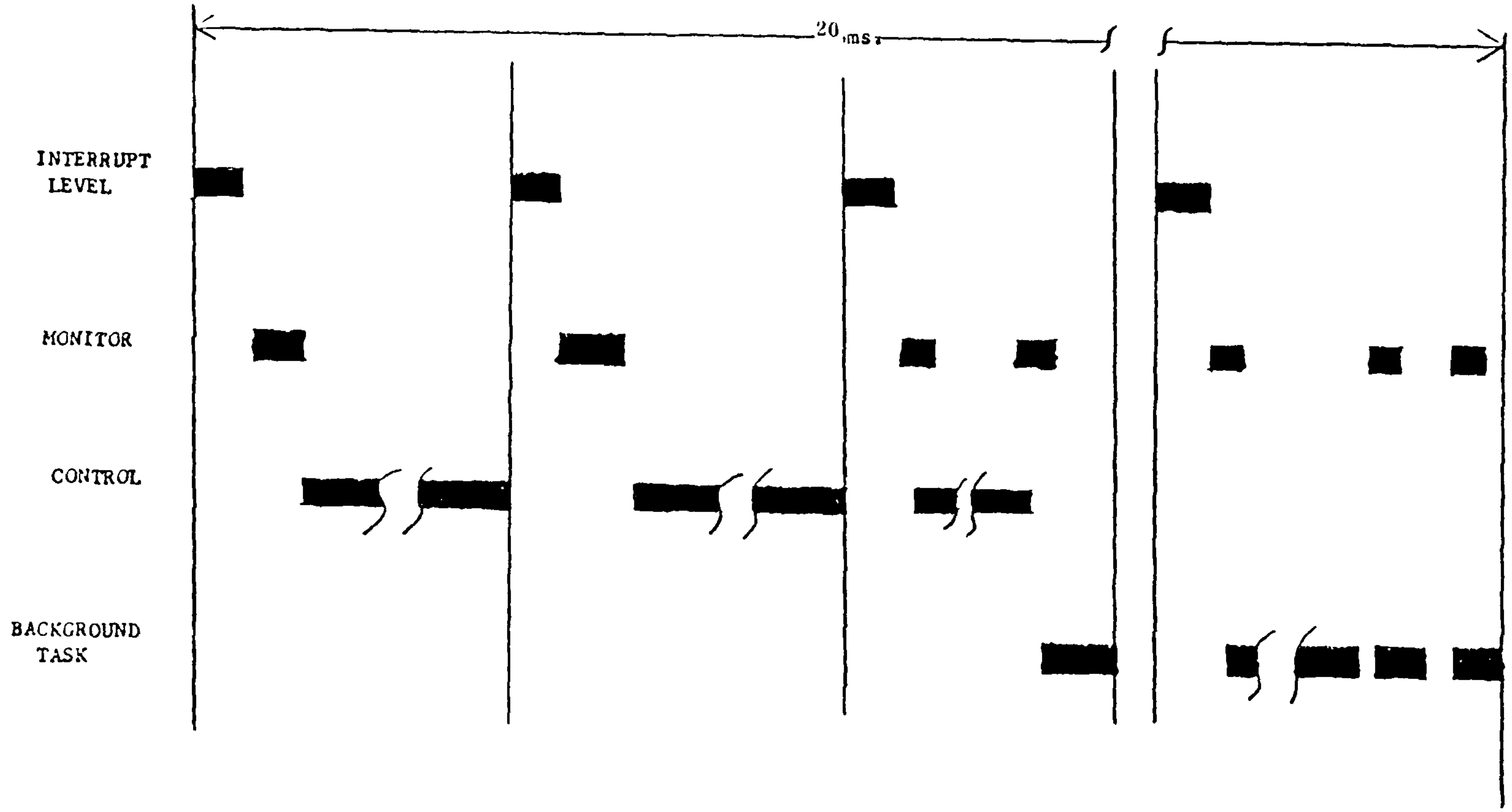


Figure 9. Sequence of Operation

requires a large amount of engine instrumentation, separate dedicated control sensors are required for proper control procedures to be implemented. Table 1 represents that list of the sensed engine signals used in the ATEGG control logic.

In addition to these measured signals it is essential to obtain variable geometry and fuel valve position feedback values. For ATEGG these feedbacks are:

- Compressor Variable Vane Position
- Turbine Variable Vane Position
- Exhaust Nozzle Position
- Fuel Flow

- Definition of Engine Limits - In addition to the design requirements of stable control of fuel flow and the three variable geometry components, the control logic is also responsible for protecting against engine damage. Some of the engine limits to be observed are the following:

  - Compressor Surge Margin Limit
  - Compressor Rotor Mechanical Speed Limit
  - Compressor Discharge Total Pressure Limit
  - Turbine Blade Temperature Limit
  - Rotor Inlet Temperature Limit

- Definition of Control Synthesis Procedure - Provided with the control system requirements (variables to be controlled, engine operational requirements and limits to be observed), the available engine parameters, and the engine operational environment, the control mode development can begin. The control synthesis procedure used in deriving the ATEGG control logic was classical. Each control loop was studied individually, and compensation within the loop was added based on strong interrelationships between control variables. In particular the fuel loop gains were sized along an operating line with fixed geometry settings for the turbine and nozzle. When the closed loop mode of the turbine was exercised with the fuel loop active, it was necessary to lower the overall fuel loop gain to maintain the relative prescribed stability margin. Inter-loop compensation was considered but not utilized due to absence of the necessary tools to implement such a control design. The first control consideration for each control variable was whether to exercise open loop control or closed loop control. As is indicated by Figure 10 the open loop control procedure positions the control variable ($U_{COMMAND}$) according to a scheduled position request (U_{REQ}). The closed loop procedure seeks to adjust the control variable (X_{FB}) to satisfy a given engine parameter signal request. In either case the output from the logic is a signal to the actuator or metering valve which is proportional to the desired geometry or fuel flow command. Table 2 shows the mode of control selected for each ATEGG control variable and also the reference and scheduling parameters within each mode.

Table 2

ATEGG Mode of Control

Control Variable U	Mode of Control	Scheduling Parameter Y	Reference Feedback Parameter X
Fuel Flow	Closed loop	Power Lever Angle	Measured Corrected Comp. Rotor Speed
Compressor Variable Vanes	Open loop	Corrected Compressor Rotor Speed	Measured Vane Position
Turbine Variable Vanes	Closed loop	Power Lever Angle	Measured Turbine Outlet Temperature
Exhaust Nozzle Area	Open loop	Power Lever Angle	Measured Exhaust Nozzle Area

o Definition of desired steady state engine operation - The definition of the engine operating line identifies the fuel flow and the geometry positions necessary to run at various power levels within the engine operational envelope. This is most easily done by exercising a nonlinear digital simulation of the engine as was done on ATEGG. It is the task of the control logic to insure that the desired steady state input values are correctly provided through a single input, power lever angle. This is done by properly defining the reference schedules shown in Figure 10.

- Definition of control loop compensation - The "compensation" boxes in Figure 10 indicate the need for control gains and dynamic compensation to provide stable control of each loop. For ATEGG linear engine models were derived from the nonlinear simulation, and significant engine dynamic terms were identified. Coupled with the dynamics of the sensors and actuators, each loop was analyzed through Bode analysis to generate the proper compensation. Testing with a nonlinear real-time model of the engine confirmed the validity of the compensation.

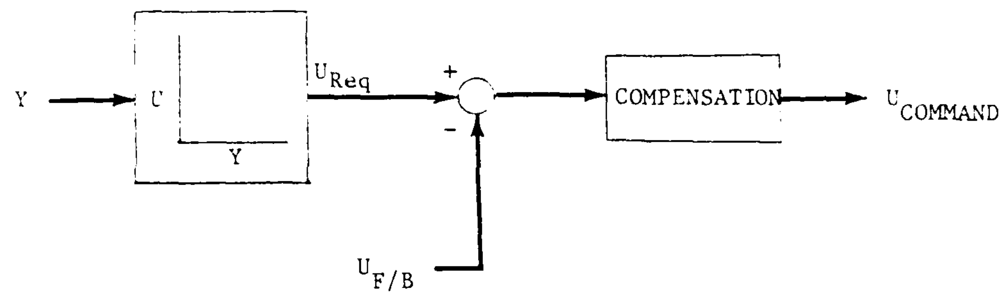
  B.U. 4 testing yielded added insight into the performance of ATEGG. This allowed updating of the nonlinear engine simulation and subsequent redefinition of the operating line. Accompanying these updates was the need to verify the control loop compensation and modify that compensation as necessary. All of this was done on ATEGG prior to B.U. 5 (reference DDA EDR 9440) yielding the control mode logic indicated in Figures 11 and 12.

(1) Fuel Control Mode

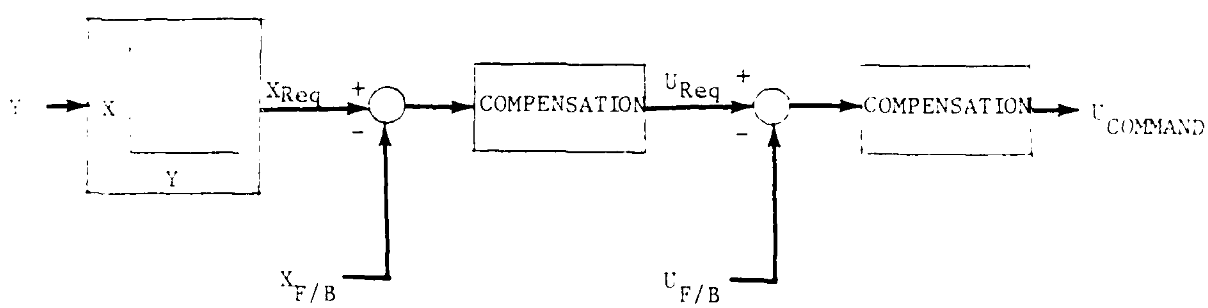
The fuel control section of the ATEGG control mode has four major responsibilities.

- Provide fuel flow necessary for engine starting
- Provide transient fuel flow limiting capability through acceleration and deceleration schedules
- Provide transient fuel flow limiting capability if engine limits are exceeded.
- Provide steady state fuel flow necessary to maintain a given thrust level.

Figure 11 shows the fuel control section of the ATEGG control mode. From this diagram it can be observed that the governor fuel flow, WF_{GOV}, controls rotor speed through a proportional plus integral control loop. The integrator

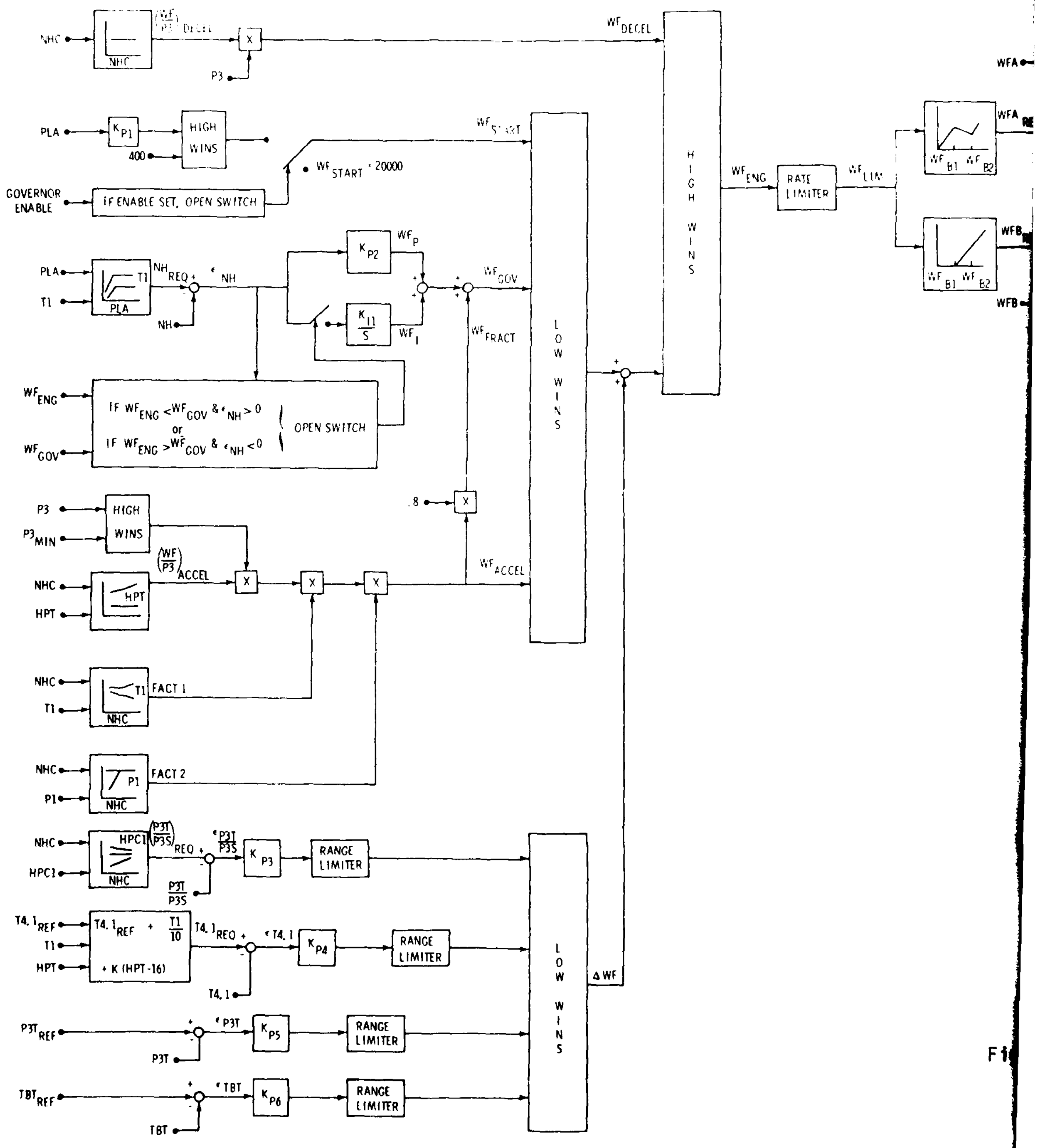


OPEN LOOP CONTROL



CLOSED LOOP CONTROL

Figure 10. Open vs. Closed Loop Control



NHC
P3
X
WF_{DECEL}
PLA
K_{P1}
400
HIGH WINS
WF_{START}
$WF_{START} = 20000$
GOVERNOR ENABLE
IF ENABLE SET, OPEN SWITCH
PLA
T1
PLA
NH_{REQ}
ϵ_{NH}
NH
K_{P2}
WF_P
$\frac{K_{I1}}{S}$
WF_I
WF_{GOV}
WF_{FRACT}
WF_{ENG}
WF_{GOV}
IF $WF_{ENG} < WF_{GOV}$ & $\epsilon_{NH} > 0$
or
IF $WF_{ENG} > WF_{GOV}$ & $\epsilon_{NH} < 0$
OPEN SWITCH
P3
$P3_{MIN}$
HIGH WINS
.8
$\left(\frac{WF}{P3}\right)_{ACCEL}$
NHC
HPT
WF_{ACCEL}
NHC
T1
FACT 1
NHC
P1
FACT 2
LOW WINS
HIGH WINS
WF_{ENG}
RATE LIMITER
WF_{LIM}
WFA
WF_{B1}
WF_{B2}
WFB
NHC
HPC1
$\left(\frac{P3T}{P3S}\right)_{REQ}$
$\epsilon_{\frac{P3T}{P3S}}$
$\frac{P3T}{P3S}$
K_{P3}
RANGE LIMITER
$T4.1_{REF}$
T1
HPT
$T4.1_{REF} + \frac{T1}{10} + K\,(HPT-16)$
$T4.1_{REQ}$
$\epsilon_{T4.1}$
T4.1
K_{P4}
RANGE LIMITER
$P3T_{REF}$
ϵ_{P3T}
P3T
K_{P5}
RANGE LIMITER
TBT_{REF}
ϵ_{TBT}
TBT
K_{P6}
RANGE LIMITER
LOW WINS
ΔWF

