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ENERGY EFFICIENT ENGINE

CONTROL SYSTEM PRELIMINARY DEFINITION REPORT

by

D. C. Howe

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney
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16. ABSTRACT
The object of the Control Preliminary Definition Program was to define a preliminary control system concept as a part of the Energy Efficient Engine program. The program was limited to a conceptual definition of a full authority digital electronic control system. System requirements were determined and a control system was conceptually defined to these requirements. Areas requiring technological development were identified and a plan was established for implementing the identified technological features, including a control technology demonstration. A significiant element of this program was a study of the potential benefits of closed-loop active clearance control, along with laboratory tests of candidate clearance sensor elements for a closed loop system.

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FOREWORD

The Energy Efficient Engine Component Development and Integration program is being conducted under parallel National Aeronautics and Space Administration contracts with Pratt & Whitney and General Electric Company. The overall project is under the direction of Mr. Carl C. Ciepluch. The Pratt & Whitney effort is under contract NAS3-20646, and Mr. Edward Meleason is the NASA Project Engineer responsible for the portion of the project described in this report. Mr. David E. Gray is Manager of the Energy Efficient Engine Program at Pratt & Whitney. This report was prepared by Mr. D. C. Howe of Pratt & Whitney.

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SECTION 1.0

SUMMARY

The Control Preliminary Definition Program was conducted to define a preliminary control system concept as a part of the Energy Efficient Engine program. The program was limited to a conceptual definition of a full authority digital electronic control system incorporating the technology which is projected to exist by 1990. System requirements were determined and a control system was conceptually defined to these requirements. Areas were identified where technological development would be most productive toward realization of the system concept. A plan was established for implementing the identified technology features, including a control technology demonstration.

Three subcontractors assisted Pratt & Whitney in this effort: two were control vendors (Hamilton Standard Division and Bendix) and one, a pump vendor (Chandler Evans). Their input to the study included size, weight, cost, and reliability information and technology readiness information required for selecting the principal and backup control systems.

A significant element of this program was a study of the potential benefits of closed-loop active clearance control and clearance sensors that would enable the realization of these benefits. Study results indicated that the fluidic and microwave clearance sensor concepts were the most likely candidates for application to advanced engine high-pressure compressor, high-pressure turbine and low-pressure turbine components. Potential fuel burn benefits of up to one percent are indicated for a long-range 440 passenger trijet utilizing closed-loop active clearance control in the high-pressure turbine only. This includes the effects of deterioration recovery over a 4000 cycle engine operating period.

SECTION 2.0

INTRODUCTION

The National Aeronautics and Space Administration has the objective of improving the energy efficiency of future United States commercial aircraft so that substantial savings in fuel can be realized. Toward this objective, NASA established the Energy Efficient Engine Component Development and Integration program in 1978 under contract NAS3-20646. Minimum goals for this program are a 12 percent reduction in thrust specific fuel consumption (TSFC) and a 5 percent reduction in direct operating costs (DOC) compared to the Pratt & Whitney JT9D-7A engine. In addition, FAR Part 36 (1978) noise rules and EPA-proposed 1981 exhaust emissions standards must be met.

The Energy Efficient Engine Component Development and Integration program is based on the results of the completed Energy Efficient Engine Preliminary Design and Integration Studies (Ref. 1). Through the extension of the technology base developed under this early program, the Energy Efficient Engine Component Development and Integration program will develop and demonstrate the technology for achieving higher overall efficiency (thermodynamic and propulsion) in future environmentally acceptable turbofan engines. To meet these program objectives, the current program consists of the following two tasks:

- o Task 1 -- Flight Propulsion System analysis, design, and integration
- o Task 2 -- component analysis, design and development.

More specifically, Task 1 provides for the preliminary design of a flight propulsion system based on various iterative analyses and design updates and the preliminary definition of engine control systems.

Three basic control systems were defined: a high technology system, a moderate technology system, and a conservative technology system. The high technology system, the most advanced and principal system, requires the maximum technological development. The other two systems, requiring lesser technologies, provide backup for the principal system in the event that the needed technology programs are not pursued. The backup controls, which sacrifice performance but are fully functional, furnish flexibility in establishing technology development priorities.

A full authority, digital electronic system was the choice for the high technology control. The required advanced technology, aggressively projected to be available by approximately 1990, provides the maximum improvement in engine performance and life, simplifies engine operation, and minimizes system size, weight, and cost. A study was conducted to investigate the benefits associated with expanding the control system capability to include a closed-loop active clearance control system and the definition of suitable clearance sensors. This study effort is discussed in Section 4.0

The control program was limited to conceptual definitions, and no detailed system design or analysis was conducted. Pratt & Whitney was assisted by Hamilton Standard Division (HSD) and Bendix--control vendors--and by Chandler Evans (Ceco)--a fuel-pump vendor.

Abbreviations used in this report are defined in Appendix A.

SECTION 3.0

INITIAL CONTROL SYSTEM DEFINITION

3.1 DEFINITION OF REQUIREMENTS

3.1.1 Engine Definition

The Energy Efficient Engine, as defined for the control system definition, is a twin-spool, high-bypass fan, mixed-exhaust configuration with an integrated engine-nacelle structure. The combustor is a staged, high efficiency type burner, utilizing aerating simplex nozzles for the pilot fuel flow and simplex nozzles with carburetor tubes for the main flow. To preclude nozzle coking, the main nozzles are purged with nitrogen when the main flow is turned off. An active clearance control system is employed in the high pressure compressor and in the high pressure and low pressure turbines.

The engine fuel pump and alternator are driven from a gearbox located on the core. Control electronics can be mounted in the nacelle or in the core area. There are four stages of variable vanes and a set of starting bleeds in the high pressure compressor, and there is also a set of intercompressor bleeds. A fan-air thrust reverser is incorporated in the nacelle.

Table 3-I shows the estimated ranges utilized in this study for the control parameters,and Table 3-II provides a more complete definition of fuel handling requirements. The values presented are preliminary and should be reviewed in the future to allow for engine evolution and unforseen factors.

TABLE 3-I
ESTIMATED RANGES FOR CONTROL PARAMETERS

Parameter	Maximum	Minimum
Inlet Temp.	356°K (640°R)	234°K (520°R)
Ambient Press. (abs)	104 kPa (15 lbf/in.^{2})	11.0 kPa (1.6 lbf/in.^{2})
N_L	4000 rpm	300 rpm
N_H	13,500 rpm	500 rpm
Burner Press. (abs)	34500 kPa (500 lbf/in.^{2})	13.8 kPa (2 lbf/in.^{2})
Turbine Gas Temp.	1724°K (3100°R)	Ambient
Turbine Blade Temp.	1362°K (2450°R)	Ambient
Fuel Flow	6525 kg/hr (14500 lbm/hr)	112.5 kg/hr (250 lbm/hr)
SVA F/B	TBD	TBD
Bleed F/B	Open	Closed

TABLE 3-II
FUEL HANDLING REQUIREMENTS

N_H (rpm)	Manifold Press. kPa ($lbf/in.^2$)	Fuel Flow kg/hr (lbm/hr)	Comments
13,300	10,350 (1500)	65 (14,500)*	Max. Fuel Flow
9,165	586 (85)	450 (1000)*	Idle SLS
9,532	518 (75)	315 (700)*	Min. SS Fuel Flow (idle descent)
3,500	35 (5)	198 (440)	SLS Lightoff
		112 (250)	Min. Flow (altitude relight)

*Note: Bleed and actuators require a transient fuel flow of 990 kg/hr (2,200 lbm/hr) for one second.

Control system component locations and ambient temperatures with additional parametric information are provided in Appendix D, Figures D-1 and D-2 respectively. Engine station notations are presented in Figure D-3.

The range of control parameters for this study was estimated by means of engine performance tables and the engine operating envelope shown in Figure 3.1-1.

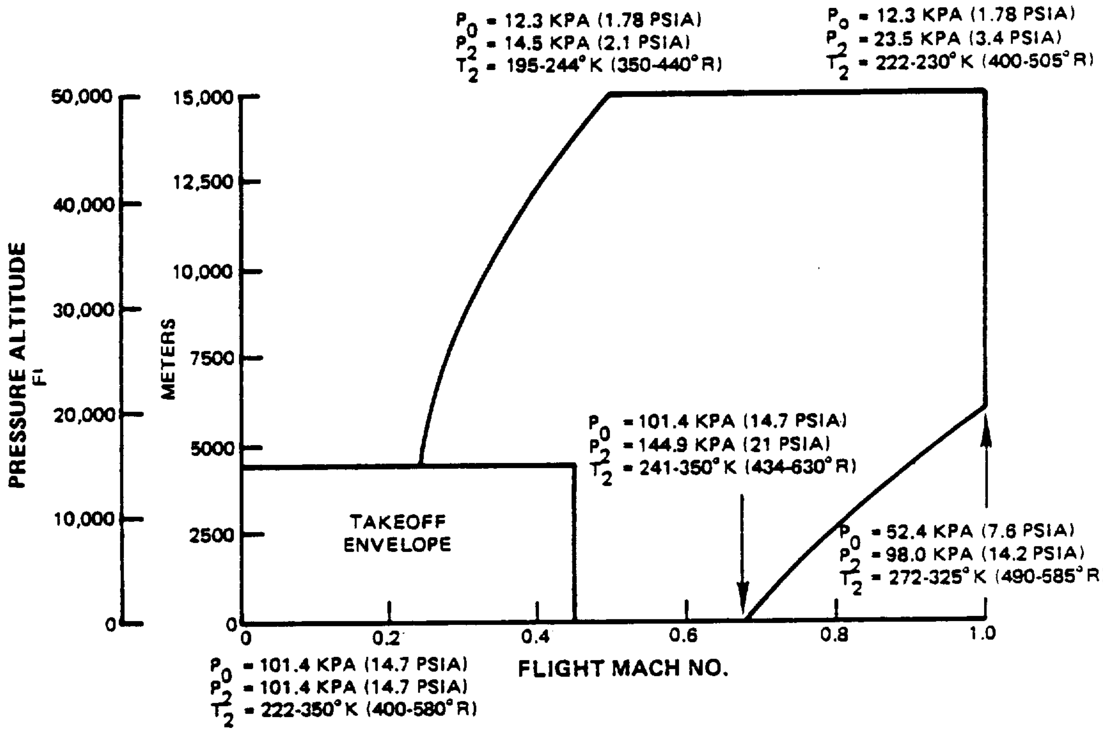

Figure 3.1-1 Energy Efficient Engine Operating Envelope - - The control range parameters were based on the operating envelope and engine performance tables.

3.1.2 Control Functions

The major control functions or outputs are:

1) Fuel Flow

   a. Fuel valve(s) (modulated) and/or fuel pump(s) (modulated)
   b. Purge dump valve (discrete)
   c. Secondary transfer valves (discrete)

2) Control of engine bleeds

   a. Intercompressor bleed (discrete or modulated)
   b. Start bleed (discrete)
   c. Active clearance control valve (discrete)

3) Control of high pressure compressor variable geometry (modulated)

4) Control of two position thrust reverser

3.1.3 Operating Requirements

1) Allow the engine to perform to its potential within the bounds of engine limitations:

- o Prevent compressor stall
- o Prevent excessive temperature levels during transients
- o Maintain stable engine operation between engine idle and maximum power

2) Provide engine rating for all flight conditions

3) Prevent catastrophic engine failure if the control fails:

- o Synthesize lost sensors
- o Derate performance
- o Failsafe direction failures
- o Shut down engine

3.1.4 Control Inputs

1. Power Lever Angle
2. Discretes (Air packs, ground/flight idle, TBD)
3. ARINC data
4. Low Rotor RPM (N_L)
5. High Rotor RPM (N_H)
6. Fan Inlet Temperature (T_2)
7. Fan Inlet Total Pressure (PT_2)
8. Ambient Static Pressure (PSO)
9. Burner Pressure (PS_3) or (Pb)
10. Turbine Inlet Temperature ($T_{4.1}$)
11. Fuel Valve Feedback
12. Stator Vane Feedback
13. Reverser Position (discretes)
14. Intercompressor Bleeds (discrete or modulated)

3.1.5 Fuel Metering Requirements

The Energy Efficient Engine presents a unique set of fuel metering requirements for the control system. The low emissions energy efficient burner requires two axially separated, independently metered fuel flows: a pilot flow and a main flow. The split between pilot fuel flow and main fuel flow is based on fuel-air ratio and not upon the conventional fuel flow rate. In addition, because of burner stability requirements, the flow split may vary between transient and steady state engine operation. Engine start and idle power settings are on pilot flow only; engine power settings above idle are on pilot plus main flow.

Because the burner nozzles are axially separated, complete fuel atomization by the main nozzles without assistance from a high velocity pilot spray is necessary and this requires aerating simplex pilot nozzles, simplex main nozzles with carburetor tubes, and a flow schedule shift from pilot flow to pilot flow plus main flow at a constant total fuel flow. The flow schedule shift is illustrated by Figure 3.1-2. A schedule shift with variable percentage split between pilot and main nozzles is well within the capabilities of an electronic control, but would tax the capabilities of a hydromechanical control. The pilot flow system incorporates a bypassing and dump valve which recirculates pilot fuel to pump interstage and drains the pilot fuel nozzle manifold to an ecology tank during cutoff.

To avoid coking of fuel in the main nozzle and support assembly, all fuel must be purged from the nozzle and assembly when the main fuel is not flowing. This purging is accomplished with nitrogen. For size and weight reduction, the purge is combined with the main nozzle shutoff function in one valve, with the nitrogen supplying the pressure. Eight of these valves, mounted on the burner bulkhead, perform the main nozzle shutoff and purge function.

The lines supplying fuel to the main nozzles are shrouded and air cooled to prevent varnishing and coking in these fuel lines, thus eliminating the need for a fuel recirculation manifold and additional lines.

3.2 EFFECTORS AND ACTUATORS

3.2.1 Geometry Actuation

Geometry actuation requirements for the engine were specified on the basis of cost, weight, and reliability tradeoffs. Actuation of compressor bleeds and stator vanes and a thrust reverser mechanism are required. Control system requirements for these functions are presented in the following sections.

3.2.2 Bleed Actuation

The intercompressor (station 2.5) bleed is operated by means of a single two-position fuel hydraulic piston. The simple two-position bleed is acceptable because engine thrust is governed as a function of N_L speed, which is relatively unaffected by intercompressor bleed. Actuation is obtained by discrete electrical signal from the electronic control to the servo valves that control the pressure to the hydraulic actuator. The bleed is designed to fail open, protecting the engine from low pressure compressor stall and idle and during decelerations. Fail-open operation results in a thrust penalty at high power operation on hot days.

If future engine operation indicates that modulated bleeds are required to avoid undesirable thrust transients during bleed operation, the control system can be readily revised to accommodate this requirement. A modulated bleed control loop would be similar to the SVA loop and would utilize the same technology.

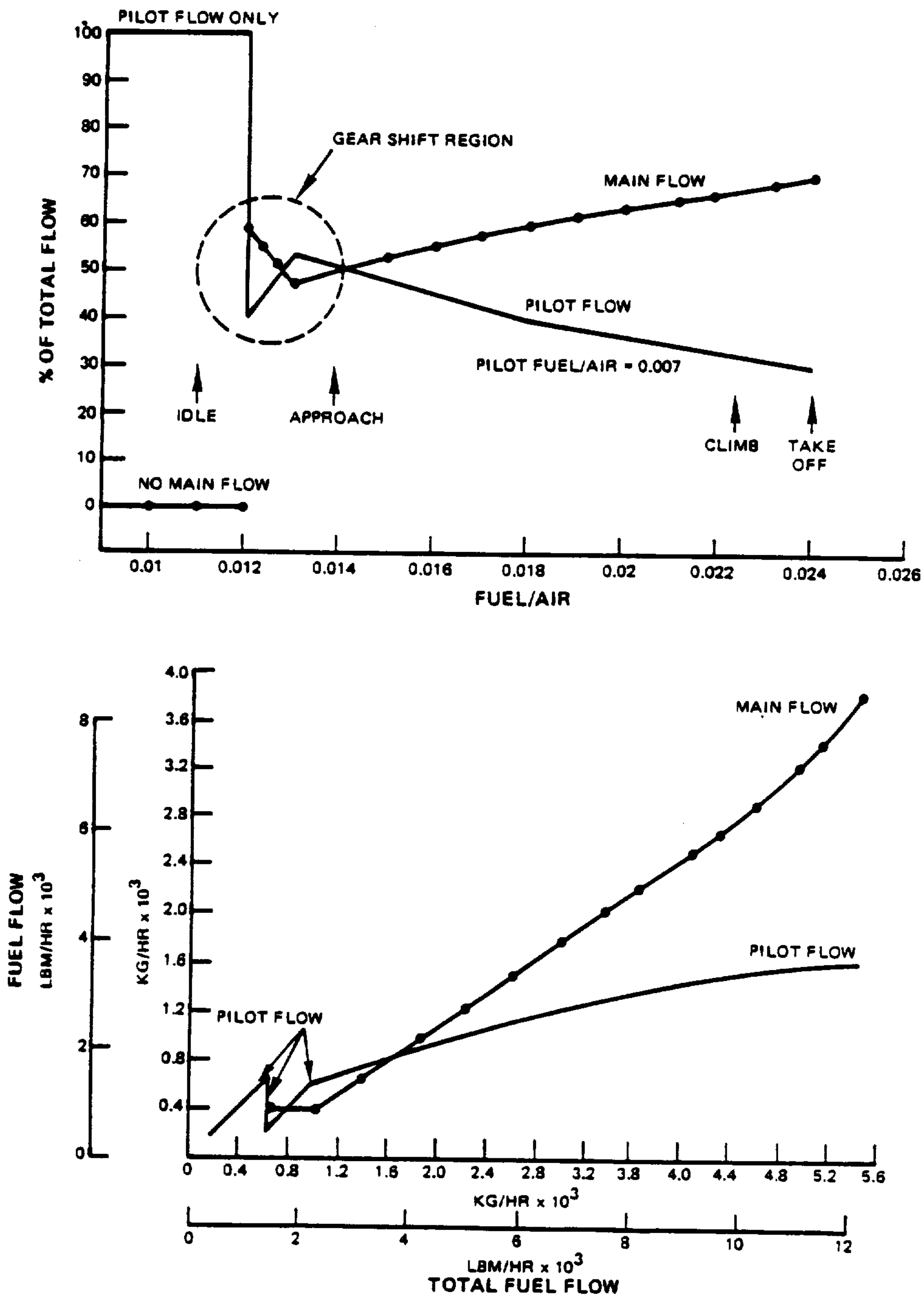

Figure 3.1-2 Fuel Schedule - - The flow shift from pilot to pilot plus main flow is necessitated by the unique design of the energy efficient burner.

The high pressure compressor (start) bleeds are located at the 10th stage, and are used only during engine starts. There are four separate two-position pneumatically actuated, solenoid activated bleeds that operate by discrete electrical signals from the electronic control. All four bleeds can be operated simultaneously or individually to satisfy engine start requirements. The bleeds are designed to fail closed on loss of electrical power.

3.2.3 Stator Vane Activation

The high-pressure compressor Inlet Guide Vane and the first three stages of stator vanes are variable and are actuated by a single fuel hydraulic piston through a system of links and levers. Control of stator vanes is fully modulated and controlled by an electrical signal from the electronic control. Feedback of vane position is discussed in Section 7.1.10.7 of this report. The stator vanes fail open in the event of loss of signal or actuator failure. This failure mode ensures takeoff thrust, but does not protect against engine stall below maximum climb power.

3.2.4 Thrust Reverser Actuation

The thrust reverser is actuated by a single air motor driving a ball screw system. Control signals for both forward and reverse are provided by the electronic control. Two discrete feedback signals (fully retracted and fully deployed) will be provided to the control system. The system will be designed to move the reverser to the fully retracted position in the event of loss of signal.

3.2.5 Active Clearance Control - Open Loop

The active clearance control (ACC) system varies blade tip clearances in the rear of the high pressure compressor and in the high pressure and low pressure turbines. For the purposes of the control preliminary definition, control of the ACC system is by discrete on-off signals to two air control valves. One valve controls fan air to the high pressure compressor case, and one valve transfers between 10th stage and 15th stage high pressure compressor air to the high pressure and low pressure turbines. Although the ACC system is open loop, clearance measurement technology compatible with electronic controls is defined in anticipation of future modulated ACC systems.