F1

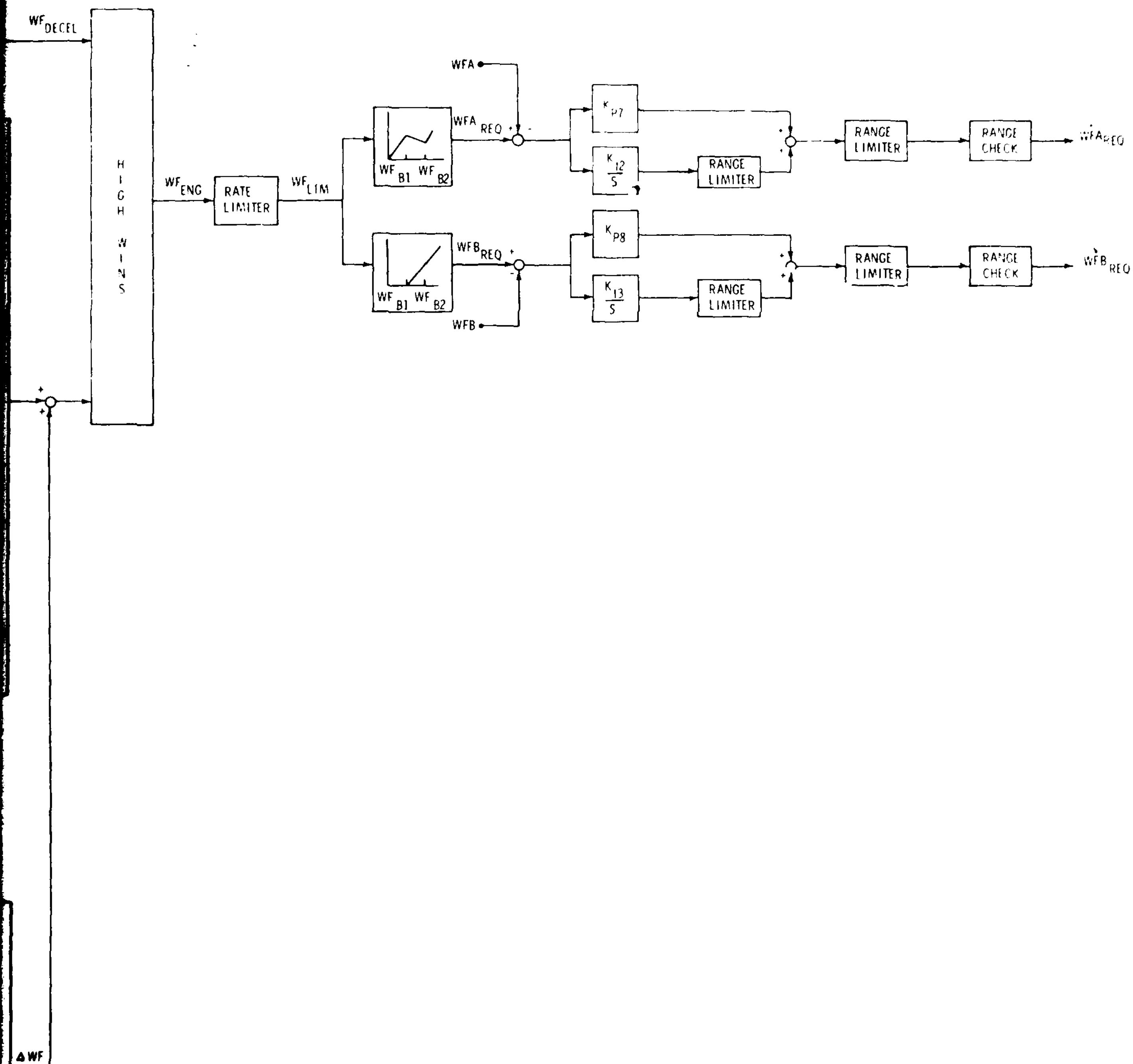
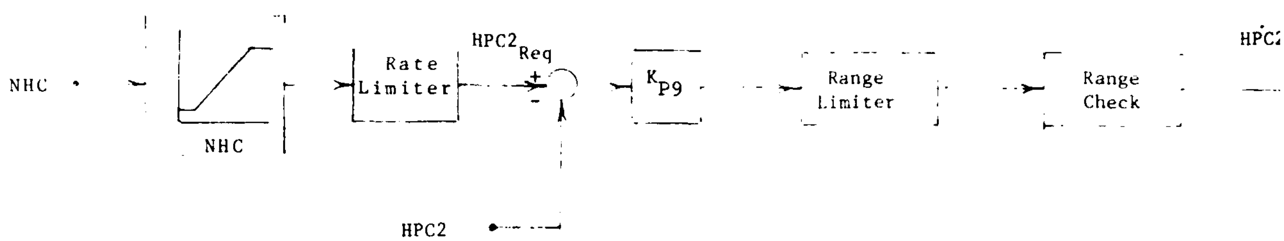
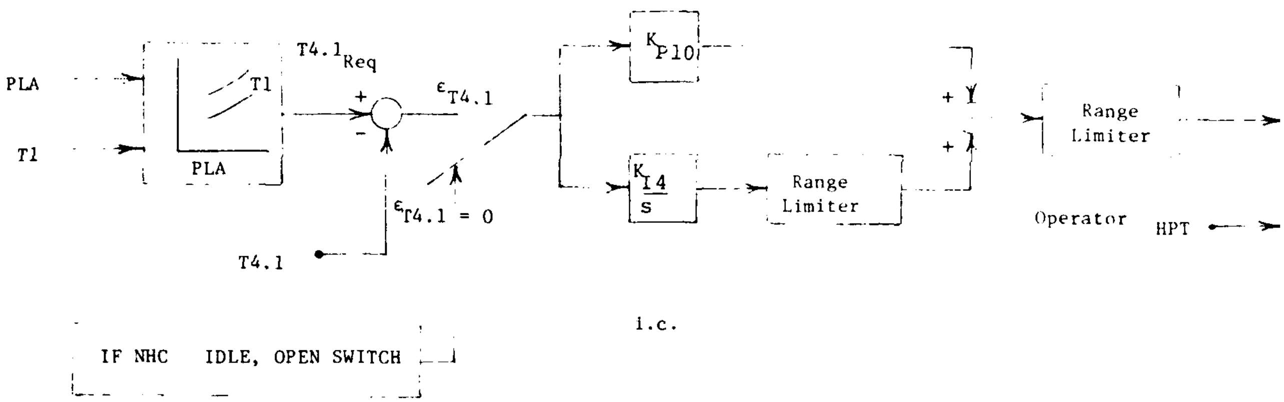
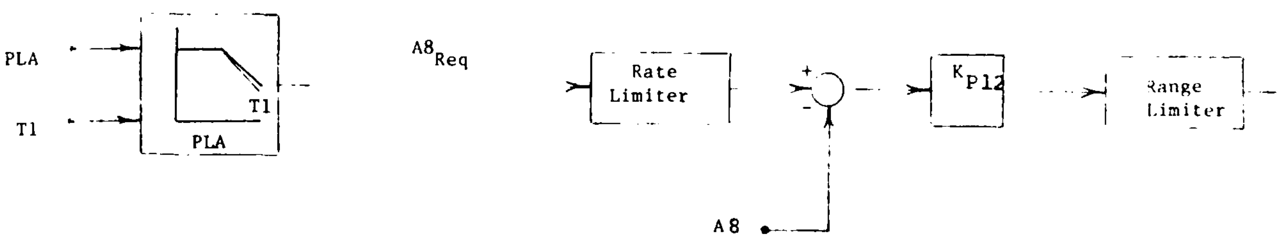


Figure 11. ATEGG Fuel Control Mode


NHC
NHC
Rate Limiter
HPC2Req
+
-
KP9
Range Limiter
Range Check
HPC2
HPC2


PLA
T1
T1
PLA
T4.1Req
+
-
εT4.1
εT4.1 = 0
T4.1
KP10
KI4
s
Range Limiter
+
+
Range Limiter
Operator
HPT
i.c.
IF NHC IDLE, OPEN SWITCH


PLA
T1
T1
PLA
A8Req
Rate Limiter
+
-
KP12
Range Limiter
A8

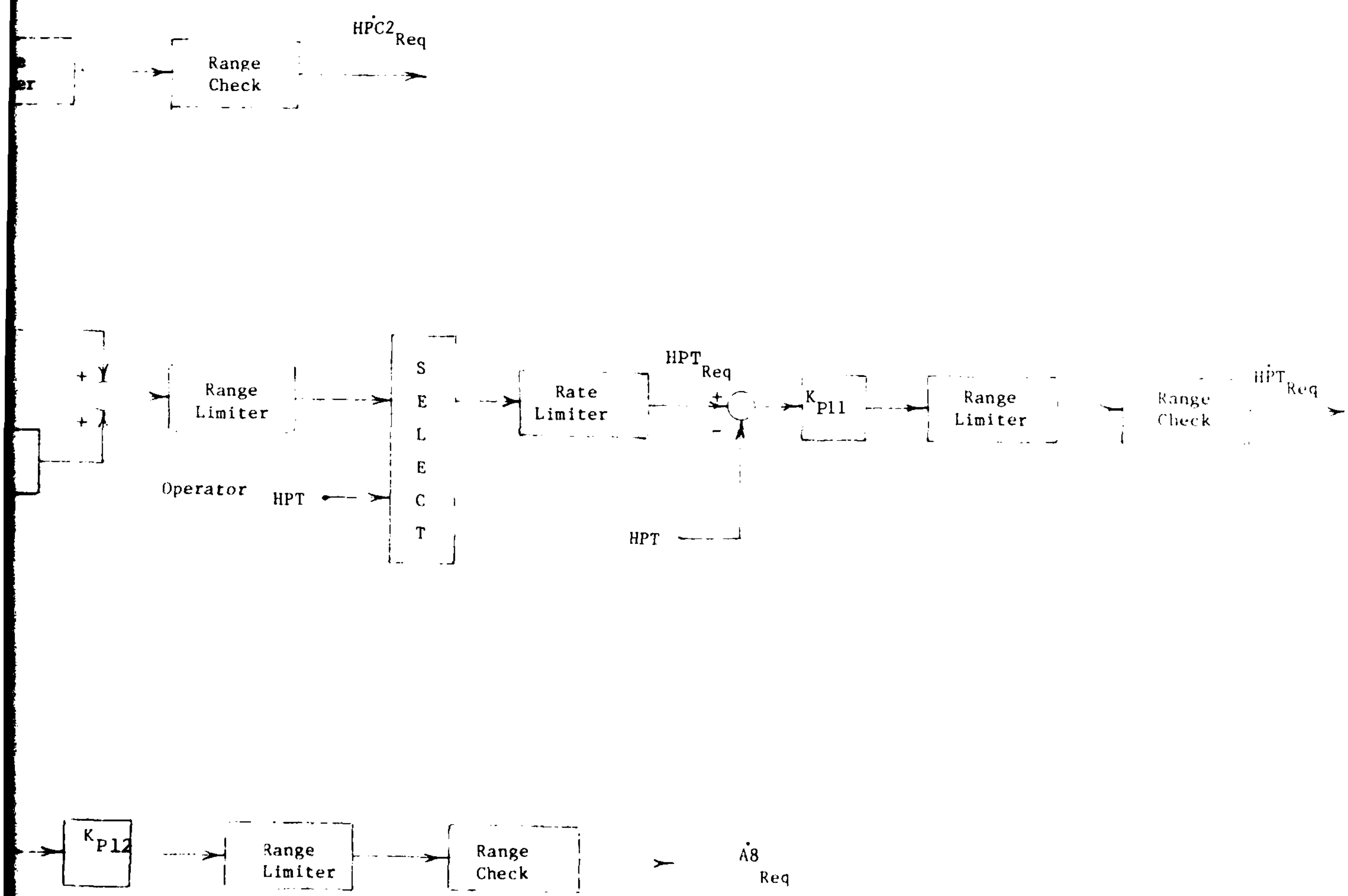


Figure 12. ATEGG Geometry Control Logic

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is a limited authority integrator which is active only when within a given percentage of the desired "steady state" rotor speed. The integrator's authority is limited due to the contribution of fuel flow from the acceleration schedule, WF_{FRACT}.

Fuel flow during engine transients is limited by an acceleration mode and a deceleration schedule. The deceleration schedule monitors fuel flow as a function of corrected speed and compressor discharge pressure. The acceleration mode is more crucial as it limits fuel flow, WF_{ACCEL}, to prevent engine surge during excursions from low to high power. A primary schedule of NHC vs. WF/P3 serves to track engine dynamics and aid surge recovery through decreasing fuel flow to achieve a desired WF/P3 ratio for a sudden drop in P3. Other biases on the acceleration fuel flow are HPT area, T1, and P1. The HPT bias compensates for the decelerating tendency of the engine as the turbine opens by adding more fuel. The T1 bias limits the acceleration fuel flow for colder than nominal days where less fuel is required to achieve a given NHC. The P1 bias supplements acceleration fuel flow for an unrammed engine below 90% NHC. Below this speed the engine is fully choked only if rammed. Therefore, a given corrected fuel flow will not produce the same corrected speed, all geometry settings being equal, between rammed and unrammed inlet conditions.

As can be seen from Figure 11, comparative logic exists to choose the appropriate fuel flow signal, WF_{GOV}, WF_{ACCEL}, or WF_{DECEL}, during operation across the power region. A separate portion of the fuel control mode decreases the fuel flow command by some amount, WF, if particular engine limits are exceeded. The engine parameters which are limited are compressor discharge pressure, turbine outlet temperature, turbine blade temperature, and compressor discharge total to static pressure ratio. The above fuel control logic modulates fuel in the power region from idle to intermediate thrust. A "hand valve" modulates fuel during a start to idle. In this mode the controller commands a given fuel flow request based on PLA and then sends this request to be closed in the fuel valve positional loop.

The output request from the "high wins" box (Figure 11) is range limited, and subject to fuel splitter logic before leaving the digital domain and travelling to the metering valve as a fuel flow rate request. This fuel flow splitter logic is necessary due to the dual fuel system configuration on ATEGG.

The fuel splitter logic allows engine starts and subsequent operation near idle on the pilot fuel system only. Above idle the logic permits the main fuel system to be brought in such that steady state operating points away from idle may be run with a 50/50 fuel flow split between the two systems.

This part of the logic was amended prior to B.U. 5 to allow variable fuel splits (other than 50/50) between the pilot and main fuel systems. The WF_{B1} was set such that the engine could start on the pilot system only, and WF_{B2} was defined to satisfy the following:

$WF_{B1} + WF_{B2} = WF_{REQ}$ = flow above which a specified fuel system split is desired

$WF_{B1}/WF_{B2} = R$ = desired split

Several options exist for exercising the fuel system. These include the following:

- Operator request
- Hand Valve Operation
- Governor Operation - Proportional Only
- Governor Operation - Proportional plus Integral

Manual pilot and main fuel requests were provided to facilitate fuel valve calibration.

As mentioned before a PLA-controlled "hand valve" is provided for engine starting. Thus fuel is ramped in during a start by the open loop request of fuel flow as a function of PLA. It is possible to operate steady state on the hand valve provided that the hand valve has enough authority and that the governor is not in operation. Since it is possible to enable the governor manually or automatically, the hand valve may take the engine to idle and the governor may be enabled at that point.

Governor operation can be of two forms, proportional only and proportional plus integral. The ability to manually enable the integrator provides the bimode governor.

(2) Geometry Control Mode

Besides fuel flow, ATEGG has a six stage compressor with variable inlet guide vanes and variable vanes on all stages, a single-stage turbine with variable vanes, and a variable leaf-type exhaust nozzle. This creates three more control tasks:

- Control of compressor variable geometry for surge relief
- Control of turbine variable geometry for airflow modulation
- Control of exhaust nozzle area

(a) Compressor Control Mode

The ATEGG compressor variable geometry was designed to vary the flow through the engine while providing surge relief. The present ATEGG configuration features a cam plate arrangement to position each stage of variable vanes. Through this arrangement each stage is uniquely positioned for a given corrected speed with all stages requiring the same vane reference angle at 100% NHC as shown in Figure 13. *Note that the only mode of control* for the compressor with the present actuation system is the surge avoidance control mechanism, HPC2. By changing cam plates the flow capacity of the compressor may be varied by moving the fan shaped form in Figure 13 up or down.

This present type of actuation system needs only one signal, corrected speed, to properly place each stage of variable geometry. Thus the only control logic which has been exercised is the positioning of each stage of stators per the fan shape of Figure 13. This logic is shown in Figure 12.

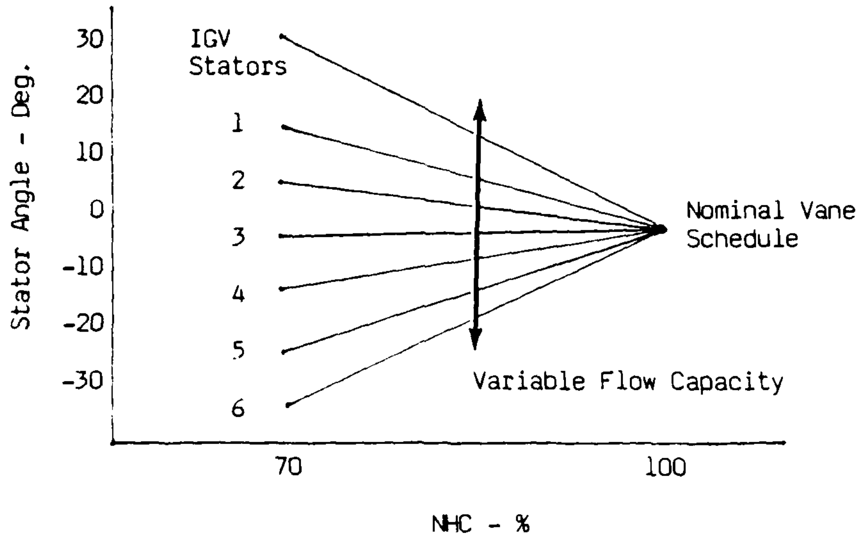


Figure 13. Compressor Surge Avoidance Relationship.

The compressor variable geometry can be positioned in two different manners:

- o Normal operation mode
- o Operator request

In the normal operation mode, as discussed above, each stage of stators is positined as a function of corrected speed. The operator request mode is used for calibration of the vane positioning system. It should be noted that the output to the actuator is a rate command which is range limited.

(b) Turbine Control Mode

The single stage of variable vanes in the ATEGG turbine assembly provides for significant flow variation and allows ATEGG to reach its high turbine rotor inlet temperatures. Figure 12 shows the logic presently coded for controlling the turbine geometry.

As in the case of the compressor two options exist for varying the turbine vanes:

- Normal operation mode
- Operator request

In the normal operation mode the variable turbine vanes are used to control turbine outlet temperature (T4.1) in a closed loop fashion. Thus a reference T4.1 is scheduled versus power lever angle and compressor inlet temperature and compared with a feedback signal emanating from an Engelhard thermocouple to generate a T4.1 error signal. The error signal is compensated through a proportional plus integral network to generate a turbine positional request (HPT_{REQ}). By comparing the request with a feedback signal the positional loop is closed to produce a rate command which is sent from the EH-K1 to the air motor actuator. When operating in this mode during an engine start, a "SELECT" box sets the temperature error to zero until the speed governor is enabled. With this and the proper initial condition on the integrator, the turbine remains open during a start to provide maximum surge margin.

The second mode of operation uses an operator command value (OPHPT) to set the turbine position. In addition to acting as a calibration aid for the system this option allows the engine to be run as a fixed turbine configuration.

- Exhaust Nozzle Area Control Mode

The ATEGG variable area exhaust nozzle is a hydraulically actuated, leaf-type nozzle. As in the case of the turbine, the positional loop for the exhaust nozzle area is closed within the digital controller. Thus a rate command is sent to the servovalve portion of the actuation system.

Under normal operating conditions the exhaust nozzle area is scheduled against power lever angle and compressor inlet temperature (see Figure 12). The operator request option (OPA8) also exists. Sufficient range and rate limiting exists in the software to provide unwanted transient excursions as undesirable rapid movements of the nozzle. Failure circuitry interfaces with the software to slew the nozzle open in the event of a digital controller failure.

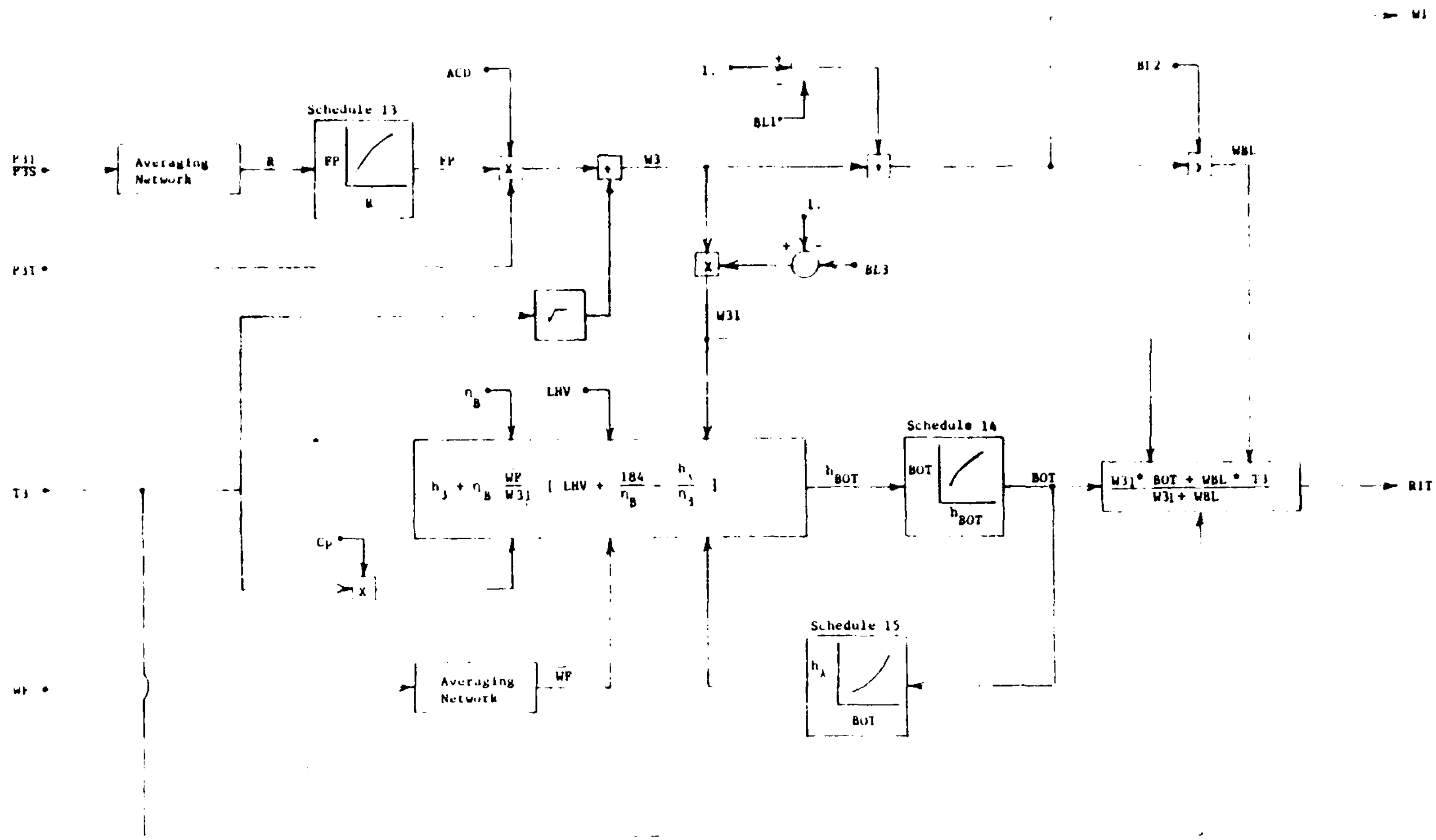


Figure 14. RIT Synthesis Logic

(3) Signal Synthesis

Signal synthesis was one of the original goals of the ATEGG controls program. To date, that effort has focused on the calculation of compressor discharge airflow and synthesis of turbine rotor inlet temperature (RIT). The procedure, outlined in Figure 14, uses measured parameters at the compressor discharge plus fuel flow requested from the control logic. The airflow and Mach number at the compressor discharge are computed based on an isentropic flow relationship using the total and static pressures at the compressor discharge. A heat balance equation for the combustion chamber uses the synthesized airflow value minus bleeds to compute the burner outlet temperature (BOT). An energy balance equation is used combining burner outlet conditions with known bleed conditions to arrive at the synthesized rotor inlet temperature. As can be seen in the diagram, the process is an iterative one using the previous value of BOT to calculate a new one.

b. Input/Output Processing

Any signal appearing in the control logic which has been fed back from the engine or control interface hardware is processed through an input signal conditioning section in the software. Figure 15 shows this interface with a multiplexing analog-to-digital converter providing the Input Signal Conditioning section with the desired variable.

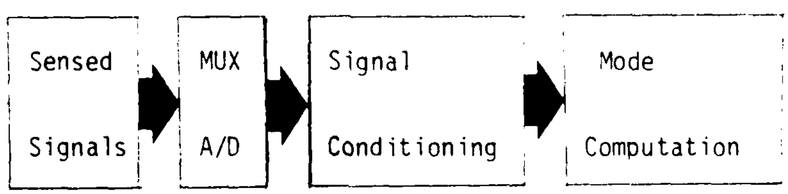


Figure 15 EH-K1 Input/Output Interface

Table 3 shows the inputs to the Input Signal conditioning software. The tasks accomplished by this section are as follows:

- Range checks - All inputs are checked for reasonableness by specifying upper and lower bounds. For each variable which is range checked, a flag is allocated to indicate if the signal is within range or not.
- Rate checks - All inputs are checked for reasonable rates of change by specifying maximum positive and negative rates expected during normal engine operation. For each variable, a flag indicates if the rate of change of the parameter is reasonable.

- ADC Offset - Any offset in the multiplexing analog-to-digital converter can be removed by a bias.

- CJ Compensation - All thermocouples are cold junction compensated.

- Thermocouple Calibration - All thermocouples have a calibration curve to equate a thermocouple voltage to a temperature in degrees Rankin.

- Speed Conversion - Inputs from the speed circuit are a count value of pulses received during a measurement interval and a Vernier count representing the time interval since the last pulse counted. Using these values a frequency is calculated which is directly proportional to speed.

- Redundant Feedback Selection - For those variables where two sensors provide feedback to the EH-K1, the Input Signal conditioning section chooses between the two sensors, and switches to the alternate sensor in the case of a failure.

- Auxiliary Signal Generation - Some signals necessary to the control logic are not directly measurable but are calculated internally within the control. These variables which are necessary are shown in Table 4.

- Dynamic Compensation - Any signals requiring dynamic compensation for stability purposes may be compensated in this section of the software.

Table 3

Inputs to Signal Conditioning Software

PLA	Power Lever Angle
NH1	Compressor Rotor Speed
NH2	Compressor Rotor Speed
T2.1	Compressor Inlet Temperature
T3	Compressor Discharge Temperature
T4.1	Turbine Outlet Temperature
TBT_{peak}	Peak Turbine Blade Temperature
$TBT_{average}$	Average Turbine Blade Temperature
HPC1FB-A & B	Position of Compressor Geometry for Flow Control (Dual Channels)
HPC2FB-A & B	Position of Compressor Geometry for Surge Control (Dual Channels)
HPTFB-A & B	Position of Turbine Geometry (Dual Channels)
A8FB-A & B	Exhaust Nozzle Area (Dual Channels)
P2.1T	Compressor Inlet Pressure
P3T	Compressor Discharge Total Pressure
P3S	Compressor Discharge Static Pressure
P4.1T	Turbine Outlet Pressure
WFAFB	Pilot Channel Fuel Flow
WFBFB	Main Channel Fuel Flow

Table 4

Signals Generated

NH	Rotor Speed in percent
NHC	Corrected Rotor Speed
θ	Temperature Correction Factor
$\sqrt{\theta}$	Root of Temperature Correction Factor

c. Diagnostic Checks

The confidence level of the control is enhanced by performing diagnostic functions on the control system hardware. The diagnostics performed are:

- o CPU SELF TEST: Portions of the Control Mode are executed with fixed data and checked for a known result.

- o MEMORY CHECK-SUM: A check-sum will be obtained on the fixed content of memory program code and tables.

- o RAM CHECKS: An unused block of 128 words is checked and is reallocated to use if operable.

Violation of any of these self-checks causes a failure discrete to be set. This is an indication of computer malfunction; therefore, the computer is halted and control of the engine is passed to the UTC.

d. Interactive Module

The ATEGG software includes an interactive module which permits a communication link to the control logic. Interaction is done through a CRT. Among the options available are the following:

- o Display of control logic parameters
- o Selection of mode of operation
- o Alteration of particular parameters in the control mode.
- o Plotting of selected parameters

These functions are very helpful in providing a flexible controller for a demonstrator engine.

SECTION V
SOFTWARE VERIFICATION

The EH-K1 Software was verified in two phases prior to ATEGG B.U.5 testing. The first phase was accomplished at Bendix where a simplified simulation of the ATEGG engine was programmed on the Bendix hybrid computer and interfaced with the EH-K1 software. The system was exercised per anticipated B.U. 5 testing to insure stable operation. Having completed this the EH-K1 hardware and software were shipped to Detroit Diesel Allison for off-engine fuel system testing.

1. Phase I

The objective of this software verification was to demonstrate that the control software functioned correctly at steady state and during system transients. This was accomplished by simulating the engine and test hardware on a hybrid computer operating in real time, closing the loops with the EH-K1 controller and exercising the system.

The software package had been checked previously for Build 4 using a BDX-9000 digital computer and a similar engine simulation (reference DDA EDR 9440). Therefore the scope of this test was limited to validating the portions of the program modified for B.U. 5. For B.U. 5 the control mode was simplified by eliminating the active HPT and A8 control loops. This was done to accommodate the engine test plan which called for fixed turbine and nozzle settings for any transient testing. The operator select mode was used for each of these loops. The major items addressed during the phase I verification were the following:

- o Analysis of the fuel governor loop
- o Analysis of the fuel acceleration/deceleration loop
- o Analysis of the fuel limiting loop
- o Analysis of the signal synthesis software.

A simplified simulation of the ATEGG engine using univariant functions was programmed on the Bendix hybrid computer (a PDP-11/70 digital computer with an AD/5 analog computer). Except for the pressures the simulated feedback signals were scaled to be used directly by the EH-K1 utilizing the normal feedback channels, interface circuitry and conversion routines. The simulated pressure signals were supplied to the EH-K1 as DC voltages on unused input channels. The control's output current signals were read across load resistors as voltage drops by the hybrid for commanding the simulated servovalves. A block diagram of the simulated engine and interface hardware is shown in Figure 16.

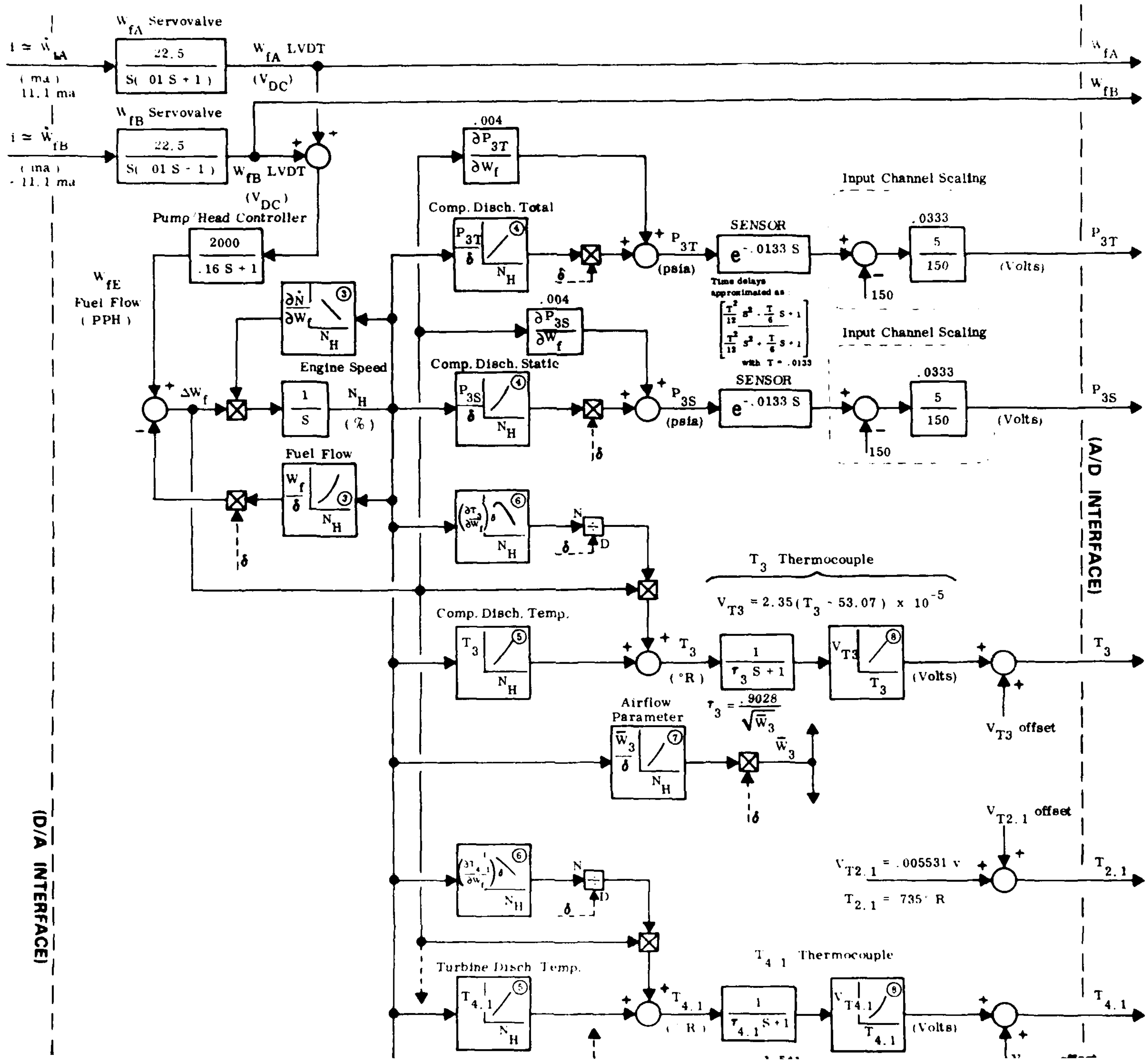
Prior to closing any loops, linear, analysis was performed to predict loop stability. The speed governor gains were modified and resized for the characteristics of the B.U. 5 operating line. The limiter gains were also evaluated. This simplified linear analysis was accomplished with the aid of linear perturbation engine models of the form

$$\delta \dot{NH} = \frac{\partial \dot{NH}}{\partial NH} \delta NH + \frac{\partial \dot{NH}}{\partial WF} \delta WF$$

$$\delta Y = \frac{\partial Y}{\partial NH} \delta NH + \frac{\partial Y}{\partial WF} \delta WF$$

where δ indicates the perturbation about a steady state operating point. Note that only one input variable, fuel flow (WF), and one dynamic variable, rotor speed (NH), are used to define the engine dynamics. As shown in the equations any output variable, Y, may be examined.