3.3 CONTROL DEFINITION METHODOLOGY

A control system is defined by a combination of analysis, cost and weight tradeoffs, logic, and engineering judgement. The conceptual definition of the engine control system has been organized in a manner to provide documentation of the analytical (tradeoff) logic elements and to minimize the intuitive element.

This organization consists of a decision logic diagram with decision matrices for selecting technology for all major components of the system. The logic diagram and matrices for the selection of system technology are presented in Appendix B. The logic diagram is an orderly documentation of the process for selecting the technology to implement the various elements of the control system. The decision matrices document the candidate technologies and rate them against factors that are significant to the performance of the control system.

Scoring for the matrix is based on the product of an arbitrary 1 to 4 performance rating factor and weighting factors that vary according to the technology under consideration. The selection of the overall system depends on the availability of technology and many other interacting factors such as component location, fire safety, signal transmission, new fuel specifications, electro-magnetic interference (EMI), and judgement based upon experience. For the final system decision, candidate control systems were considered with respect to these factors.

In defining the engine control system, certain basic assumptions and ground rules were established. These assumptions and ground rules were consistent with the conceptual definition restriction.

A. The main control element would be a full-authority, digital electronics box that utilizes electronic technology projected to be available in the late 1980's.

B. Condition monitoring would not be considered as an integral part of the control system.

C. Airframe integration would not be studied as a part of this control conceptional definition. A digital data link for communication with airframe and a future separate condition monitoring system are to be assumed.

D. Although the engine design will have open loop ACC, provisions are to be made in the control system concept for closed loop control, implying a need for proximity sensing technology.

E. Optical sensing and fiber optic signal transmission and interfacing with aircraft would be considered.

F. A detailed analysis or design of the control or fuel handling systems would not be performed. No control algorithms or software would be developed.

G. The subject of fire protection for the control system would be considered but not studied in depth--it should be noted that fire protection would be an integral part of a detailed system design.

H. Compressor surge bleeds would be assumed to require discrete on-off signals based on compressor surge protection requirements without taking into account special features such as adjusting surge bleeds according to service bleed useage, or adjusting surge margin between accelerations and steady state. These features can be implemented within the digital logic and pose no particular control problem.

I. Active clearance control would be assumed to require discrete signals to transfer and/or shutoff valves. Operation of the system to provide minimum clearance at altitude cruise conditions was assumed. However, ACC during climbout can be provided with control logic with no effect on the control system.

3.4 SYSTEM SELECTION

Three control systems, high technology, moderate technology, and conservative technology, are presented, providing the program manager with guidance in trading off performance vs. technology investment. As expected, the most desirable system in terms of performance, weight, and production cost requires the most technology development.

3.4.1 Control Philosophy

3.4.1.1 Control Mode

Engine power above idle will be set by N_L because N_L correlates well with thrust and is relatively insensitive to bleed and SVA effects. The control prevents N_H speed variations associated with horsepower extraction by controlling N_H at idle. Structural limitation control for high rotor speed, pressure, and turbine inlet temperature is effected by means of topping loops. Compressor and burner stability is maintained during transients by accel and decel schedules that limit fuel flow.

A simplified block diagram and a functional block diagram of the engine control system are presented in Appendix D, Figures D-4 and D-5 respectively. The functional block diagram (Figure D-5) shows that the basic mode of operation consists of fuel flow (Wfe) being calculated as the integral of a control loop error chosen according to the "select low" and "select high" logic. Thus, the control is isochronous: the selected control loop error is driven to a value of zero to obtain steady state conditions.

3.4.1.2 Electronic Unit Design

The control logic will be implemented with a single-channel, full-authority digital control with selective redundancy of critical components to provide the optimal balance between MTBF, cost, weight, and maintainability. The use of a single-channel full authority digital control was established as a ground rule for the study, Section 5. Where possible, fiber optics will be used to eliminate EMI, to increase reliability, and to decrease cost and weight. Candidates for fiber optics are feedbacks, (fuel valve, SVA, bleeds), PLA, discrete signals to the control, and communication with other avionics equipment. Control sensors that provide direct digital output will be used where possible to eliminate input conditioning circuits.

3.4.2 High Technology Control System

The High Technology Control System is the selected control for the Energy Efficient Engine--the remaining two controls are backup systems. The technologies for this system, shown schematically in Figure 3.4-1, provide the optimal cost, weight, and performance trades within the constraints of reasonable expected technology advances. A fallback technology position is provided for areas where unsubstantiated technology is advocated. Cost and weight savings due to the chosen system are described in a memo "Energy Efficient Engine Control System Cost and Weight Comparisons with 9D Baseline," R. E. Babineau to J. Bissett, August 1, 1978, (see Appendix C).

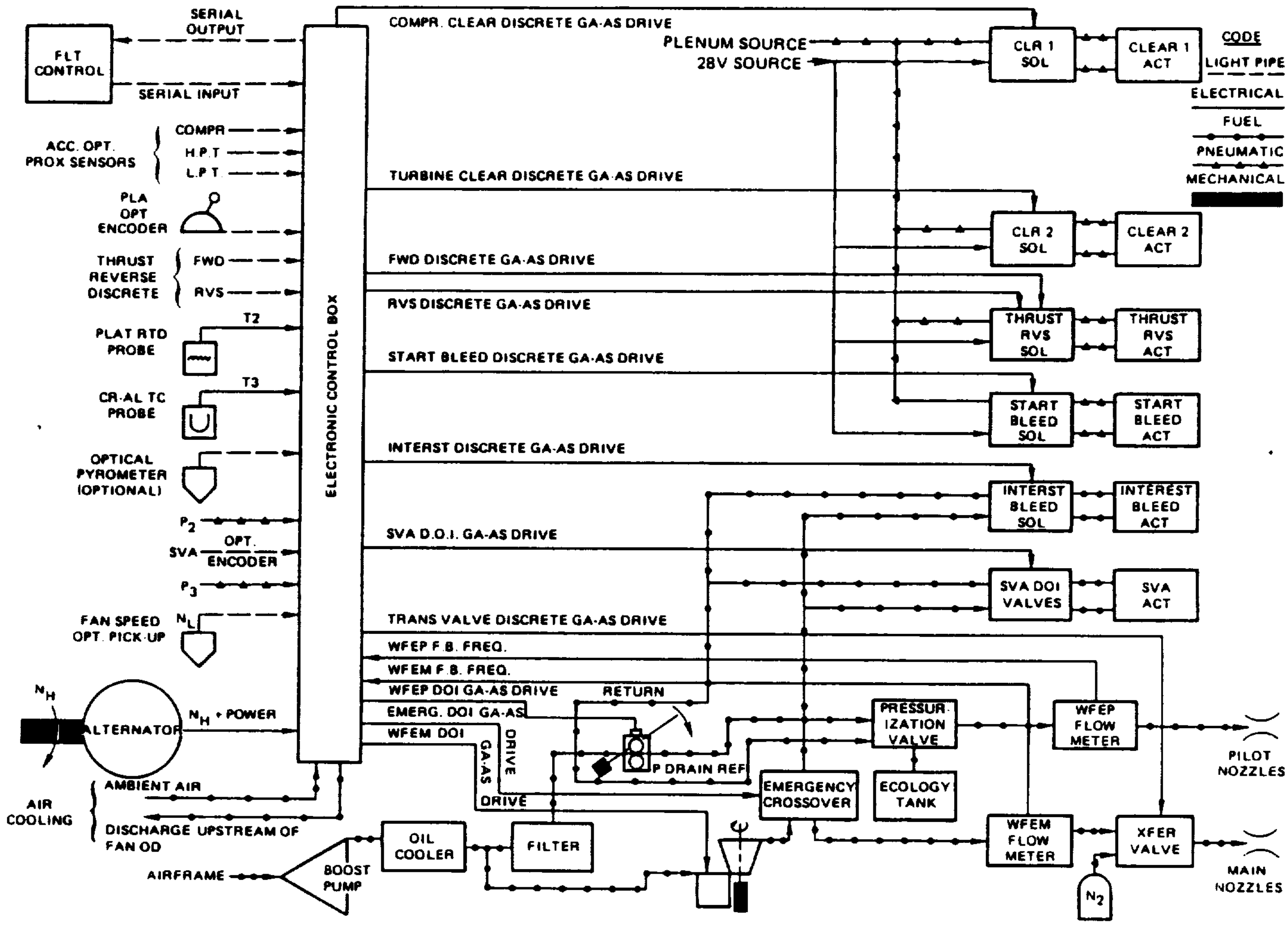

Figure 3.4-1 Selected Fuel Control System - - The system was selected to provide optimal cost, weight, and performance.

3.4.3 Moderate Technology Control System

The moderate technology control system (Figure 3.4-2) uses many components that are either in production or could go into production without further research development. Most of the components in this category are natural extensions of present technology devices.

The most noticeable advance in this system over the conservative system is in the use of separate metering pumps for pilot and main fuel flow and air cooling of the electronics. The use of two metering pumps results in a substantial reduction in fuel temperature rise at high turndown ratios, while air cooling of the electronics results in substantial reduction in engine cost and weight due to elimination of fire bulkheads necessitated by fuel cooling.

Fuel flow to the engine is metered directly to the pump, with no bypass or return flow. The pump consists of a variable displacement vane pump for primary and an inlet throttled vapor pump for main flow. When not operating on main flow, the main pump is run dry to eliminate fuel temperature rise. This control would include both a proximity sensor for active clearance control and an optical pyrometer for limiting turbine blade temperature. The elements shown in Table 3-III would be typical of a moderate technology system.

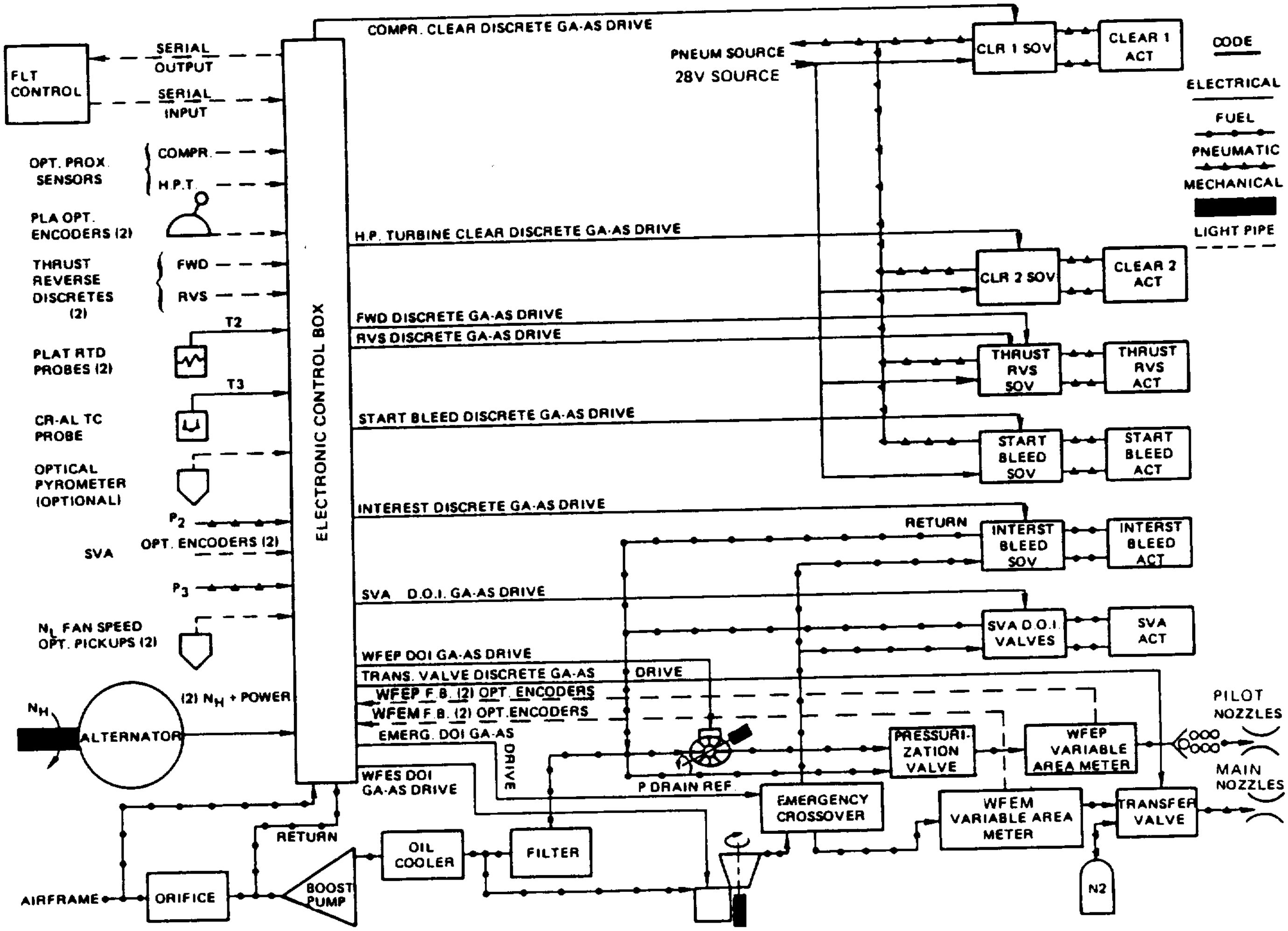

Figure 3.4-2 Moderate Technology Fuel System - - Many of the components of this backup system are either currently in production or could go into production without any additional development.

3.4.4 Conservative Technology Control System

The conservative technology system consists of control components that are either presently in production or are derivatives of current production parts. This system could be built today with reasonable confidence of success. The conservative system is shown in Figure 3.4-3. The control would consist of the components listed in Table 3-IV.

The fuel pump would be a single output gear type with a pressure capability of 10,350 MPa (1500 lbf/in.^{2}) and a maximum flow rate of 6750 kg/hr (15,000 lbm/hr). The fuel handling would use either two metering valves with suitable bypass and pressure regulator valves or one metering valve and a flow splitter valve.

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TABLE 3-III
TYPICAL ELEMENTS OF A MODERATE TECHNOLOGY SYSTEM

Function		Technology
Fuel Flow Handling	WFEP, WFEM	Variable Flow Fuel Pumps with Variable Area Flowmeters, Optical Encoder Feedbacks
Sensors	PLA	Optical Encoder
	SVA	Optical Encoder
	N_L	Optical Pickup
	N_H	Alternator Pickup
	P_1, P_2, P_3	Vibrating Cylinder or Vibrating Quartz Crystal
	T_2	Platinum Resistance Probe
	T_3	CR-AL Thermocouple
	TBT	Optical Pyrometer
	EGT	Not Measured
	Clearances: Compressor L.P. Turbine H.P. Turbine	Optical Proximity Sensors
Effectors	Fuel Flow, Stator Vane Actuator (SVA)	Digital Output Interface (DOI), Dual Solenoid Valves with Remote GaAs Drivers
	Compressor Bleeds, Thrust Reverser, Active Clearance Control, Transfer Valve	Discrete, Solenoid Operated Valves with Remote GaAs Drivers,
Power Supply	Source	Dedicated Permanent Magnet Alternator
	Regulation	Shunt Regulator
Control	Chip Design	Mix of: VLSI LSI MSI SSI Discrete
	Processor Type	CMOS-VLSI or I^2L
	Processor Architecture	Fixed Instructions Single Processor
Control	Memory Mode	C-MOS
	Read Only Memory	Mix of: PROM UVROM
	Random Access Memory	Static C-MOS (Non Refreshed)
	Data Link	Serial Optical
Packaging	Cooling	Air Cooling
	Location	Fan Case Mount on Vibration Isolators

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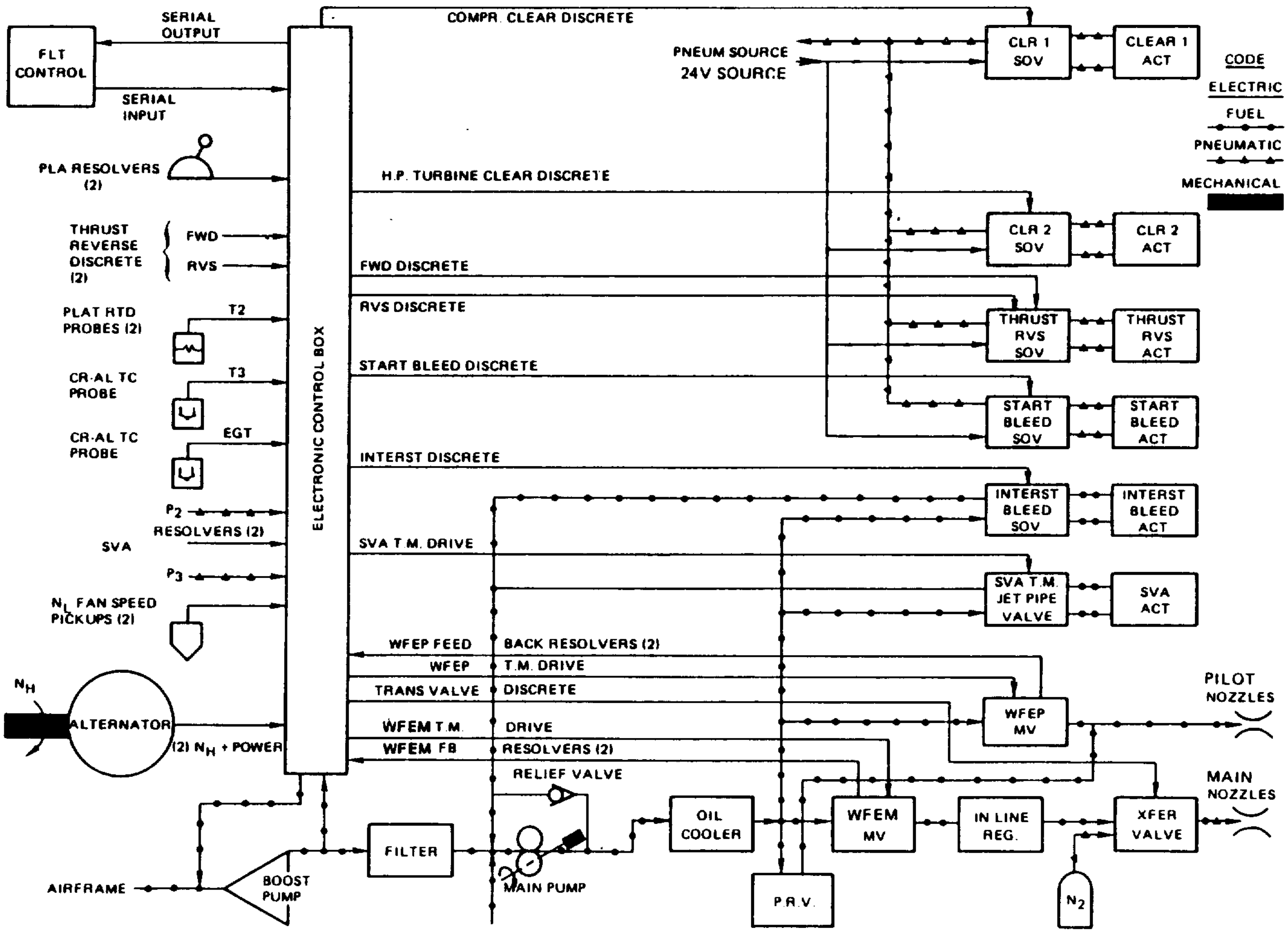


Figure 3.4-3 Conservative Technology Fuel System - - This is the most conservative of the backup systems.

Figure 3.4-4 represents the most conservative controller approach, utilizing discrete MSI/SSI circuitry for input/output and two-microprocessors with external memory: one to process the inputs; the other to perform the control computations and outputs. The two processor approach reflects the current situation of insufficient internal memory and insufficient processor speed available in qualified parts. Such an approach for the mid-1980's would yield a minimal decrease in cost, size, and power consumption over the present state-of-the-art, and is not a favorable candidate for development.