The above analysis assumes these partial derivatives are constant about a point. By combining several linear models in a piecewise fashion a simplified nonlinear engine model of the form shown in Figure 17 can be obtained. This formed the base for the hybrid model in Figure 1 with five outputs (Y's) being specified: P3T, P3S, T3, T4, and T4.1. As each control loop was closed with the hybrid computer the loop gain margin (calculated analytically) was evaluated (coarsely) by raising the loop gain until a limit cycle or a lightly damped response was reached. The final gains were based on this empirical



W_{fA} Servovalve
22.5
S(.01 S + 1)
W_{fA} LVDT
(V_{DC})
W_{fB} Servovalve
22.5
S(.01 S + 1)
W_{fB} LVDT
(V_{DC})
Pump Head Controller
2000
.16 S + 1
W_{fE}
Fuel Flow
(PPH)
Engine Speed
Fuel Flow
Comp. Disch. Total
Comp. Disch. Static
Comp. Disch. Temp.
Airflow Parameter
Turbine Disch. Temp.
SENSOR
Time delays approximated as
with T = .0133
Input Channel Scaling
.0333
5
150
(Volts)
(psia)
T_3 Thermocouple
$V_{T3} = 2.35(T_3 - 53.07) \times 10^{-5}$
$\tau_3 = \frac{.9028}{\sqrt{\bar{W}_3}}$
V_{T3} offset
$V_{T2.1}$ offset
$V_{T2.1} = .005531$ v
$T_{2.1} = 735°$ R
$T_{4.1}$ Thermocouple
(A/D INTERFACE)
(D/A INTERFACE)

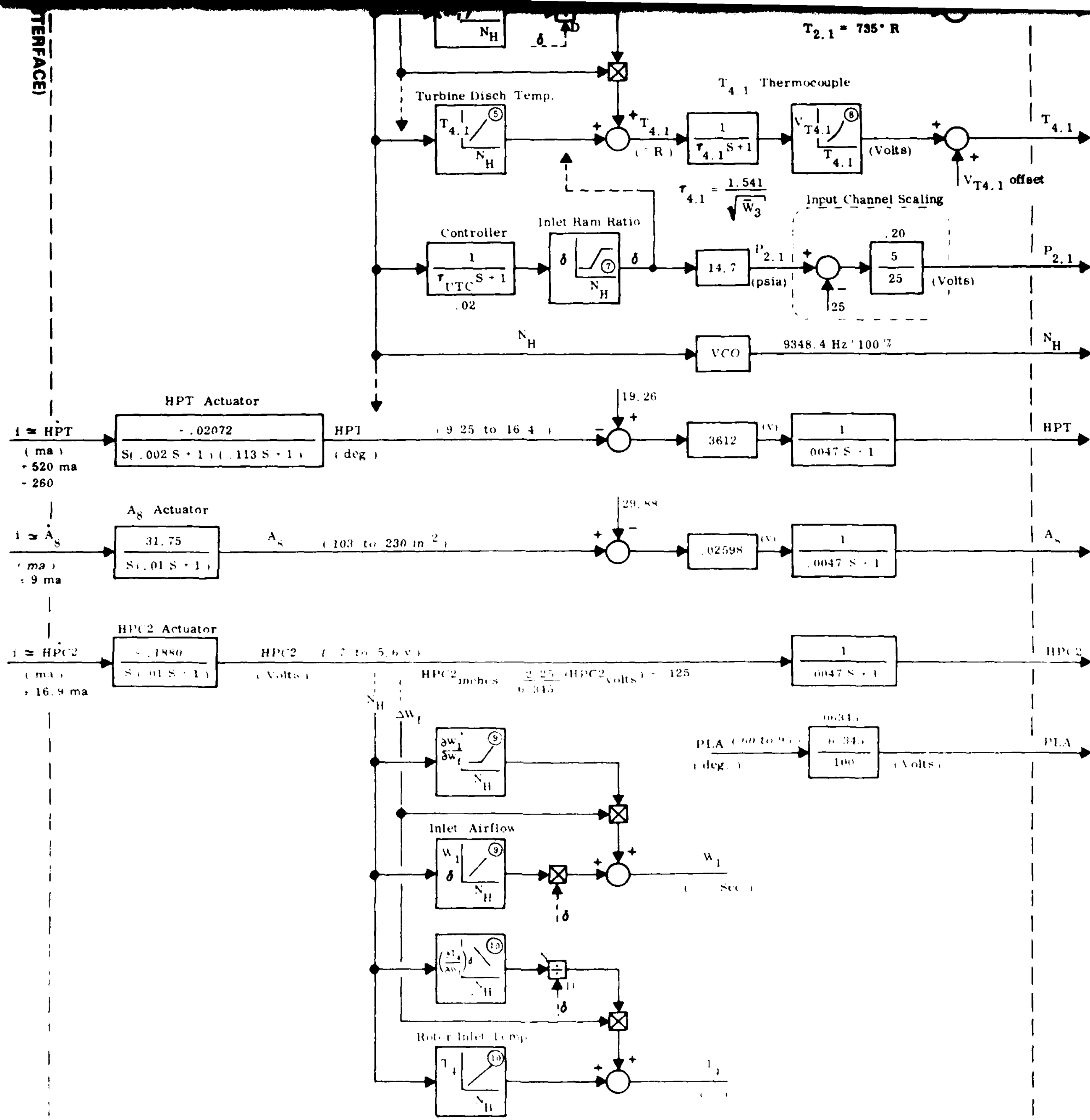


Figure 16. ATEGG Hybrid Model

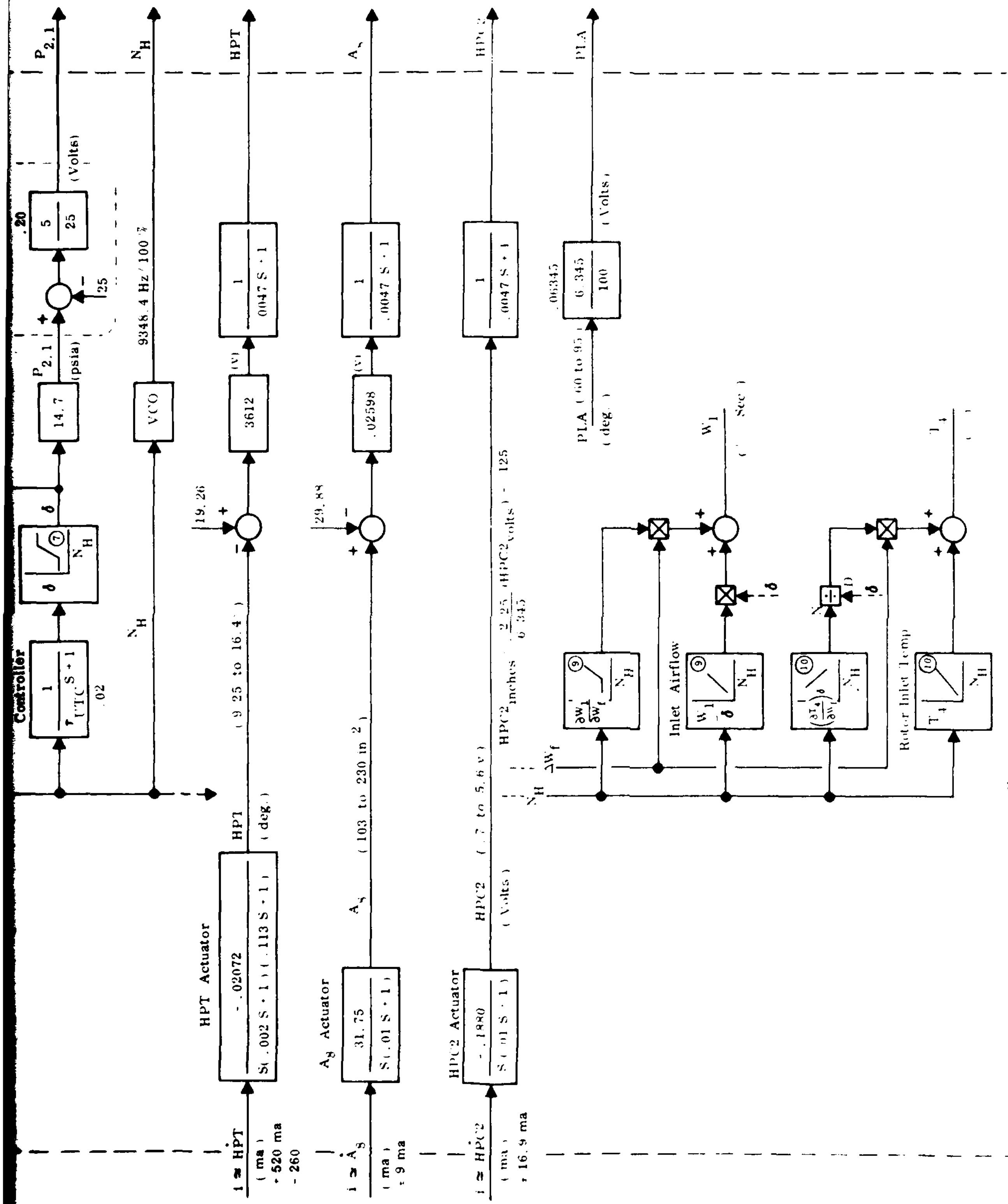


Figure 16. ATEGG Hybrid Model

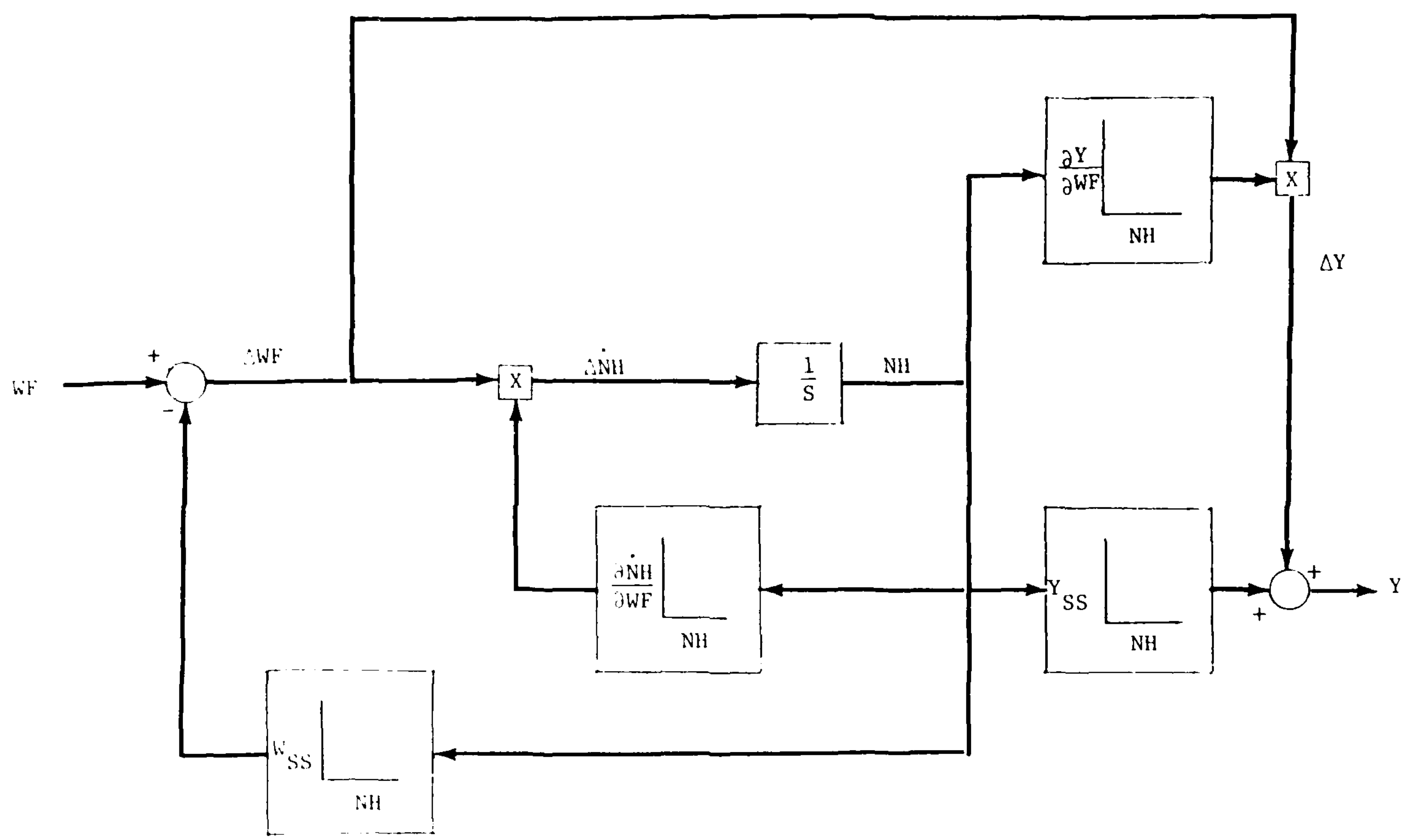


Figure 17. ATEGG Nonlinear Model

sizing method to produce a worst case minimum gain margin of 6 dB in each of the control loops.

Definition of the actuators and sensors was identified in the hardware specification of AFAPL-TR-77-57. The fuel valve definition is based on testing performed prior to B.U. 4.

a. Fuel Governor

The proportional and integral gains in the speed governor are sized for a minimum stability margin of 6 dB. Examining the way in which the model varies with inlet pressure, a direct method for compensating inlet pressure changes is to increase the control gain directly with inlet pressure and decrease the proportional plus integral time constant inversely with inlet pressure. This is done in the ATEGG control logic by varying the integral gain as a multiple of ram pressure ratio (RPR) and holding the proportional gain constant. This results in the following gain definitions:

$$K_I = 5.62 \text{ (RPR) pph/sec/rpm}$$

$$K_P = 6.47 \text{ pph/rpm}$$

These gains were used in exercising the hybrid model at various PLA settings throughout the engine operational envelope. The engine was found to be stable at all points examined.

b. Fuel Acceleration/Deceleration Loop

Transient operation of the hybrid model was used to evaluate the response characteristics of the controller. The acceleration schedule was shaped to maintain a minimum compressor surge margin for all inlet conditions. Transients were run between idle and intermediate PLA settings with fixed and variable RPR. The variable ram pressure ratio is used to simulate the effect of scheduling RPR vs. corrected speed as would occur with the high pressure spool reacting to a fan in front of it. This option exists for the transient endurance portion of B.U. 5 with the UTC acting as the controller of RPR. The transient results are summarized in Figures 18 and 19. Figure 18 represents the high pressure spool as it would act with a fan in front of it while Figure 19 shows the high pressure spool acting like a turbojet engine. In these figures the fuel flow requests from the controller (W_{fA} and WF_{fB}) and the engine fuel flow (W_{fE}) are plotted vs. engine speed. The system is stable and shows a speed overshoot of approximately 1.5% on accel and 3.5% undershoot on decel with variable inlet and a .02 second lag between NHC and RPR. This represents the dynamics associated with the ducting system carrying the conditioned air to the inlet of the engine. Increasing the lag to 2 seconds yields only .6% overshoot on accel, but the undershoot increases to 4.5%. With a fixed RPR an overshoot of .75% exists on accel while a 1.4% undershoot is present on decel.

A portion of the undershoot on deceleration is due to the residual value of the governor integrator, W_{fI}. Initially during a step deceleration the governor integrator attempts to track the PLA ramp and builds up a large (relative to steady state idle) negative correction on fuel flow before the decel limit is reached and the integrator held. This negative correction causes the governor requested fuel flow to be low as speed approaches the point and speed undershoots. Decelerations from lower speeds show less undershoot because the deceleration schedule is closer to the steady state line and the integrator is held more quickly in the initial transient It was thought that the nominal -35 deg/sec PLA rate limit would improve this undershoot compared with the originally programmed -17.5 deg/sec. There wasn't any noticeable improvement. However with the case where the negative PLA rate limit is raised to the largest number in the computer, the undershoot is reduced from 3.5 to 2%.

c. Fuel Limiter Loops

The fuel limiting loops, used to limit fuel flow in order to protect the engine from temperature and pressure limits, were exercised successfully with the B.U. 5 test configuration. Limiting of compressor discharge pressure (P3T) and turbine outlet temperature (T4.1) was exercised with fixed and

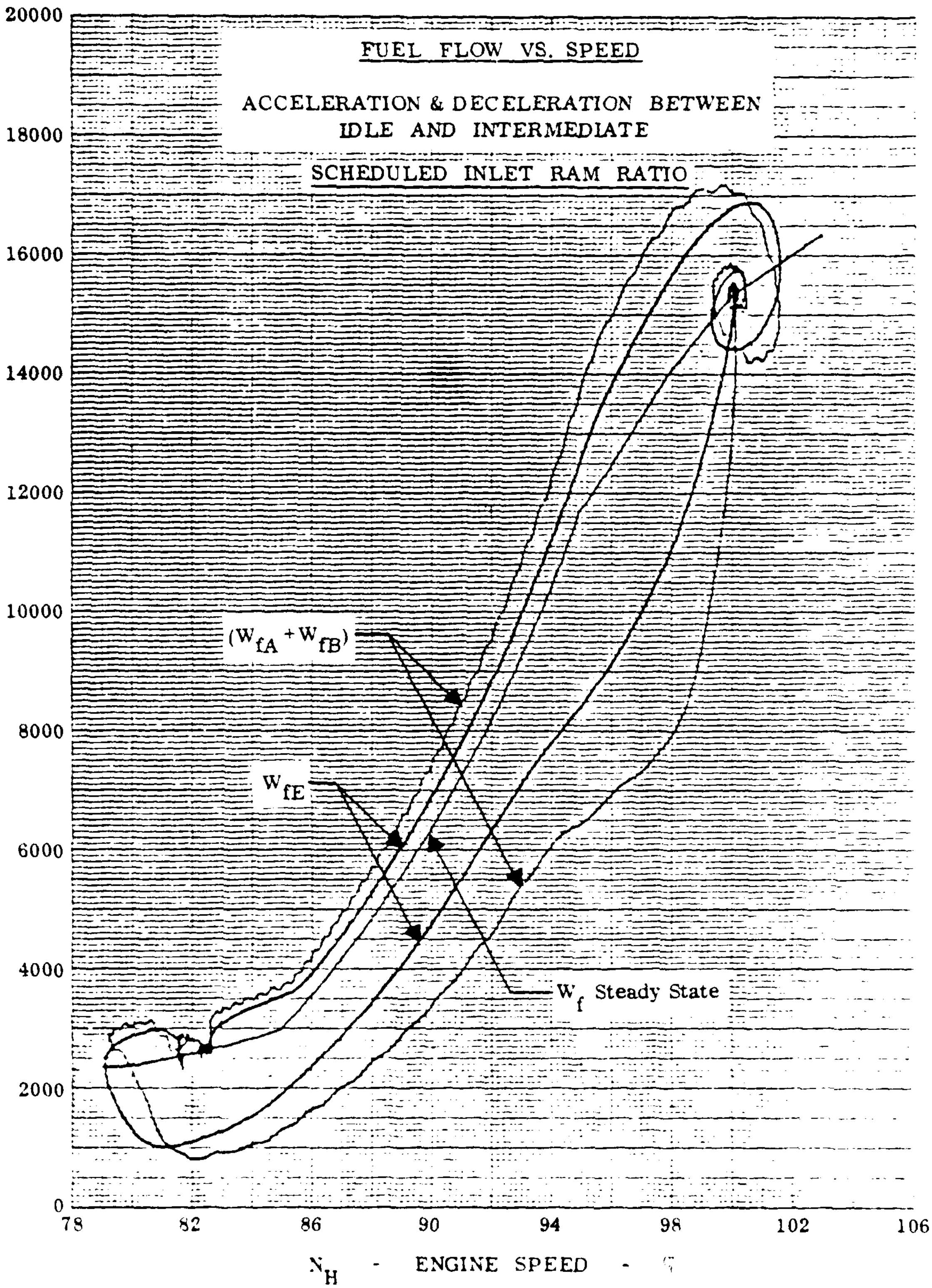


Figure 18. Transients between Idle and Intermediate - Scheduled RPR

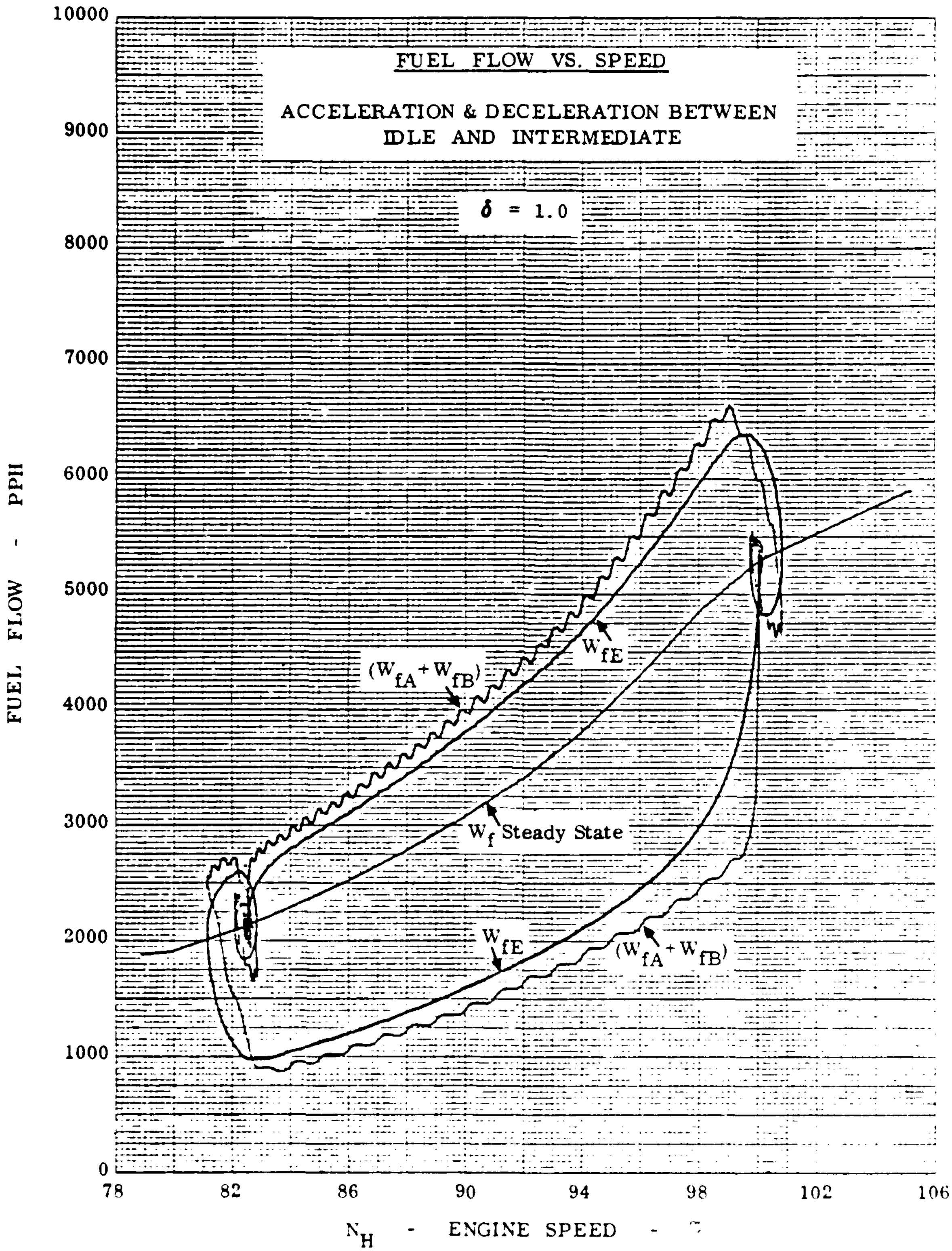


Figure 19. Transients between Idle and Intermediate - Fixed RPR

variable RPR. In each case the limiter reference was adjusted to be equal to the steady state value at 90% speed, and then PLA was stepped from idle (82.5% NHC) to intermediate (100% NHC). The proportional gains in the limiter loops were sized via linear analysis using the engine partials at 90% NHC to insure stability at the pulldown point. Figures 20 and 21 show the results of the fuel flow limiting runs.

Table 5 summarizes the results of Figures 20 and 21. The pulldown indicates the percentage that the desired limiting parameter is reduced with respect to its 90% NHC reference point. Thus

$$\text{Pulldown} = \frac{Y_{100\%\ NHC} - Y_{SS}}{Y_{100\%\ NHC} - Y_{90\%\ NHC}} * 100\%$$

where Y is either P3T or T4.1. As indicated by the table the amount which tne limited parameters can be decreased is subject to the maximum allowable gain in the limiting loop for stability purposes. Neither of these limiters functioned properly during pre- B.U. 4 feasibility testing. This was due to the turbine bias on fuel flow being passed through to the governor fuel flow. For the B.U. 5 configuration, a fixed turbine configuration, the logic does function properly.

Table 5
Summary of Pulldowns

Limiter	Inlet	NHC_{SS} - %	Pulldown - %
P3T	Fixed	92.0	31
	Variable RPR	90.5	95
T4.1	Fixed	90.5	96
	Variable RPR	91.0	90

K_{P3T} = 180 pph/psia

$K_{T4.1}$ = 25 pph/^{o}R

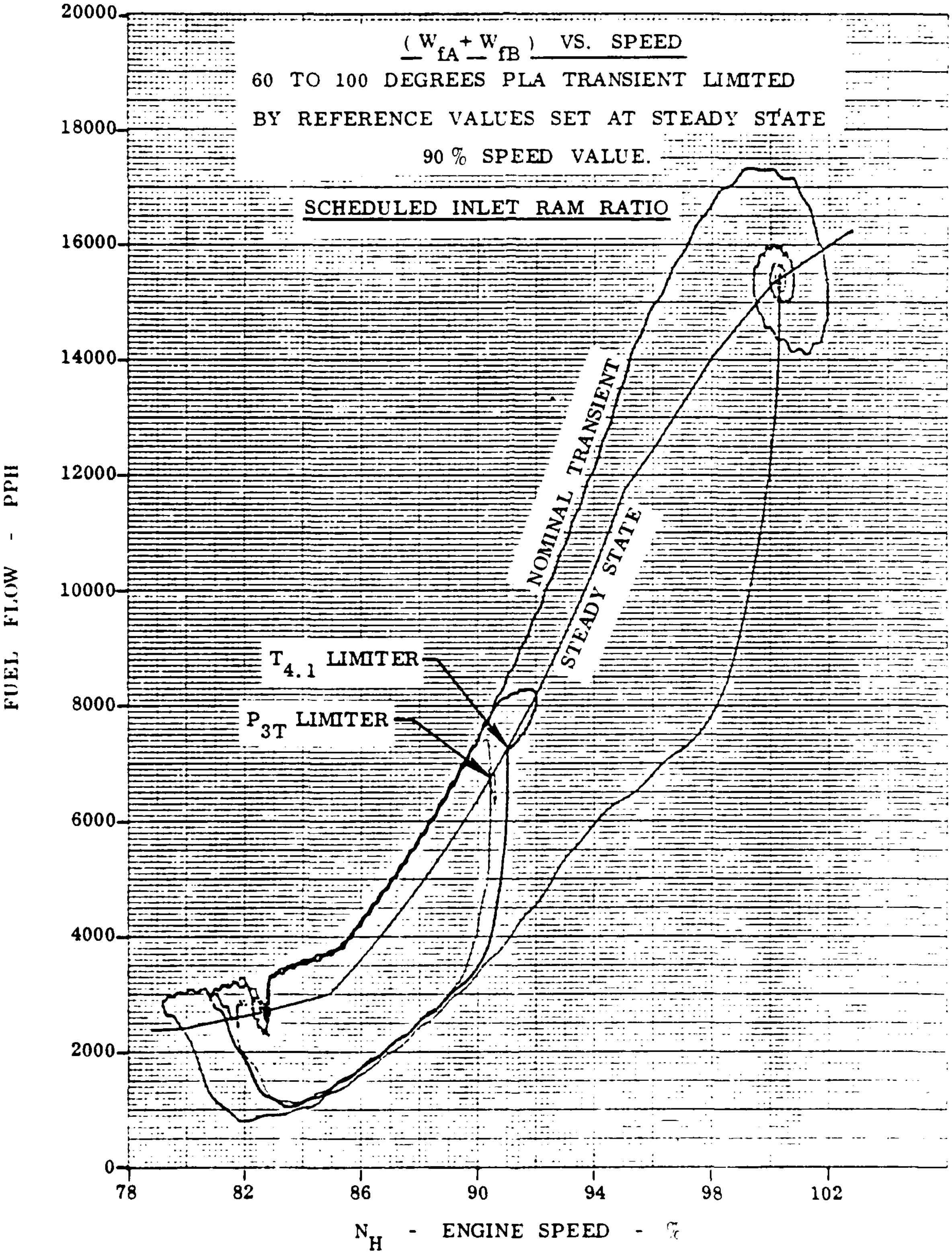


Figure 20. Parameter Limited Transients - Scheduled RPR

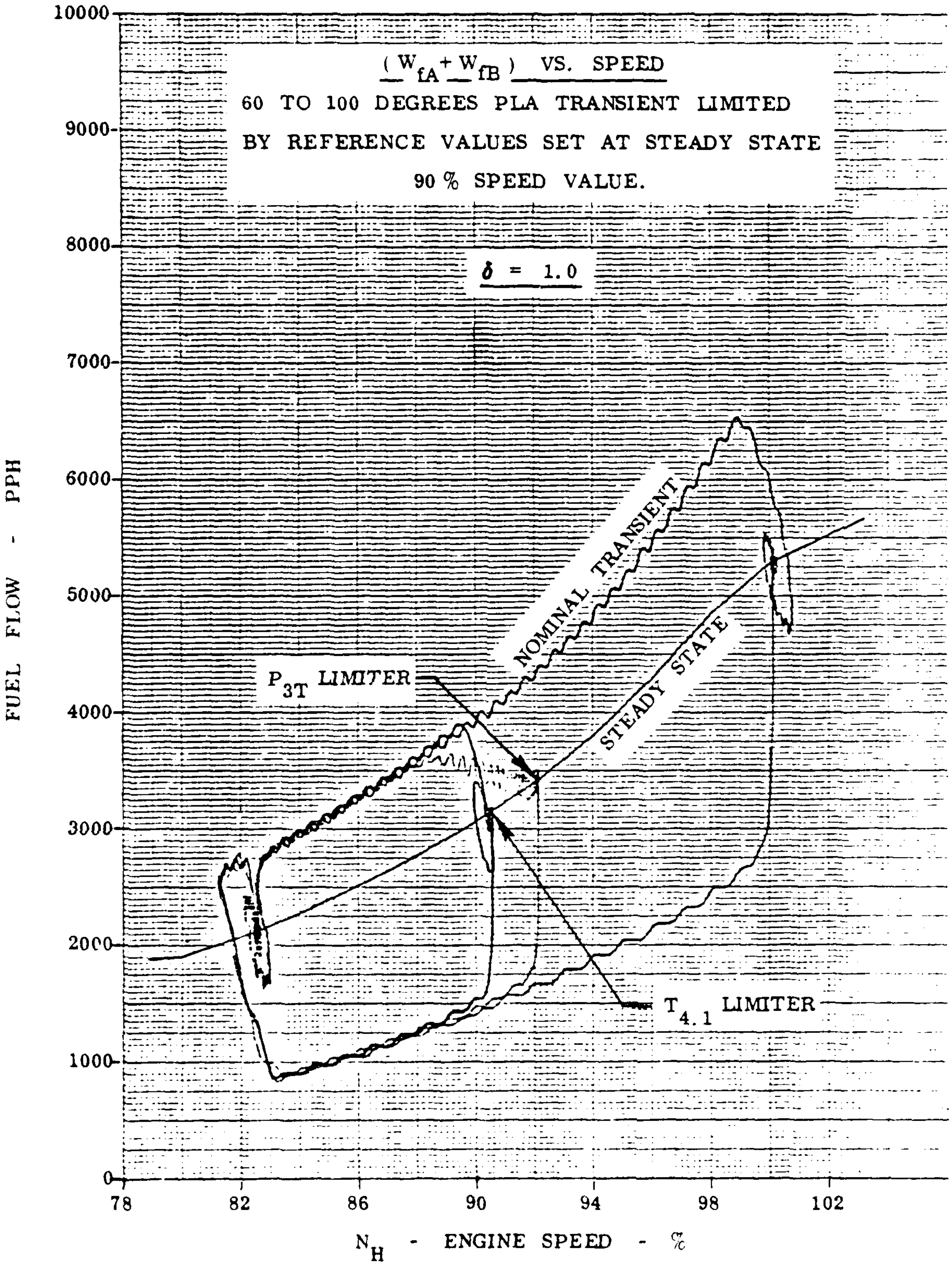


Figure 21. Parameter Limited Transients - Fixed RPR

d. Analysis of Signal Synthesis Software

The RIT Synthesis Logic has undergone several changes from its B.U. 4 definition including new bleed percentages due to engine seal changes, new burner efficiency values based on B.U. 4 testing, and signal conditioning to reduce noise on the P3PR and WFFB signals.

In the testing it was found that the synthesized rotor inlet temperature lagged the hybrid rotor inlet temperature, T4, on both accels and decels. This lagging is attributable to the EH-K1 sensing the output of the T3 thermocouple lag. The lags associated with the filtering networks were considered minimal with respect to this thermocouple lag.

2. Phase II

Phase II of the software verification involved interfacing the EH-K1 with the GMA200 fuel system. For initial checkout of the EH-K1 fuel modulation circuitry, operator commands of fuel flow were used. This set-up was used to calibrate the system and check for system nonlinearities such as offset and hysteresis. In the second portion of testing with the fuel system, authority for fuel modulation was turned over to the EH-K1 control logic. For this portion a simplified analog engine model was constructed to aid the closed loop control evaluation.

a. Operator command

Figure 22 shows one-half of the GMA200 fuel system. The GMA 200 fuel requirements call for two such identical systems to be used. For these purposes each system was tested separately with operator commands for fuel flow request from the EH-K1. These operator commands were made through the interactive portion of the EH-K1. The operator commands were used to look for offset and hysteresis in the system.

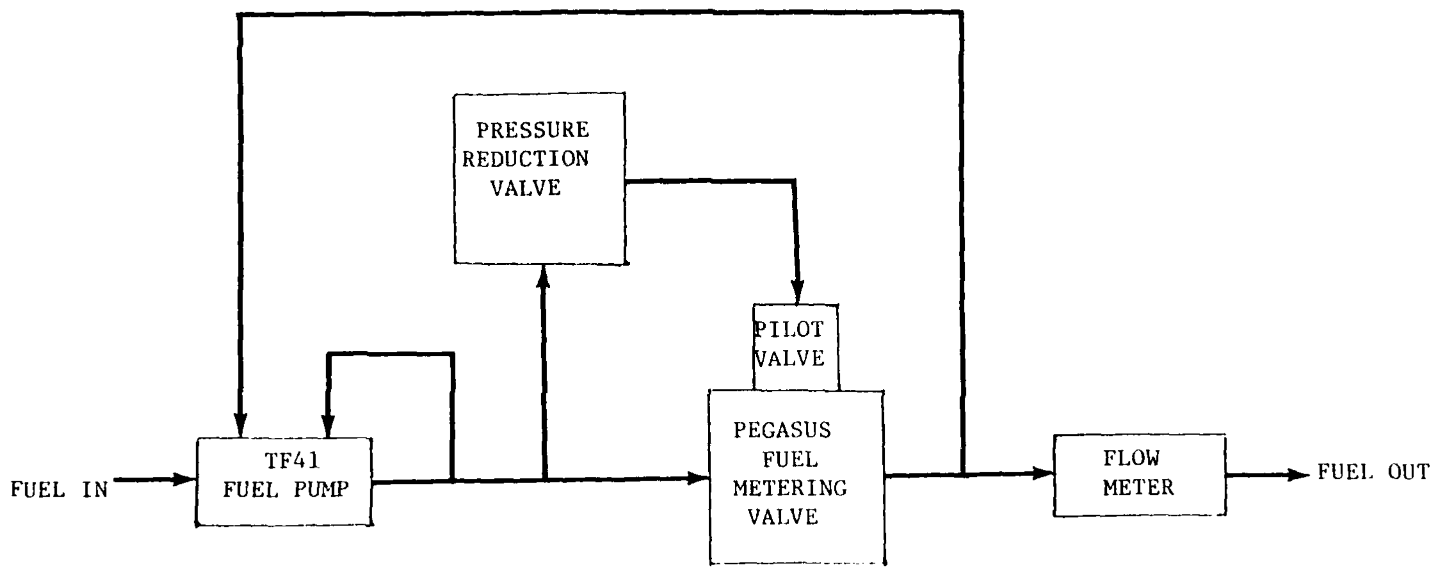
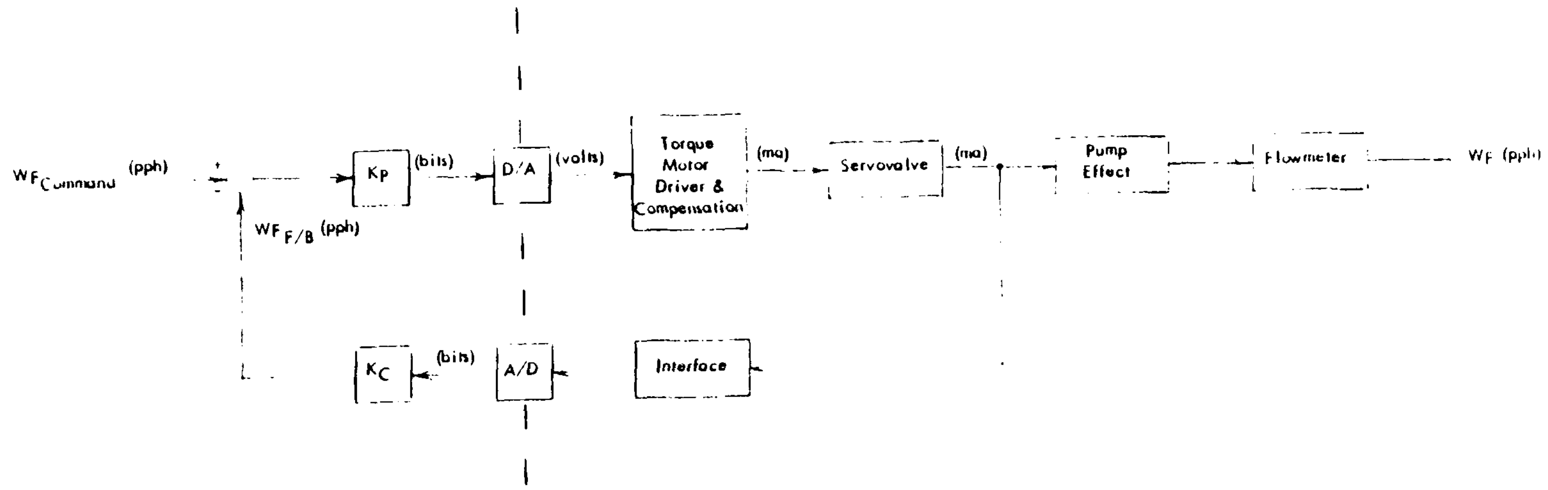