TABLE 3-IV
CONSERVATIVE TECHNOLOGY SYSTEM COMPONENTS

Function		Technology
Fuel Flow Handling	WFEP, WFEM	Variable Flow Fuel Pumps with Shedding Vortex Flowmeter Feedbacks
Sensors	PLA	Optical Encoder
	SVA	Optical Encoder
	N_L	Optical Pickup
	N_H	Alternator Pickup
	P_1, P_2, P_3	Surface Acoustic Wave (SAW)
	T_2	Platinum Resistance Probe
	T_3	CR-AL Thermocouple
	TBT	Optical pyrometer
Clearances:	Optical Proximity Compressor L. P. Turbine H. P. Turbine	Sensors
Effectors	Fuel Flow Stator Vane Actuator (SVA)	Digital Output Interface (DOI), Dual Solenoid Valves or Torque Motor With Remote GaAs Drivers
	Compressor Bleeds Thrust Reverser Active Clearance Control Transfer Valve	Discrete Solenoid Operated Valves With Remote GaAs Drivers
Power Supply	Source	Dedicated Permanent Magnet Alternator
	Regulation	Shunt Regulator
Control	Chip Design	Mix of: VLSI LSI MSI Discrete
	Processor Type	NMOS-VLSI
	Processor	Fixed Instructions
	Architecture	Single Processor
	Memory mode	N-Mos
	Read Only Memory	UVROM
	Random Access Memory	Static NMOS (Non-Refreshed)
	Data Link	Serial Optical
Packaging	Cooling	Air Cooling
	Location	Fan Case Mount On Vibration Isolators

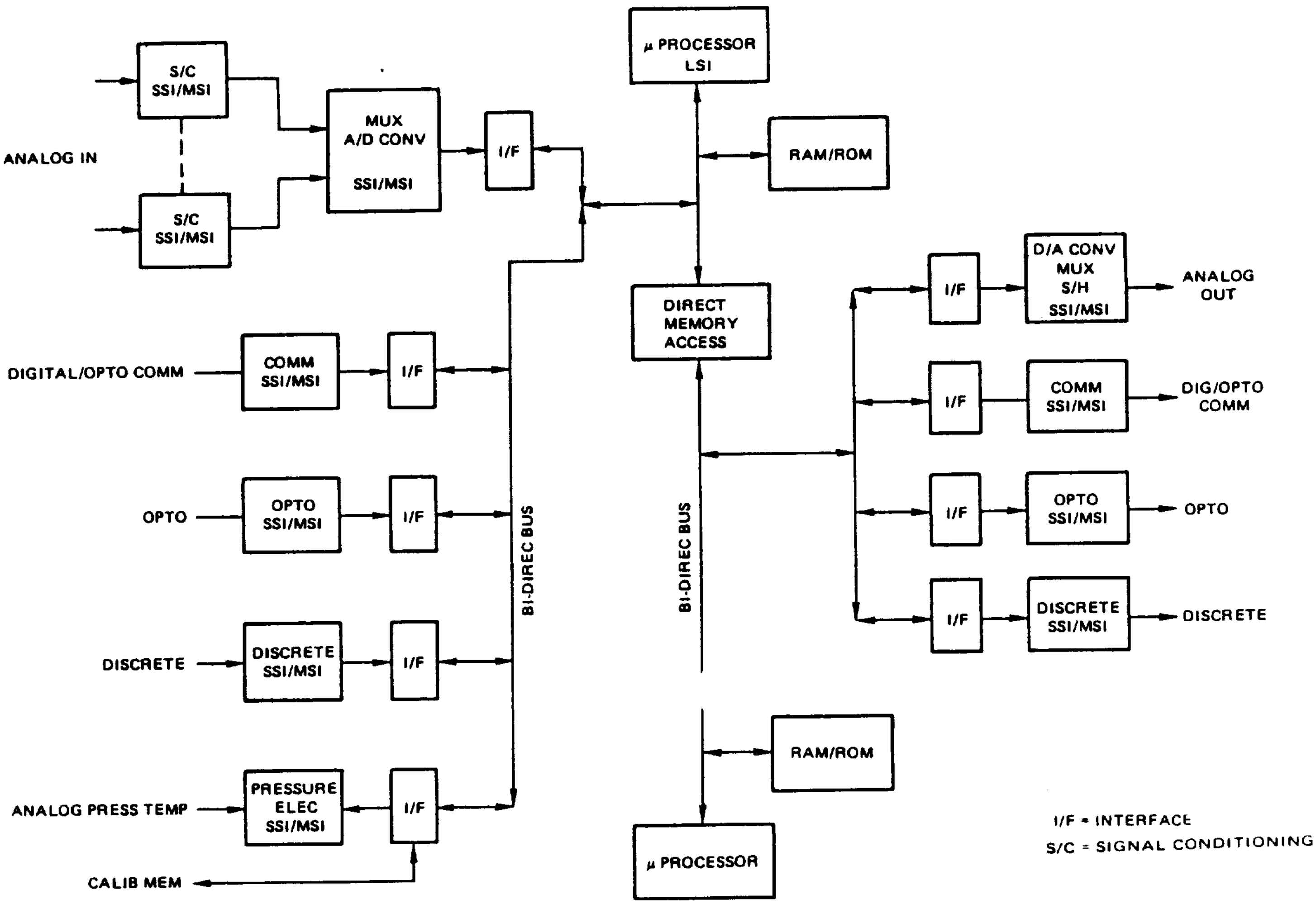


Figure 3.4-4 Conservative Electronic Controller Architecture - - The conservative technology control system utilizes components that are either currently in production or are derivatives of current production items.

3.5 TECHNOLOGY SELECTION

The purpose of the Energy Efficient Engine Program is to design an engine that is fuel efficient, performance retentive, and provides reduced maintenance and direct operating costs. The control system conceptual definition was conducted with these objectives in mind. In Pratt & Whitney judgement these goals will be best accomplished with an electronic control system. The control system preliminary definition was therefore based on an electronic control, and much of the candidate technology for the control system concept is applicable to electronic control systems. Although the technology is specifically aimed at the requirements of the program conceptual system, it is considered generally applicable to any advanced commercial engine embodying overall Energy Efficient Engine and component design concepts. The technology is in varying states of development: from the feasibility stage to production availability.

Appendix B provides tradeoffs for selection of technology for the various system elements. The candidate technologies and selections are summarized in the following paragraphs. Some of the more innovative technologies are briefly described. The technology selections are summarized in Tables V, VI, and VII (Section 6).

3.5.1 Electronic Controller

The electronic controller provides all computations required to effect control of the engine fuel flows and the geometry actuators. It is a full authority digital electronic controller and includes controller health monitoring capabilities in addition to its control functions. The controller includes the circuitry for signal conditioning the electrical signals from the sensors and transducers, output driver circuits for the actuator controls, data communications bus with the aircraft system, central processor unit and memories, and power supply. Engine parameters used in the controller are available to a condition-monitoring unit by means of a serial data link.

The electronic controller is designed to be mounted on the engine fan case and employs either air or fuel cooling for controlling electronic component temperatures. Protection against shock and vibration is provided by vibration isolator mountings.

Many different controller configurations are possible with the large number of components available today. This flexibility is expected to expand with time because development of newer components is anticipated during the next decade.

Various functional areas of the electronic controller were studied. The study (based on factors such as cost, weight, reliability, and technical readiness, as applied to engine control electronics) utilized projections of technology and device development available in the mid-1980's. The matrix evaluation charts included with this report represent an attempt to rate the various areas and components to indicate the most favorable approach to a controller design. The following major elements of the electronic controller were studied:

Central Processing Unit (CPU)
Read Only Memory (ROM)
Random Access Memory (RAM)
ROM/RAM Processing
Chip Design
Processor Design
Cooling
Power Supply
Data Link
Mounting
Signal Conditioning

3.5.2 Pumping And Fuel Metering

The fuel pumping system must provide flow for both pilot and main metered flows and for actuator muscles pressure for the intercompressor bleed actuator and stator vane actuator. Three basic pumping modes were considered:

1) Single fixed-displacement pump

2) Single variable-delivery pump

3) Dual variable-delivery pumps

Six schemes evolved from these three basic modes:

Scheme 1 - Single Fixed Displacement Pump

Scheme 2 - Variable Speed Gear with Inlet Throttled Centrifugal Pump

Scheme 3 - Double-Acting Variable Displacement Vane with Inlet Throttled Centrifugal Pump

Scheme 4 - Dual Variable Displacement Vane Pump

Scheme 5 - Inlet Throttled Centrifugal with Disappearing Vane Start Stage Pump

Scheme 6 - Variable Displacement Single Element Vane Pump

A flow diagram for the single fixed-displacement pump system (Scheme 1) is shown in Figure 3.5-1. This pump, a high pressure (1035 kPa (1500 lbf/in.^{2})) gear pump, could be used to provide the basis of a state-of-the-art fuel handling system. The fuel flow would be controlled by a standard metering valve/bypass valve system.