Figure 22. GMA200 Fuel System Hardware

Figure 23 shows schematically what the set-up is for each side of the fuel system. Stepped operator commands showed the pilot fuel system to be responsive but noisy with $\pm$100 pph fuel flow perturbations at a point. The gain limit for the loop was established by raising K_p and K_I to increase the loop gains while maintaining the K_p/K_I lead term associated with the fuel valve drive network. The loop gain limit was determined to be between 2 and 3 times the nominal gains. When the main fuel system was tested in this same manner the response was unacceptable. Figure 24 shows a typical response for the pilot system versus the main system for a step between 2000 and 4000 pph. Large overshoots and undershoots were apparent with stepped requests. In addition although at-a-point fuel modulation was quieter than for the pilot system, drifting occurred. Both the slow response and the drifting were attributed to a sticky pilot stage of the fuel valve. Examination of feasibility testing done prior to B.U. 4 showed a similar sluggish trend of the main fuel system. Raising K_p and K_I for the main system as was done for the pilot system confirmed that the valve response was less for the main system. Tripling K_p and K_I did not cause the main system to go unstable, but quadrupling them did.

An attempt was made to alleviate some of the noise at-a-point by altering the gain distribution in the fuel valve positional loop. Referring to Figure 23 this was done by decreasing the valve response. On the pilot system the pilot stage supply pressure was dropped from 350 psi to 100 psi. This provided enough strength to modulate fuel through the anticipated flow range while decreasing the gain and bandwidth of the servovalve. This permitted the gains K_p and K_I in the fuel valve positional loop to be increased to maintain the same loop gain. The redistribution of gain on the pilot system halved the about-a-point fuel flow perturbations. On the main system the supply pressure to the pilot stage of the servovalve was decreased only slightly since the valve characteristics were already depressed from those of the pilot system. The proportional and integral loop gains were doubled and the result was a much more responsive fuel system with no drifting. Figures 25 and 26 show responses to step commands for each configuration. These responses were judged acceptable for B.U. 5 testing, but improvements are sought to prevent the drifting and noise.



Assumed Transfer Function Forms:

$$D/A : TF = -.00488 \left(\frac{1 - e^{-.02s}}{s} \right)$$

$$\text{Torque Motor Driver and Compensation: } TF = \frac{-.555\,(.01s + 1)}{.001s + 1}$$

$$\text{Servovalve : } TF = \frac{.45}{s(.01s + 1)}$$

$$\text{Pump Effect: } TF = \frac{1.2 \times 10^5}{.16s + 1}$$

$$\text{Interface: } TF = \frac{11}{.0053s + 1}$$

$$A/D: \quad TF = -\frac{e^{-.01s}}{.00488}$$

Figure 23. Fuel Valve Loop Schematic

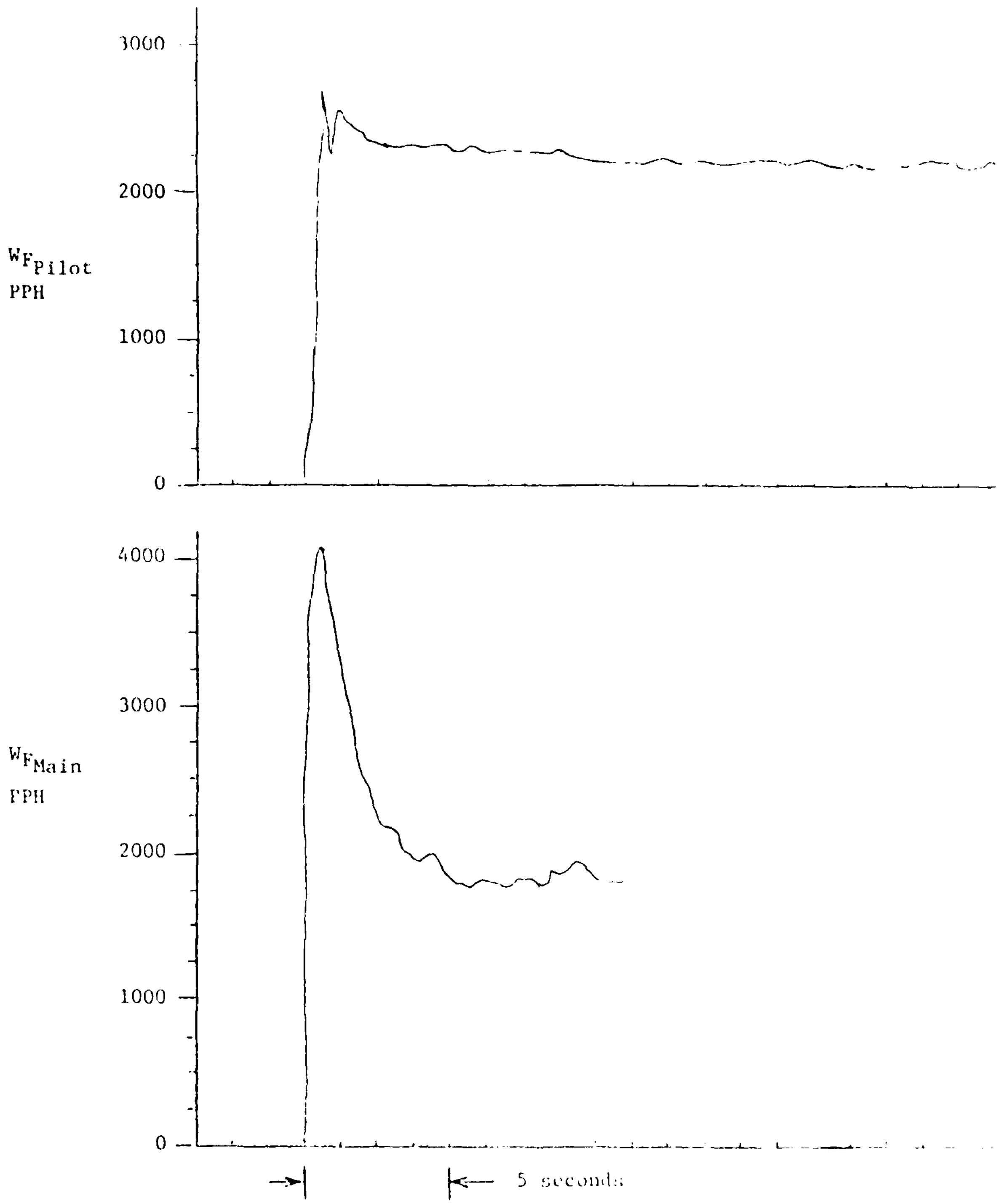


Figure 24. Stepped Responses of Pilot and Main Valves

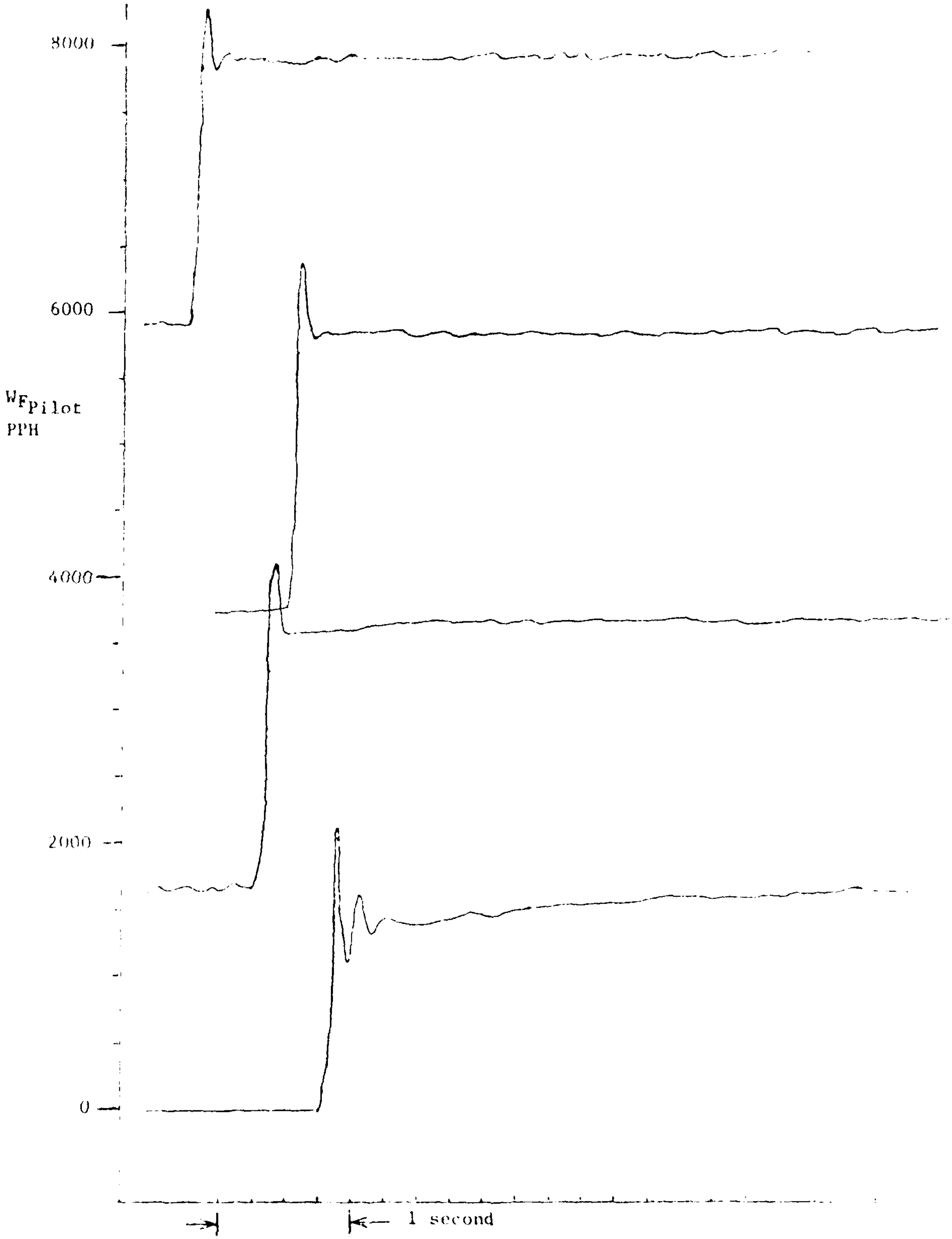


Figure 25. Pilot Valve Response - Final Configuration

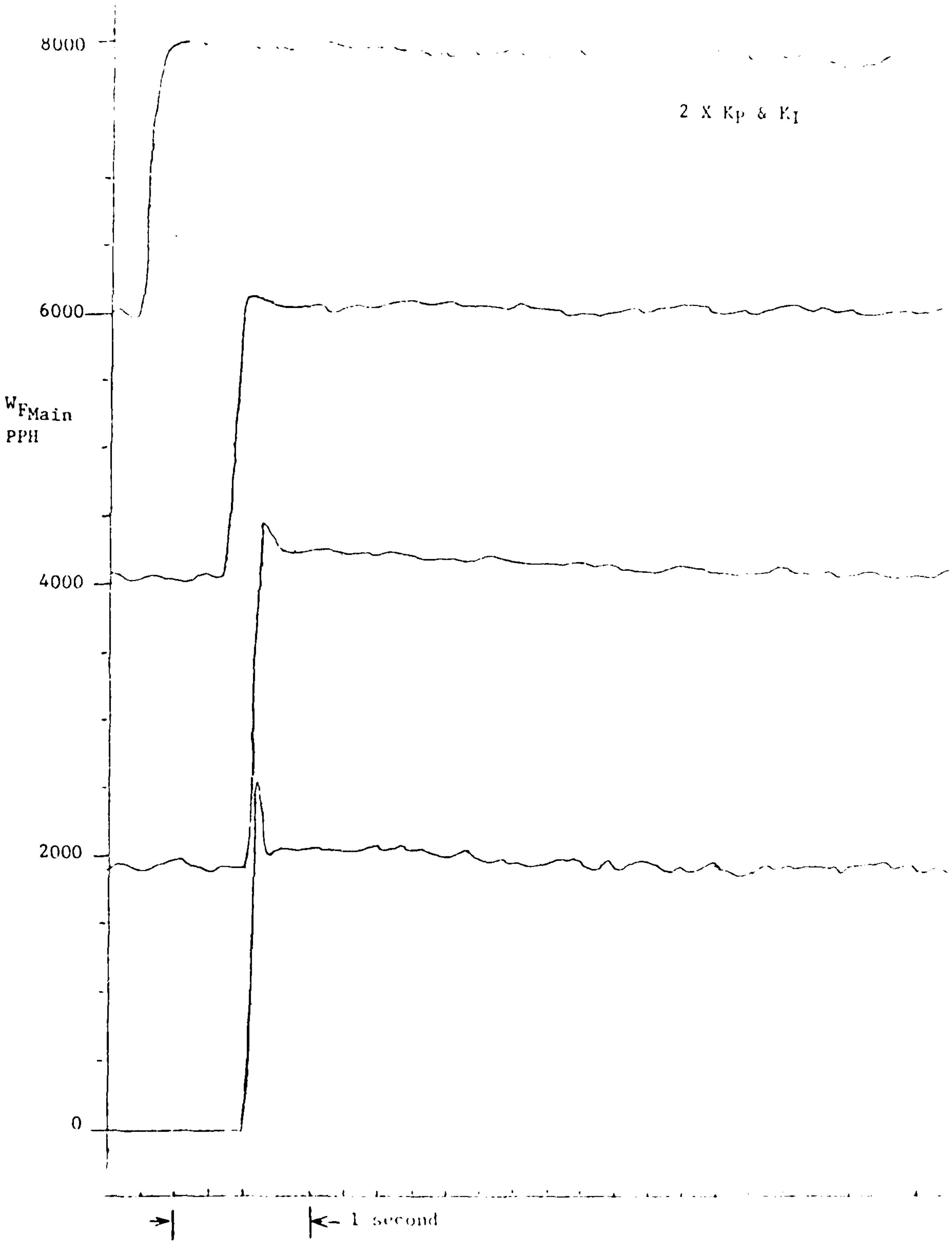


Figure 26. Main Valve Response - Final Configuration

A hysteresis check was made by introducing a triangular wave of low frequency (0.1 Hz) at the input of the A/D in Figure 23. When comparing LVDT feedback vs. input command, neither fuel system exhibited any appreciable hysteresis. No offset existed either indicating that the slow integral channel in the fuel positional loop succeeded in removing any offset in the system.

b. Fuel System Testing - Closed Loop

In the second portion of testing with the fuel system, authority for fuel modulation was turned over to the EH-K1 control logic. The test set-up was as shown in Figure 27. The fuel system hardware is as shown in Figure 22. The remainder of Figure 27, except for the control, is an attempt to represent the engine as simply as possible through analog circuitry and hardware.

The schedule of N_H vs. W_F is the inverse of the required to run line for steady state operation as set up on a function generator. The transfer function following this represents the engine lag analog circuit with representing the engine time constant. This lagged speed signal then is fed through a voltage controlled oscillator to convert the DC voltage signal to an A/C signal suitable for feedback to the EH-K1. The lagged speed signal is also input to a function generator to approximate the response of compressor discharge pressure to engine speed. This voltage signal is sent to a pressure control valve which is attached to a 450 psia air supply, thus providing a regulated pneumatic signal necessary for inputs to the pressure transducer in the EH-K1.

An additional function generator interacts with the high pressure air supply to yield compressor inlet pressure as a function of engine speed if desired. This is an attempt to simulate the anticipated inlet condition for cyclic endurance running on the B.U. 5 of ATEGG. With this set-up the fuel control logic was exercised to insure that stable steady state operation can be achieved for various configurations of the following:

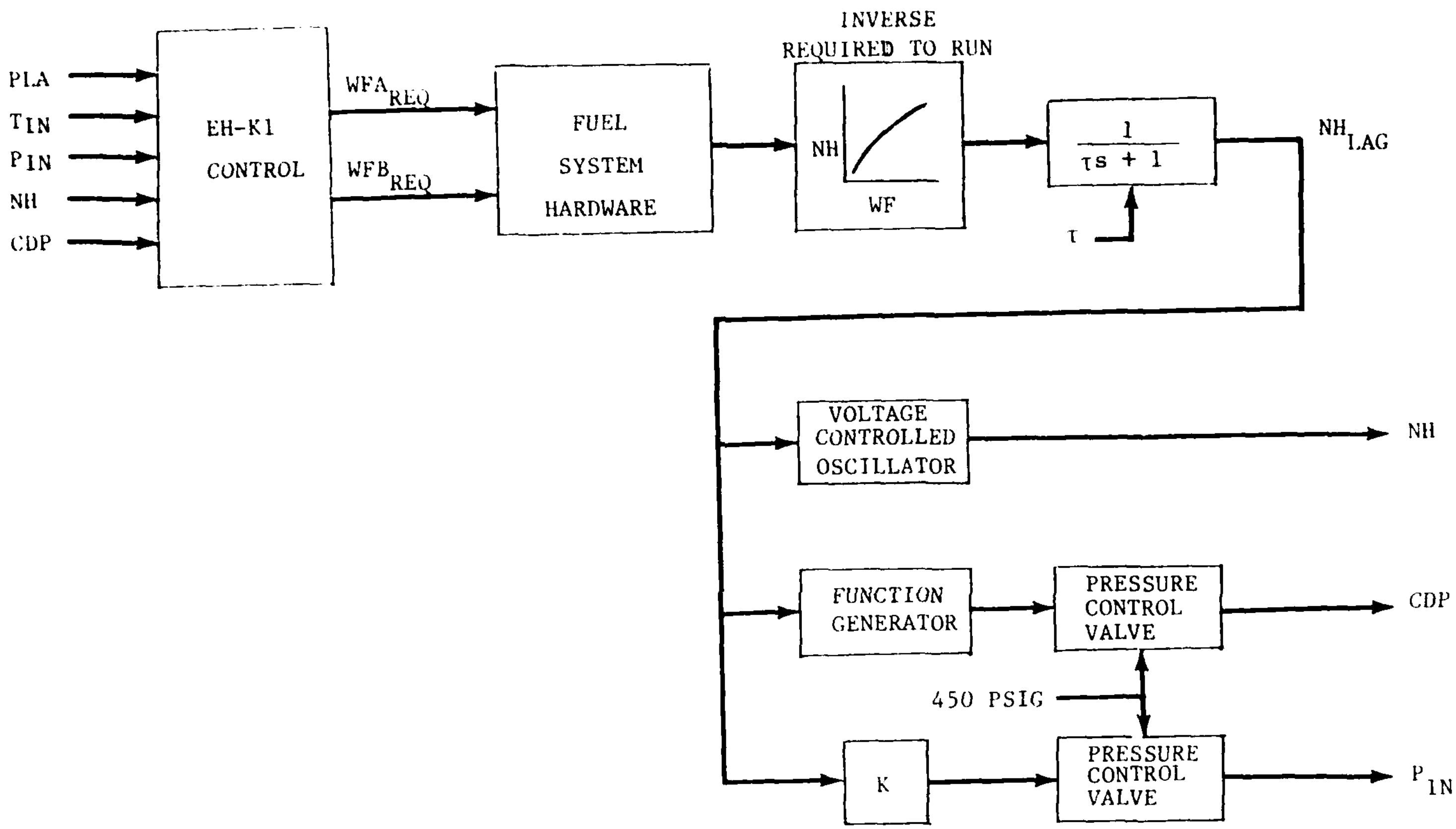


Figure 27. Test Set-up for Governor Running

$\cdot$	-	engine time constant
P_{in}	-	compressor inlet pressure
T_{in}	-	compressor inlet temperature
PLA	-	power lever angle

Table 6 shows the points which were run to simulate the B.U. 5 test schedule. Stable operation was indicated at all points tested. In exercising the fuel control logic the fuel splitter logic was also tested and found to be operating successfully.

When operating with P_{IN} as a f(NHC) it was not possible to decelerate all the way to idle. This was attributed to improper scheduling of the CDP vs. NH_{LAG} relationship resulting in a higher CDP at a given NHC than is really the case. Since CDP interacts with the deceleration schedule this elevated CDP causes a value of WF_{DECEL} which exceeded the required to run.

Another problem experienced was the hanging up of the main fuel valve on a transient from idle to intermediate. This occurred before the main valve was extensively flowed. This flowing served to alleviate the pilot stage's sticky behavior. No other problem existed in the closed loop testing.

Table 6

Governor Verification Summary

T_{IN} - °F	P_{IN} - psia	PLA - deg.	$\cdot$ - sec.
275	14.7	60	1.0
275	14.7	95	0.5
275	f(NHC)	60	1.0
275	f(NHC)	65	1.0
275	f(NHC)	75	1.0
275	f(NHC)	85	1.0
275	f(NHC)	95	1.0

SECTION VI
ATEGG B.U. 5 ENGINE TEST

SUMMARY

The objectives of B.U. 5 engine tests were to satisfy the remaining engine demonstration committments of ATEGG XI. Table 7 summarizes the points run versus the contract committments. In the table TADP represents turbine aerodynamic design point. The temperature corresponding to this point is classified, and thus the values have been expressed in a percentage form. As can be seen from the table, points 1, 2, and 4 clearly satisfied contract committments. Although point 3 lacked the proper amount of time at temperature and point 5 failed to fall within the desired temperature range, the total time at temperature was deemed acceptable. Previous plans to run cyclic endurance were eliminated, and B.U. 5 testing ended with the ATEGG operating under digital control by the EH-K1.

I. Piggyback Operation

The test portion of the JTDE Control Feasibility Demonstration was formulated as a "piggyback" operation in which the amount of dedicated control testing would be minimized to reduce the risk of ATEGG damage.

During the B.U. 5 testing which was accomplished under UTC control, the EH-K1 monitored the engine operation. During this "piggyback" operation, the EH-K1 monitored its normal engine control parameters but sent no signals to actuators. Table 8 shows the engine signals monitored and the instrumentation used to measure each parameter. The table also shows the engine instrumentation which provided the SEL data acquisition system with its measurements of the corresponding parameters.

Table 7

ATEGG XI Committments

Test	Test Conditions (^{o}/RPR)	NHC (%)	Committment/Test Time (min.)	RIT - % TADP
Endurance #1	275/1.5	98	3.5/10.6	101.8-105.6/103.7
Endurance #2	275/1.5	98	3.5/ 2.2	105.6-109.3/107.4
Endurance #3	275/1.5	98	3.5/ 4.4	109.3-113.0/111.1
Endurance #4	275/1.5	93	3.5/10.3	101.8-105.6/103.7
Endurance #5	275/2.4	93	3.5/ 4.9	101.8-105.6/ 99.1

Table 8

ATEGG Instrumentation

Notation	Engine Parameter	Instrumentation used in EH-K1	Instrumentation used for SEL
NH	Compressor Rotor Speed	Tachometer	Tachometer
T1	Compressor Inlet Temperature	Chromel/Alumel Thermo-couple (2 clusters)	2 5-element rakes (math average)
T3	Compressor Discharge Temperature	Chromel/Alumel Thermo-couple (1 channel)	2 5-element rakes (math average)
T4.1	Turbine Outlet Temperature	Engelhard Thermocouple (1 channel)	3 3-depth rakes (math average)
TBT	Turbine Blade Temperature	Solar Optical Pyrometer	Solar Optical Pyrometer
P1	Compressor Inlet Pressure	1 3-depth probe (averaged)	6 single-depth probes (manifold average)
P3T	Compressor Discharge Total Pressure	6 dual-depth probes incorporated in the fuel nozzles (manifold average)	1 5-element rake (math average) & 1 5-element rake (mechanical average)
P3S	Compressor Discharge Static Pressure	4 single-depth probes incorporated in the OGV's (manifold average)	4 I.D. Static probes (manifold average) & 4 O.D. Static probes (manifold average)
P4.1	Turbine Outlet Pressure	1 3-depth probe (manifold average)	1 3-element rake (math average) & 1 3-element rake (mechanical average)

Figure 28 is an overall signal diagram showing how the EH-K1 and related instrumentation were connected during the piggyback portion of the engine test. Prior to engine fire-up the control was tested with the engine actuators controlling surge avoidance, turbine area, and nozzle area. This testing verified proper actuator movement. The control was then connected in a piggyback arrangement with all inputs connected to actual engine sensors and outputs connected to a loop closer box, which closes actuator loops via simplified electronic analogs of the actuators as shown in Figure 28. The engine geometry actuators and fuel valves were normally controlled by the Universal Test Control (UTC) during the engine running completed.

Figure 29 shows the hardware location in the test stand and control room. The EH-K1 was engine mounted on a specially designed raft and heat shield previously used on an IR&D program. The strip chart recorders shown were used to provide continuous monitoring of the following signals: P3T, NH1, T1, T4.1, PLA, HPC2, HPT, A8, WFA, WFB. These signals plus P1, P3S, and P4.1 were also recorded on the System Engineering Lab (SEL) central data system, which provides a non real time record of data.

Data correlation was done on these parameters by comparing the EH-K1 sensed values with the SEL data obtained. Excellent correlation was shown with respect to NH, T3, P1, P3T, P3S, and P4.1 with no more than 1% error existing between the EH-K1 and SEL results for any of the steady state test points examined.

The compressor inlet temperature, T1, as sensed by the EH-K1 was consistently 5-10 degrees lower than that recorded by SEL. This was due to placement of the probes, as the Chromel/Alumel Thermocouple used by the EH-K1 was in the inlet plenum chamber while the SEL instrumentation was in the duct which transported the conditioned air. Although the corrected speed indicated by the EH-K1 was somewhat higher due to this, misscheduling within the control logic was considered neglibible.

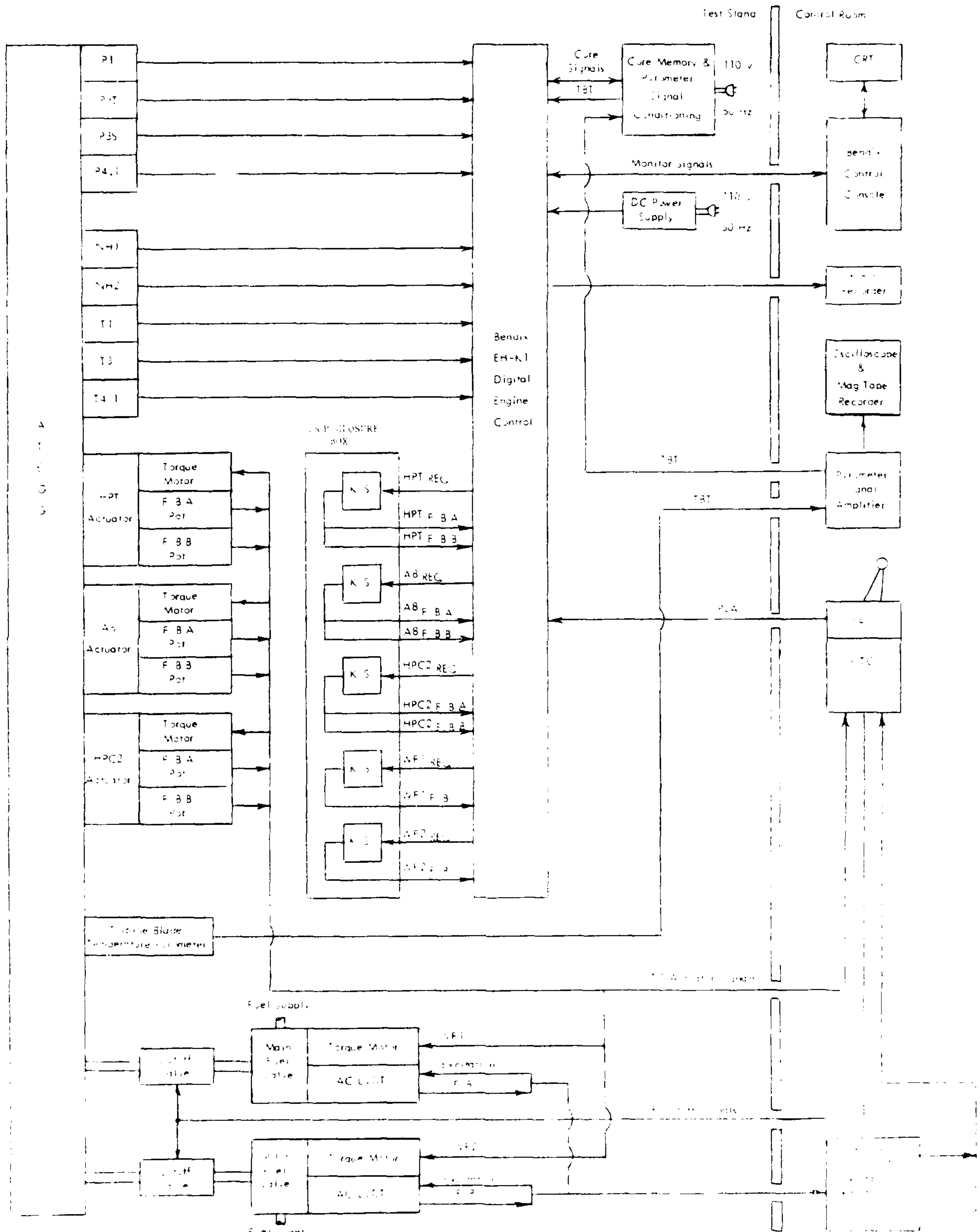


Figure 28. ATEGG Piggyback Test Set-up

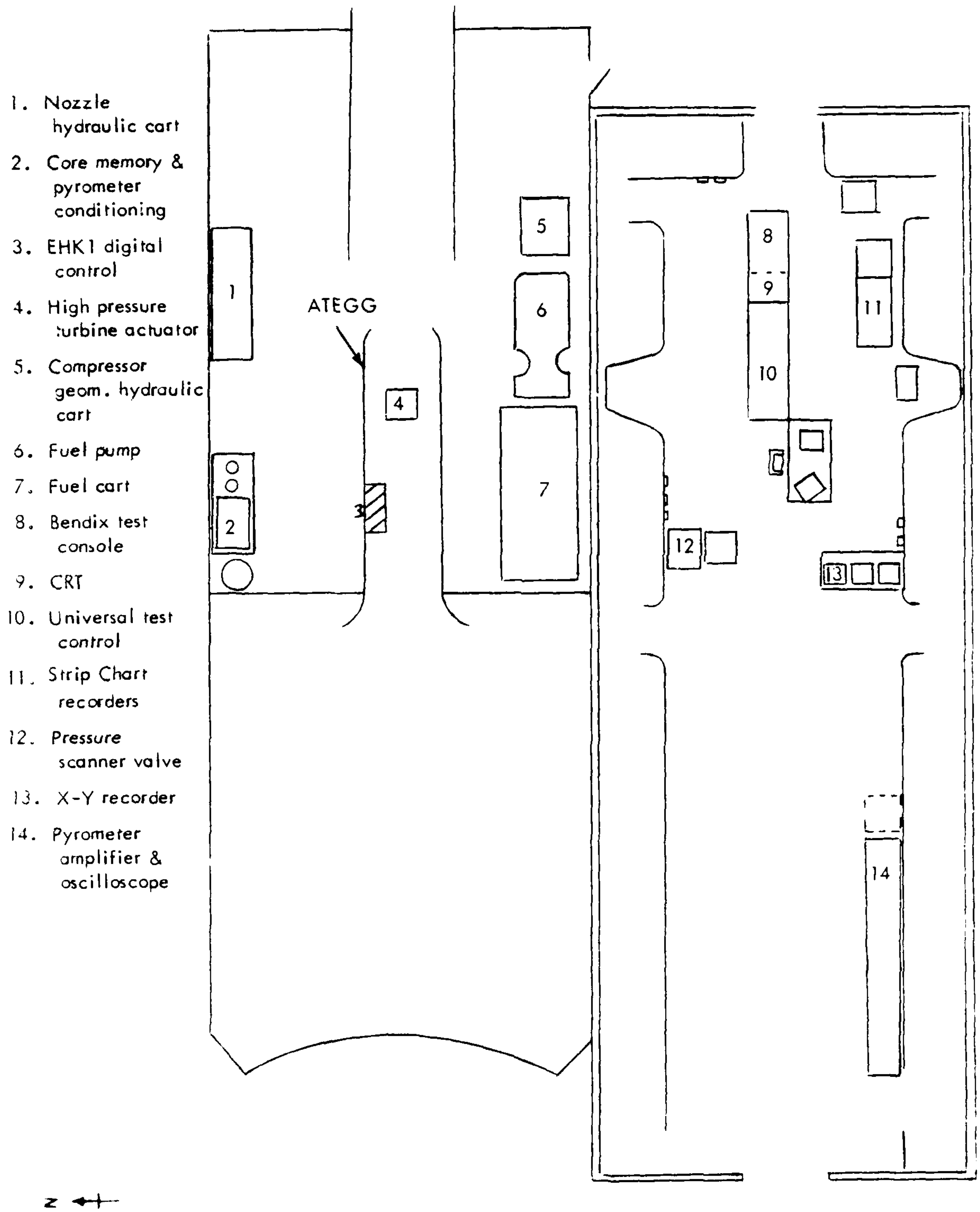


Figure 29. Test Cell 882 & Control Room Layout

The AFAPL-developed Engelhard thermocouple, used to measure turbine outlet temperature, was corrupted by noise during early B.U. 5 testing. This was attributed to the signal not being properly isolated as it was sent to SEL, to the EH-K1, to the UTC, and to the strip chart recorder. The UTC and strip chart recorder links were removed, and further B.U. 5 testing yielded a quiet T4.1 signal consistent with biased rake average.