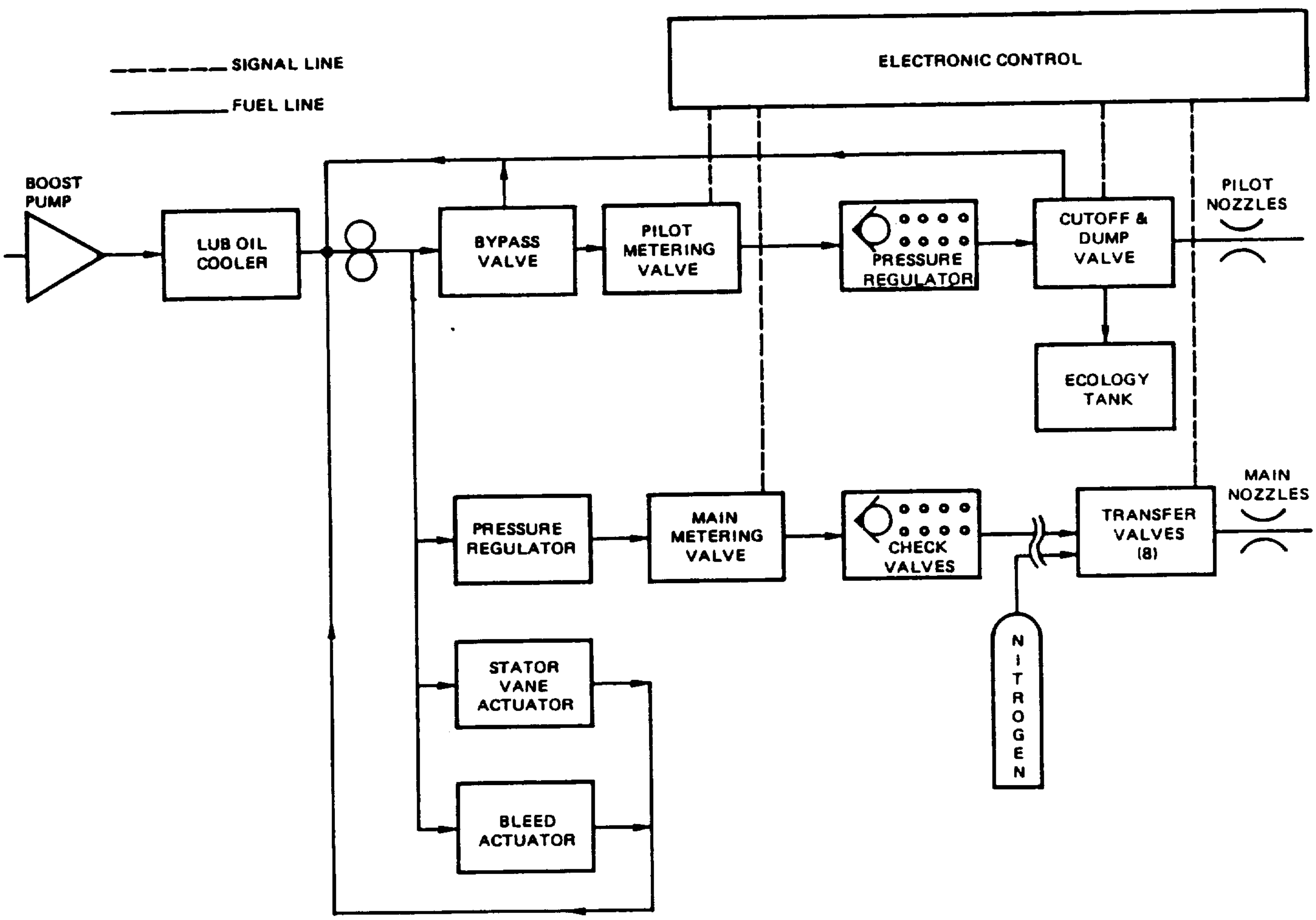


Figure 3.5-1 Single Fixed-Displacement Pump Scheme -- This pump, a high-pressure gear pump, could be used to provide the basis of a state-of-art fuel handling system.

A flow diagram for the single variable-delivery pump system is shown in Figure 3.5-2. This pump operates in a manner similar to the fixed displaced system except that pilot metering valve ΔP is maintained by controlling pump flow. Two types of pumps were considered: a variable stroke vane pump (Scheme 6) and an inlet throttled vapor core pump with disappearing starting vanes (Scheme 5) for developing starting pressure and flow.

The dual variable-delivery pump mode reduces fuel control system weight and temperature rise by placing the pilot and main fuel pumps in a single housing. Flow diagrams for the dual pumps mode are shown in Figure 3.5-3 and Figure 3.5-4.

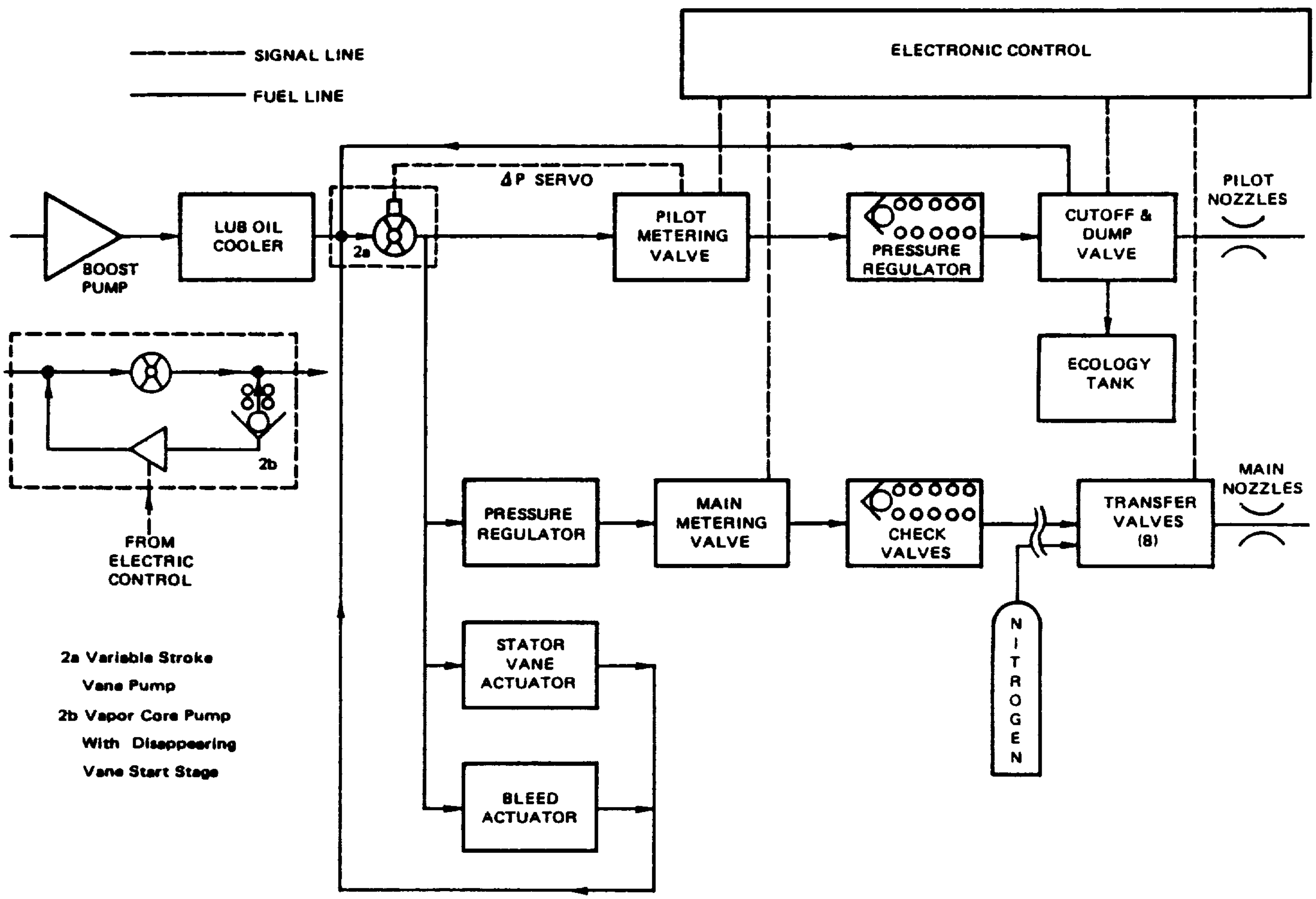


Figure 3.5-2 Single Variable Displacement Pump Scheme -- Variable stroke vane pumps and inlet throttled vapor core pumps were considered.

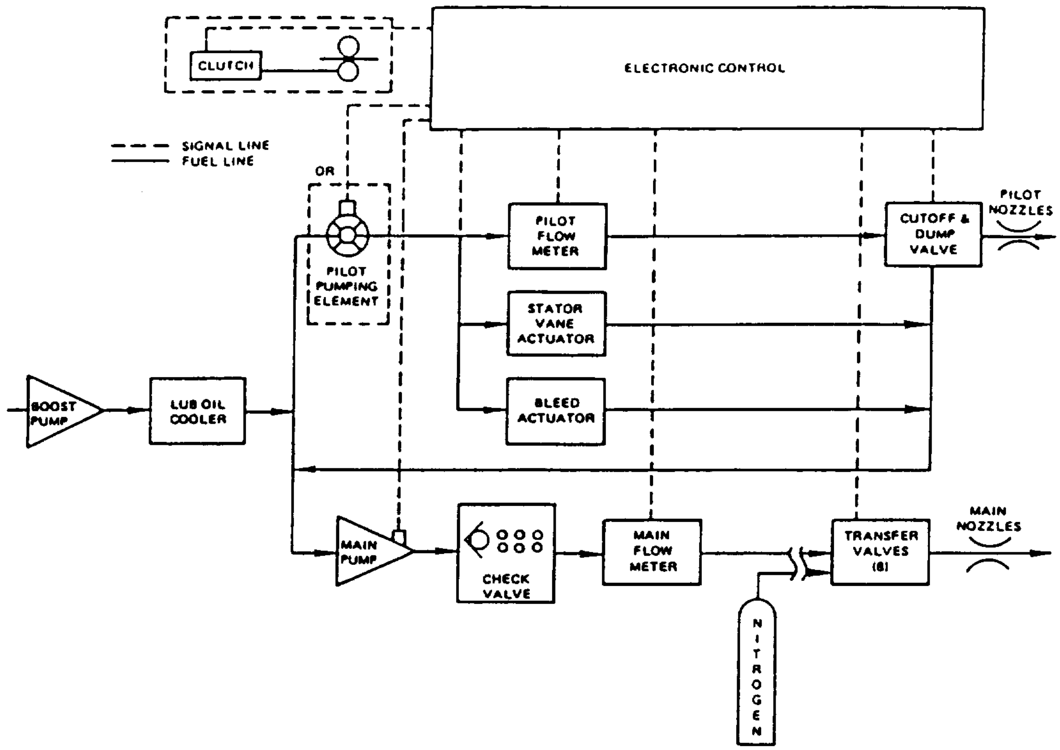


Figure 3.5-3 Dual Pumping Elements-Actuators in Parallel with Fuel Flow -- by using two separately controlled fuel pump in a single housing, weight and temperature rise is reduced.

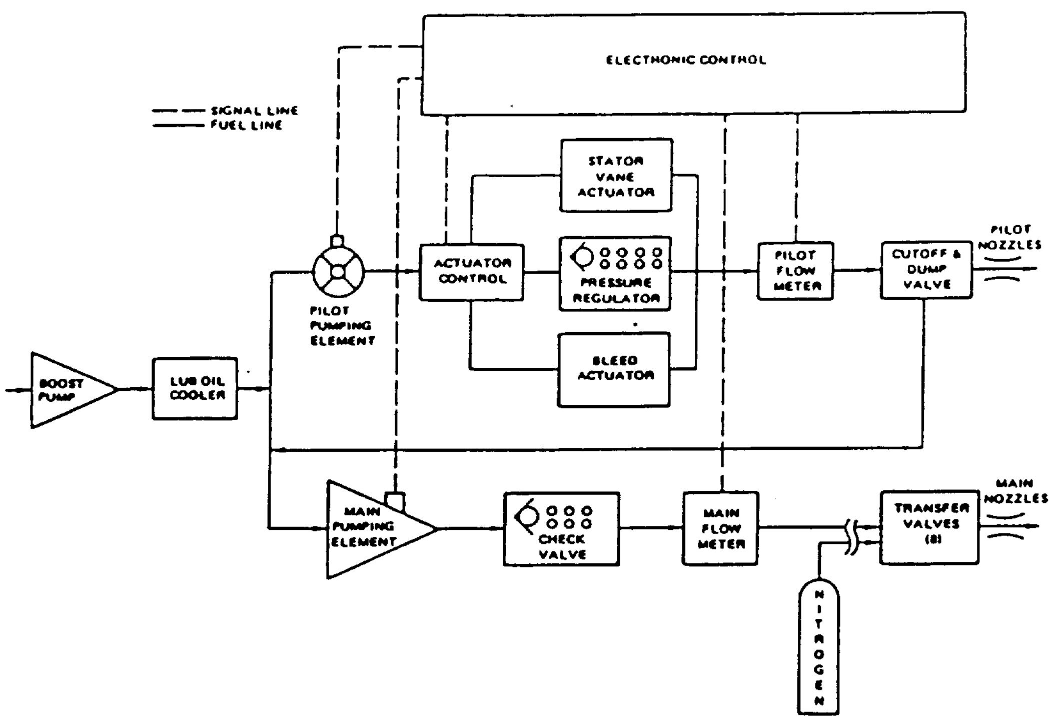


Figure 3.5-4 Dual Pumping Elements-Actuators in Series with Pilot Flow -- This pumping scheme, the variable speed gear pump/vapor core combination, had the highest performance factor.

Several versions of the two pumps were explored by Chandler Evans. Three of the versions, presented in order of decreasing performance, are:

1) Variable speed gear pump for pilot flow with an inlet throttled vapor core centrifugal main flow, (Figure 3.5-4, Scheme 2).

2) Variable displacement vane pump for primary with an inlet throttled vapor core centrifugal main flow, (Figure 3.5-5 Scheme 3).

3) Double-acting vane pump with pilot and main flow controlled on opposite sides of the pump, (Figure 3.5-5 Scheme 4).

The three basic pumping modes, single fixed-displacement pump, single variable-delivery pump, dual variable-delivery pumps, were arranged into two groups:

1) Actuators in parallel with the pilot pump

2) Actuators in series with the pilot pump.

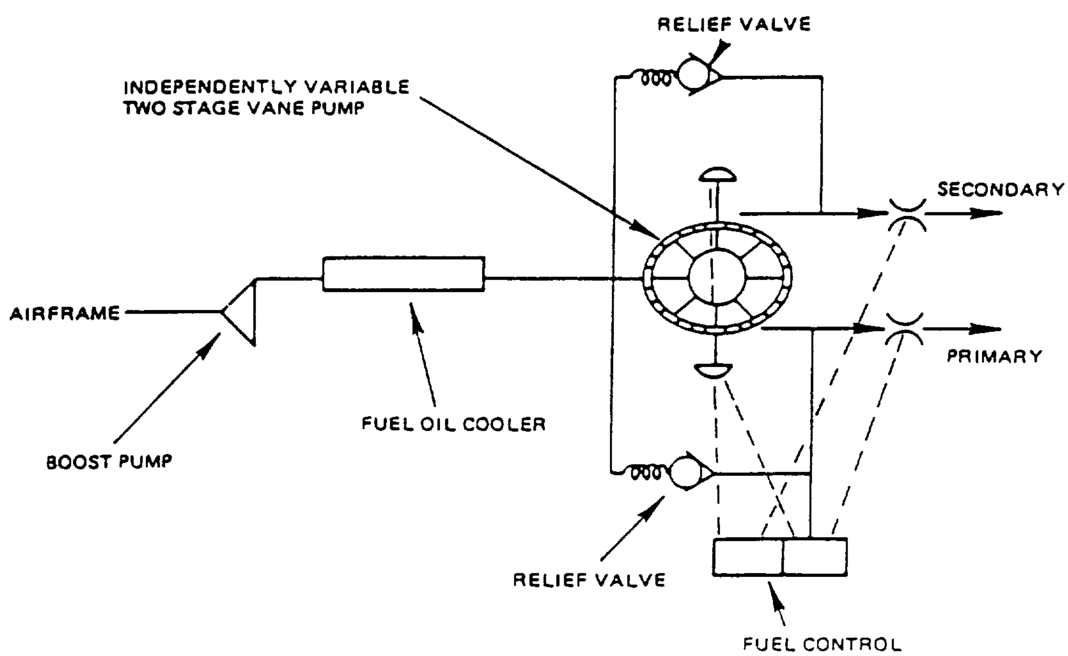


Figure 3.5-5 Double Acting Vane Pump -- This pumping scheme would provide the desired fuel performance, but was rejected because of its low rating in cost, weight, and reliability for this application.

All three basic pumping modes use a measuring device in both the pilot and main fuel lines to determine fuel flow. The feedback signals are compared with a reference fuel flow to determine the command to the pump(s). The vapor core pump is run dry when main fuel flow is not used. A check valve in the main output prevents manifold fuel from draining back into the pump during primary only operation. Metering valve P and stroke measurement can be substituted for a flow meter in the main flow line.

The selected pumping scheme is the variable speed gear pump/vapor core combination (Scheme 2), and the second choice is the variable displacement vane pump/vapor core pump combination (Scheme 3). The most significant difference between the two systems is cost, vane pumps being inherently costlier than gear pumps. The inlet throttled centrifugal with disappearing vane start stage (Scheme 5) is third. Scheme 5 was downgraded based on the following:

1) Scheme 5 requires a flow splitter or two metering valves and a housing to meter individual flows to the pilot and main burner. This eliminates the weight and some of the cost and reliability advantage of Scheme 5 over Scheme 3.

2) The mounting and installation advantage of Scheme 5 is largely due to the single flow outlet. The advantage is more than lost when the complexity of the fuel flow body is added to the system.

3) The single pump would be required to operate with a 38 to 1 turndown ratio. If soft lighting flow is required, the turndown ratio would be 58 to 1, which represents a substantial burden on pump design. The pilot pumps in Schemes 2 and 3 require a turndown ratio of 10 to 1 or a ratio of 17 to 1 if a soft light is required. Main pump turndown is 12 to 1; therefore, Schemes 2 or 3 have a substantially lower heat rise.

The selected pump scheme consists of a centrifugal boost stage and a positive-displacement, twin-gear primary stage driven through a variable speed "torque converter". The main manifold is fed by a direct-drive, vapor core pump.

The gear pump configuration is conventional, with many similar units (including the JT9D) now in the field. The vapor core pump, although a relatively recent development, is also a well established concept that has been proven in the Chandler Evans AFP-20. The vapor core pump is essentially an inlet throttled centrifugal pump. The valve used to throttle the inlet is of variable area, permitting the flow through the pump to be varied to meet the engine demand schedule.

The unique feature of the selected scheme, which is the key to its projected high desirability, is the variable speed "torque converter" drive. Variable speed drive systems have been examined in the past, and the technology of planetary gear systems is well established, particularly in the automotive transmission field. However, such variable speed gear systems have been extremely heavy, voluminous, and lacking in energy efficiency. The drive system envisioned for this application simply consists of two wet face clutch disks (driver and driven members) immersed in a fuel bath. The separating distance between clutches is governed by a loading piston whose pressure load is obtained from a fuel control-servo system. Large fuel demands result in close contact of the disks through loading of the piston, and reduced demand results in unloading the piston and separating the disks.

This concept has been tested on a limited basis on a high flow boost stage drive clutch, and the speed of the driven member has been observed to be a function of disk spacing. Modulation of secondary flow is, of course, a simple function of inlet valve setting.

3.6 SUBCONTRACTOR RECOMMENDATIONS

Three subcontractors (Hamilton Standard Division, Bendix, and Chandler Evans) aided Pratt & Whitney during the Control Preliminary Definition effort. Hamilton Standard Division and Bendix are control vendors, and Chandler Evans is a pump vendor. The recommendations of these subcontractors are summarized in this section.

3.6.1 Hamilton Standard Division

The control recommended by Hamilton Standard Division (HSD) as having the best control features is:

- Electronic Controller - The technology recommended for the Energy Efficient Engine is one single chip VLSI MOS processor using a fixed instruction set. The recommended support items included:

- Read Only Memory - single chip PROM
- Random Address Memory - single chip static MOS
- Airframe data link - serial optical
- Discretes - GaAs JFET switches for controlling all relays.

The recommended sensors are:

- Fuel flow - shedding vortex
- PLA and SVA position - optical encoder
- N_L - optical pickup
- N_H - alternator
- Pressures - Surface Acoustic Wave (SAW)
- T_2 Platinum Resistance
- T_3 CrAl
- Turbine Blade - optical pyrometer
- Turbine clearance - optical proximity pickup

The HSD recommended controller is estimated to be 31.88 x 23.13 x 9 cm (12.75 x 9.25 x 3.6 in.) in size and 7.52 kg (16.7 lbm) in weight. The controller is estimated to require 24 watts of electric power and to be fuel cooled.

o Hydromechanical Components - The recommended advanced control system uses a metering type pump with two controlled outputs. The two outputs are closed-loop controlled by sensing pilot and main fuel flow with separate "shedding vortex" meters. The pump, SVA, and bleed actuators are controlled by pulsing solenoids driven by GaAs JFET switches mounted on the solenoid to reduce control heat. The actuators receive high pressure flow from the pilot pump in parallel with the burner, and the flow is returned to the pump interstage Solenoids powering start bleeds, clearance control bleeds, and other high powered discretes are actuated by GaAs switches located on the solenoid.

3.6.2 Bendix

The Bendix control system, which is recommended for further investigation as a result of this study, is summarized below:

o Electronic Controller - The approach recommended by Bendix for the electronic controller design is a single CPU employing a VLSI single-chip microcomputer having sufficient on-chip RAM/ROM and computational power to handle engine control solutions similar in complexity to those of today. Support circuitry consists of LSI chips of the following nature:

  o sensor signal conditioning
  o monolithic A/D converter with BUS interface (possibly with its own CPU)
  o optical communications chips (signal conversion, data manipulation and formatting capability, BUS interface)
  o D/A converter and drivers with BUS interface (possibly with its own CPU)
  o Digital Output Interface chip with BUS interface

The functions of PLA, discrete aircraft inputs, and airframe data to and from the control are handled by a satellite processor mounted in the cockpit and which communicates with the control by means of an optical service data link.