A Solar optical pyrometer was used to indicate turbine blade temperature. This device provides peak blade temperatures and average blade temperatures over most of the engine operating range. This range does not include low speed points, near idle as blade metal temperature is below the pyrometer's threshold. Most of early B.U. 5 running was idle variable geometry characterization. Therefore no turbine blade temperature information through the Solar device was obtained. Later modification of the test equipment heat shield closed the opening for the pyrometer such that no optical pyrometer data was obtained during B.U. 5.

The compressor discharge total to static pressure ratio, P3PR, was a much quieter signal than it appeared on B.U. 4. This was due to the signal conditioning included in the RIT synthesis logic. This quieter P3PR resulted in a synthesized airflow signal which varied by only $\pm .5$ pps.

Synthesis of rotor inlet temperature in the piggyback mode was unsuccessful due to the unavailability of a fuel flow signal. Although the loop closure box provides a fuel flow feedback it was necessary to adjust PLA for every steady state run point in order to duplicate the actual fuel flow.

2. Digital Testing

Following the running of ATEGG to achieve the performance points specified in Table 7, switchover was made from the loop closure box to the fuel system and geometry actuators to prepare for the digital controlled portion of the engine testing. Appendix A shows the digital control test procedure prepared for that testing. As can be seen in the test plan the pre-engine testing consisted of calibration of the variable geometry components and the fuel system. For the fuel system the handvalve was exercised to exhibit the controllability necessary for a successful engine start. This was shown for the established handvalve limits shown below:

PLA range	0 to 60 degrees
PLA rate limit	2.4 degrees/second
Maximum fuel flow authority	3000 pph

The failsafe operation worked as planned. A halt to the EH-K1 caused authority for fuel flow and compressor variable geometry control to be passed to the UTC while the nozzle was slewed open.

Successful completion of this pre-engine test plan allowed final preparation for the actual engine testing. This involved altering the start logic, reducing software rate limits, and amending the fuel flow splitter logic.

In the start region the normal mode of operation calls for the engine to start under handvalve control (manual fuel flow command through the EH-K1) and, upon approaching idle, make a smooth transition to governor control. For a less complicated start procedure the automatic transition logic was removed so that a flag could be set to enable the governor logic. Thus steady state operation is attained on the handvalve near an idle condition, and when that the governor fuel flow request is close to handvalve fuel flow, the governor is enabled. The bimode governor option allowed the integrator within the fuel control logic to be set separately such that a proportional only governor could be run, the proportional mode was used for the B.U. 5 digital testing.

Rate limits on HPT and A8 were reduced to agree with previous rate limits on those geometries when under UTC control and are shown in the test plan. In addition the output fuel flow command from the control logic was rate limited to 400 pph/sec. in the increase direction.

After making these software changes the digital testing began. During two starts the engine lit properly, but fuel dropped out during the start between 30 and 40% NH. This problem will be further examined before B.U. 6.

Nearly an hour of running time was accumulated on ATEGG under digital control. Referring to part 2 of the test plan the first start brought the engine up to 80% NHC under handvalve control. As the inlet temperature increased to its desired 275^{o}F and the ram pressure ratio approached 1.2, the governor fuel flow request approached the request from the handvalve. When the governor request dropped below the modulated fuel flow value the governor was enabled. Under governor operation the bleeds were adjusted in preparation for the power calibration run. Upon entering a request to close the turbine to 3^{o} per step 2.4 in the test plan, an emergency switchover to the UTC occurred. The switchover occurred smoothly.

The EH-K1 halt causing the switchover was the result of not enabling the air supply (test operator error) to the HP turbine actuator. The fault logic detected this as a failed actuator and transferred control.

On the next start the engine was brought to 80% NHC, switched to the governor and advanced on the governor to the 85% NHC point. Advancing the PLA from 85%, Step 2.5, activated the main fuel system. The splitter logic is shown in Figure 30. The splitter logic is designed to run a 50-50 fuel split because on previous builds this was thought to significantly improve the burner pattern factor. A dedicated test on B.U. 5 did not substantiate this hypothesis; however, the fuel splitter logic was completed before this test.

In order to reduce the time at run 50-50 fuel splits, the slope of the main fuel vs fuel request, ref. Figure 30, was made very steep. As PLA was advanced and the main fuel flow was initiated there was little effect on engine operation until the mains is at 400-500 pph. The ignition of the main system at this flow caused a speed increase which because of the governor decreased fuel and shut off the mains. Additional attempts to light and sustain the mains were made, but because the transient nature of the pilot/main/governor interaction it was decided to stop the test.

Although software mods to decrease the slope of main vs WF request slope and the addition of hysteresis to maintain the 500 pph ignition flow would

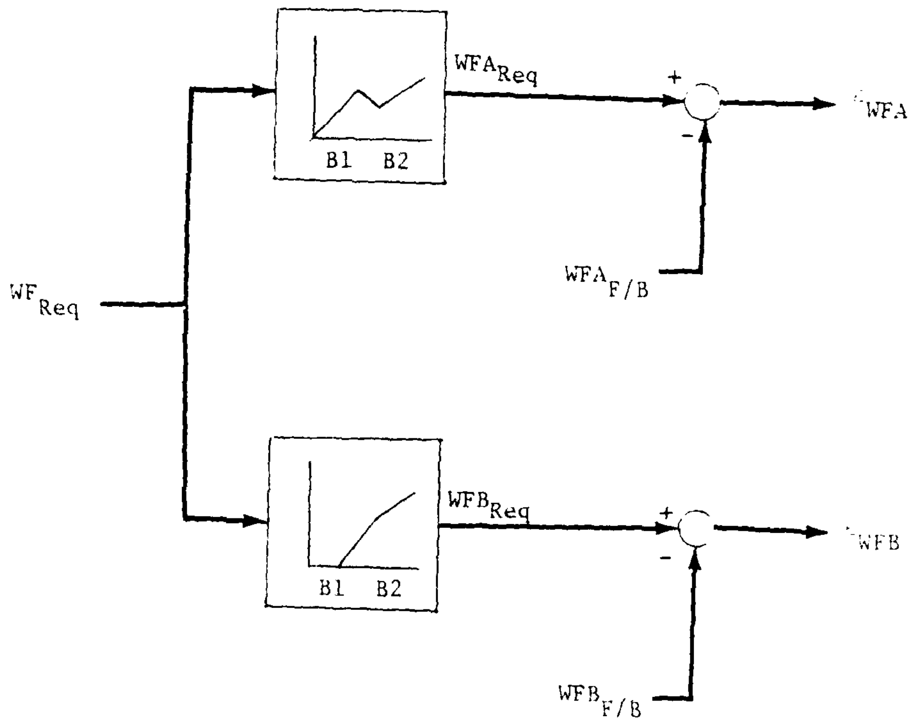


Figure 30. Fuel Splitter Logic

probably have solved the problem, all B.U. 5 ATEGG contract points had been achieved and the B.U. 5 testing was stopped.

The control activity started on this program will be continued in B.U. 6. Proposed modifications to the splitter logic are described in the Recommendations section of this report.

SECTION VII
CONCLUSIONS

The GMA 200 ATEGG Ditigal Controls Demonstration followed the JTD Gas Generator Full Authority Ditigal Control Feasibility Study. The original goals of the demonstration program were to update the control logic developed in the feasibility study and incorporate this software within a digital control system for piggyback and closed loop testing on ATEGG. These goals were successfully accomplished during Builds 4 and 5 of ATEGG.

The piggyback portion of the testing required modification of the breadboard controller tested during the feasibility study. The breadboard controller was replaced with a fuel cooled, engine mounted digital controller which interfaced with engine instrumentation, a test console core memory, and software thus providing a digital control system capable of "stand alone" operation on ATEGG. A test console and CRT were added to the system to provide on-line interaction with the digital controller. During the piggyback testing on Builds 4 and 5 of ATEGG, engine outputs were connected to the controller and monitored. These outputs, including signals from several dedicated control sensors developed on separate IR&D projects, were correlated with test instrumentation signals and found to be completely valid as far as representing the state of the engine for control purposes. The outputs from the control logic software based on these engine outputs indicated correct operation of the control software including fuel flow and variable geometry control logic, fault logic, fail safe routines, and display routines.

Limited closed loop testing conducted with the digital controller indicated proper operation of the start logic, the fuel control logic, and the geometry positional loops. The testing also pointed to some weak areas in control design including the fuel splitter logic, closure of the fuel positional loop, and diagnostics to insure fail-safe operation on a one-of-a-kind engine.

This limited full-authority operation of the engine did serve to indicate many areas where digital control and its flexible format can be of benefit to this and future advanced engine programs. These benefits in performance and reliability dictate a structured digital control program. DDA's digital control program regards GMA 200 ATEGG as an opportunity to pursue advances in software and hardware on an engine featuring variable geometry and high temperature capability. It is intended that as in the case of the engine any advanced control technology obtained in ATEGG will be incorporated in future control system applications.

SECTION VIII
RECOMMENDATIONS

As a result of lessons learned on B.U. 4 & 5 ATEGG testing, the EH-K1 software has planned software and hardware revisions to be made before B.U. 6 testing of ATEGG. The software changes should provide for tighter control loops, simpler control structure, improvements in the fuel limiting circuitry, improvements in the signal synthesis software, and modification of the fuel splitter logic. The hardware changes will be made to complement these goals of the software revisions.

ATEGG geometry positions - compressor surge, HP turbine area and exhaust nozzle area - were fed back via dual linear potentiometers. The control logic used one pot as a prime and switched to the other in the event of a detected fault. Non-linearities in the pots and/or non-uniform actuation indicated a need to average the feedback pots with reversion to a single channel in the event of failure. This software change will be incorporated in future builds.

Changes will be made to close the fuel flow positional loop with an analog controller as the fuel valves response is too fast for satisfactory control with a 50 Hz sampled data system.

A simpler control structure is planned for B.U. 6. The present governor fuel flow computation uses a speed reference from a multivariant table look-up to provide fuel flow through proportional plus integral compensation plus a fraction of the acceleration fuel flow to calculate WF_{GOV}. This multivariant table will be reduced to a univariant table such that PLA requests a given corrected speed. A fraction of the deceleration schedule will be used instead of a fraction of the acceleration schedule. This will alleviate the effect of HPT acceleration schedule bias upon governor flow.

Simplifications will also be made in the fuel flow starting portion of the software. This will provide a smoother and more automated start procedure than used during B.U. 5 testing.

The fuel flow limiting circuitry will incorporate thresholds as well as hard limits to prevent transient overshoots of critical engine parameters such as compressor discharge pressure and rotor inlet temperature.

Coefficients in the signal synthesis software will be updated to reflect the B.U. 6 form of ATEGG with the Mod II compressor.

The fuel splitter logic will be modified to allow the main fuel system to sustain combustion. This was the only area in which the digital controller functioned less than satisfactorily during B.U. 5 testing. Present thoughts are to request a more gradual light of the main system and add some hysteresis, if necessary, to allow the main system to remain lit even if the governor attempts to pull back on the fuel request.

The HPT and A8 control loops are slated to be active during B.U. 6 per the programmed control logic. Thus the logic associated with these control loops along with all the above mentioned software modifications will be exercised versus a hybrid model of ATEGG. This model will incorporate component performance characteristics consistent with the B.U. 6 configuration. The form of the model will allow updates to be easily incorporated as new test information is obtained.

Finally the interactive module in the EH-K1 software will be reviewed. This review will seek to make the EH-K1 a more flexible controller such that more programming changes may be made through a CRT in engineering units rather than making a program change in conventional software coding form. It is not necessarily suggested that these changes be made on-line, but making some changes in this form would decrease the programming time and improve the confidence level that the changes would function properly. This interactive flexibility will be especially important during B.U. 6 when engine mapping will be done with a new compressor.

APPENDIX

ATEGG FULL AUTHORITY DIGITAL

CONTROL TEST PROCEDURE

APPENDIX

ATEGG Full Authority Digital Control Test Procedure

In order to evaluate the EH-K1 Digital Controller the following tests must be performed as a minimum. All operation must be witnessed by the authorized Test Project engineer.

1. Pre-Engine Testing (Engine not operating)

The purpose of this test is to demonstrate operation of fuel flow and all variable geometry components while under control of the EH-K1 Digital Controller.

1.1 High Pressure Compressor Surge Avoidange Geometry (HPC2)

Run operator commands indicative of 70%, 80%, 90%, and 100% corrected compressor speed (NHC) looking at feedback channel A.

Send frequency signals through speed sensing feedback channel corresponding to 70%, 80%, 90%, and 100% NHC and verify proper positioning while looking at feedback channel A.

Repeat both of the above procedures for feedback channel B.

1.2 High Pressure Turbine Variable Geometry (HPT)

Run operator commands corresponding to HPT of -1^{o}, 1^{o}, 3^{o}, and 5^{o} looking at feedback channel B. Show time histories of the transients between commands to demonstrate the rate limiting logic on HPT movement.

Repeat the above procedure for feedback channel A.

1.3 Variable Area Exhaust Nozzle (A8)

Run operator commands corresponding to A8 of 110, 150, 190, and 230 square inches looking at feedback channel A. Show time histories of the transients between commands to demonstrate the rate limiting logic on A8 movement.

Repeat the above procedure for feedback channel B.

1.4 Pilot Fuel System (WFA)

Run stepped operator commands (both accels and decels) between 0 and 8000 pph in 2000 pph steps.

Run in handvalve mode and show controllability (vs. time) on x-y plotter for a typical start.

1.5 Main Fuel System (WFB)

Run stepped operator commands (both accels and decels) between 0 and 8000 pph in 2000 pph steps.

1.6 Failsafe Operation

While operating with 4000 pph operator commands through both the pilot and main fuel systems, trigger computer halt that shows a switchover to the UTC (idle flow setting).

While operating at a position indicative of 85% NHC on the high pressure compressor surge avoidance geometry, trigger a halt that shows a switchover to the UTC at that same setting.

While operating with a nozzle position of 200 square inches trigger a halt which slews the nozzle to a wide open position.

2. Engine Testing (Power Calibration)

The purpose of this test is to demonstrate 107.4% RIT at 98% speed under control of the EH-K1 Digital Controller. Inlet conditions of 275°F and up to 22.0 psia will be used.

2.1 Start to Idle

While in the operator command mode, set HPT to 5° with rate limit set at .15°/sec.

While in the operator command mode, set A8 to 217 square inches with rate limit set at 1.5 sq. in./sec.

Set fourth stage bleed (W4B) to 3% Wac.

Set sixth stage bleed (W6B) to 8% Wac.

Make a start to idle (82.5% NHC) on the pilot fuel system per the starting procedure. Stabilize the engine for 3 minutes.

2.2 Adjust the ram pressure ratio (RPR) to 1.2

2.3 Close W6B to 0% Wac.

2.4 Move HPT to desired setting for power calibration running. Move HPT in steps.

Set HPT to 3^{o}. Stabilize the engine for 1 minute.

Set HPT to 1.1^{o}. Stabilize the engine for 5 minutes.

2.5 Advance PLA slowly to a point such that 85% NHC may be attained. Stabilize for 5 minutes.

2.6 Advance Power Lever Angle (PLA) from 85% NHC setting until the main fuel system will light. Stablilize for 3 minutes.

2.7 Advance PLA slowly to a point such that 90% NHC may be attained. Stabilize for 5 minutes.

2.8 Advance PLA slowly to a point such that 95% NHC may be attained. Increase RPR to 1.4. Stabilize for 5 minutes.

2.9 Advance PLA slowly to a point such that 98% NHC may be attained. Increase RPR to 1.5. Stabilize for 5 minutes.

2.10 Decrease RPR to 1.2. Make a slow deceleration to an idle power lever setting. Stabilize for 5 minutes.

2.11 Open HPT to 5^{o}.

2.12 Adjust inlet temperature to 90^{o}F in preparation for shutdown. Stabilize for 1 minute.

2.13 Complete the shutdown procedure.

3. Engine Testing (Cyclic Endurance - not accomplished during B.U. 5).

The purpose of this test is to demonstrate transients between idle and 98% NHC through a cyclic endurance procedure. Inlet conditions of 275^{o}F and varying inlet pressure (between 17.5 and 22.0 psia) will be used.

3.1 Start to Idle

While in the operator command mode, set HPT to 5^{o} with rate limit set at $.15^{o}$/sec.

While in the operator command mode, set A8 to 217 square inches with rate limit set at 1.5sq. in./sec.

Set fourth stage bleed (W4B) to 3% Wac.

Set sixth stage bleed (W6B) to 8% Wac.

Make a start to idle (82.5% NHC) on the pilot fuel system per the starting procedure. Stabilize the engine for 5 minutes.

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3.2 Adjust the ram pressure ratio (RPR) to 1.2

3.3 Close W6B to 0% Wac.

3.4 Move HPT to desired setting for power calibration running. Move HPT in steps.

Set HPT to 3^{o}. Stabilize the engine for 1 minute.

Set HPT to 1.1^{o}. Stabilize the engine for 5 minutes.

3.5 Advance Power Lever Angle (PLA) from the idle setting until the main fuel system will light. Stablilize for 5 minutes.

3.6 With RPR controlled through the UTC as a function of NHC, make an acceleration to 98% NHC and 1.5 RPR. The acceleration time should be 20 seconds ± 5 seconds. Stabilize at this 98% NHC point for one minute. Decelerate back to idle speed and 1.2 RPR in 30 seconds ± 5 seconds. Stabilize for one minute.

3.7 Repeat 3.6 five times to satisfy cyclic endurance requirements.

3.8 Open HPT to 5^{o}.

3.9 Adjust inlet temperature to $90^{o}F$ in preparation for shutdown. Stabilize for 1 minute.

3.10 Complete the shutdown procedure.

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