The recommended controller is air cooled and estimated to be 22.5 x 17.5 x 10 cm (9 x 7 x 4 in.) in size and 6.08 kg (13.5 lbm) in weight. It requires an estimated 33 watts of electrical power with a 901.45 cm^3 (55 $in.^3$) internal power supply.

o Hydromechanical Components - Pratt & Whitney, in conjunction with a fuel pump manufacturer, has decided that variable displacement pumps and vapor core centrifugal pumps should be used. Bendix recommends that the primary and secondary fuel flows be controlled closed loop, using a flowmeter to measure flow and to modulate the pump control actuator to achieve a requested fuel flow level. The primary and secondary pump control actuators are modulated through two stage torque motors controlled by the digital computer by variable pulse width drive signals. A flowmeter is recommended for the primary fuel flow channel. This flowmeter would consist of a servo-controlled contoured valve, a head sensor element, and an electromechanical position transducer. The head sensor acts by means of a hydraulic servo to control the contoured valve to maintain a constant pressure across the valve. Measurement of the valve position provides a measure of fuel flow.

Bendix recommends that secondary fuel flow be determined by measuring the position and the pressure drop across the vapor core inlet throttling valve. Fuel temperature measurement is also required for secondary flow control.

The Bendix recommended method of obtaining hydraulic actuator power is by cascading the actuators between the primary pump and primary flowmeter. An SVA actuator with integrated actuator, torque motor servo valve, an resolver feedback is recommended. The torque motor is controlled with a pulse width modulated drive signal from the digital computer.

Pneumatically boosted solenoid operated valves are recommended for start bleed and clearance control functions.

3.6.3 Chandler Evans

Chandler Evans (CECO) conducted a parametric analysis of four fuel-pumping systems in order to determine compatibility with Energy Efficient Engine concepts. Three of the systems utilized advanced technology concepts; this technology to a large extent was founded on existing CECO data. The fourth system, which was used as a baseline, is the present JT9D-3/7 bill-of-materials system upgraded to around 1990. The most favorable system was analyzed in further detail to confirm the analysis and define areas where further analysis and/or test is desirable.

The result of the CECO parametric analysis favored the variable-speed gear pump vapor core combination, with the variable displacement vane pump, vapor core pump combination coming in second because of cost. The JT9D pumping system was third, and the variable double-acting vane scheme was last.

SECTION 4.0

CONTROL SYSTEM DEFINITION UPDATE
Closed-Loop Active Clearance Control

4.1 OVERVIEW

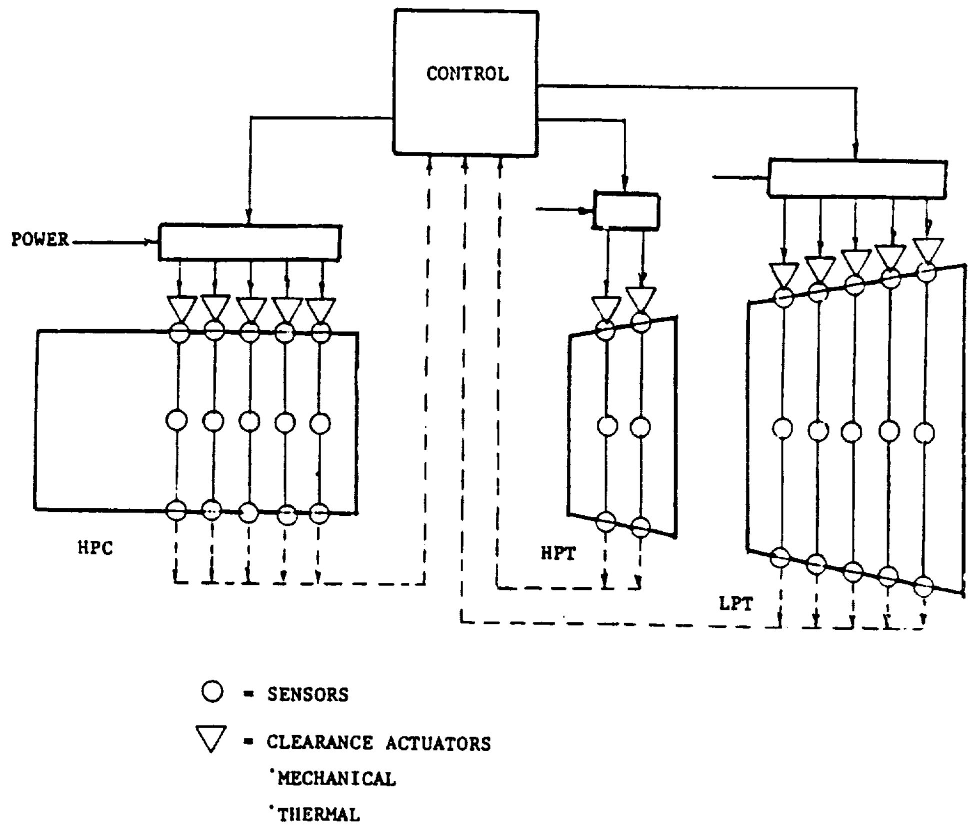
The work described in the previous sections of this report identified the Full-Authority, Digital Electronic Control (FADEC) system as the concept most suitable for optimizing the lifetime performance of commercial engines incorporating current technology "open-loop" clearance control. In an "open-loop" system, rotor and case geometry is set by clearance requirements at pinch points and predicted gust and maneuver load deflections. Clearance is modulated by cooling or heating the rotors or cases according to a pre-determined schedule of suitable parameters such as rotor speed, altitude and time. Experience has shown that open-loop clearance control in compressor and turbine components can improve TSFC at cruise operating conditions on the order of two percent relative to an engine without clearance control. However, open-loop systems are not able to compensate for engine-to-engine part tolerance variations, in-service deterioration due to blade tip rubs, time-varying conditions caused by power transients and clearance variations caused by gust or maneuver loads.

Work conducted under the Energy Efficient Engine Technology Benefit/Cost Study (Ref. 1) indicated that a closed-loop clearance control system, which continuously monitors blade tip clearance, could provide solutions to many of the above-mentioned concerns; leading to a further improvement of from 0.75 to one percent in cruise TSFC as well as potential reductions in fuel consumption during climb and descent. Critical to the success of such a system is a clearance sensing device suitable for flight engine applications. The decision was subsequently made to update the engine control system definition to include sensing elements and actuation devices necessary to accomplish closed-loop active clearance control in engine compressor and turbine components. This work is described in the following sections of the report.

4.2 DEFINITION OF REQUIREMENTS

4.2.1 System Requirements

The first step in defining clearance sensor requirements was to realize that the maintenance of tight running clearances between blade tips and cases would require not only maintaining uniform closure rates but also compensation for case out-of-roundness due to circumferential thermal distortions. Studies have shown that case out-of-roundness would negate clearance objectives and cause rubs. Therefor,at least three, and possibly, four sensors could be required at each measurement station. Case cooling airflow would have to be controlled differentially, in order to achieve desired clearances around the engine circumference. The number of measurement stations required has not been determined, but there would probably have to be at least one station for each engine component where clearances are being measured (i.e.high-pressure compressor, high-pressure turbine or low-pressure turbine). Therefore, it appears obvious that multiple sensors per engine will be required, along with multiple cooling air valves. Such a system is shown schematically in Figure 4.2.1. The engine electronic control (EEC) would have to receive and process



OBJECTIVES:

(1) ACHIEVE DESIRED CLOSURE
(2) ACHIEVE CASE CONCENTRICITY

REQUIREMENTS:

·FULLY-MODULATED BLEED FLOW
·MULTIPLE SENSORS

Figure 4.2-1 Closed Loop Clearance Control System Requirements

the signal from each sensor (and possibly excite the sensor as well), calculate the error in the position of each of the valves, and command each valve to change position accordingly. The magnitude of the additional EEC computional burden has not been estimated and is partially dependent on the type of sensor which is selected.

Studies also suggest that case response to cooling through active clearance control flow modulation will not accomodate fast engine transients and maneuver loadings. Thus, achieving clearance goals under steady-state conditions would result in rubs under these types of conditions. Therefore, a means of rapidly increasing clearance, on demand, is desirable. To summerize; system requirements for a closed-loop active clearance control system include:

(1) Clearance sensors to provide continuous monitoring of the actual clearance at several positions within the engine.

(2) Electronic control features to process the clearance sensor data and command appropriate action of the clearance modulation valves.

(3) Means for differential clearance modulation to provide improved case roundness while maintaining desired clearances.

(4) Means for rapidly increasing clearance when required to accomodate rapid engine transients.

4.2.2 Clearance Sensor Requirements

The second step in defining clearance sensor requirements was to define those peculiar to the sensing device itself. These generally fall into the catagories of performance requirements, operational requirements and engineering requirements.

Performance requirements are those that relate to the range, accuracy, response rate, sensitivity and resolution of the sensing device. Range refers to the variation in rotor speed and number of blades in the engine component whose blade tip clearance is to be assessed. Accuracy refers to clearance measurement accuracy, Response rate , the speed with which a clearance signal is acquired, processed, transmitted and displayed, Sensitivity, the degree to which sensor performance may be affected by blade tip thickness, blade material, seal material, and axial motion in rotor relative to the sensor head position, and Resolution, the clarity and definition of the clearance signal produced by the sensor. These requirements are summerized in Table 4.2.1 for high-pressure compressor, high-pressure turbine and low-pressure turbine applications.

Operational requirements are those associated with installation, operation and maintenance of the system. Specific criteria relate to ease of installation, ease of calibration and ease of handling (particularly as it applies to sensor fragility). These all relate to how easy it is to maintain the system. Other factors include the power and source of power to operate the sensor plus any special equipment required to operate the sensor, sensor durability and any sensor cooling requirements, particularly in high-pressure turbine applications. The objective is to make the system as simple and trouble-free as possible.

Engineering requirements are those associated with design objectives for the system. These include establishing technical concept viability along with size, weight and modularity criteria that will result in a viable flight-weight system. Interface compatibility with the engine control system is also important as is tolerance to environmental conditions such as gas-path temperatures and pressure, vibration and sensor tip contamination. Electronic systems must be resistant to electromagnetic interference. System efficiency is a function of signal-to-noise ratio for electronic systems, signal source, the signal detector as well as the signal handling system and ancillary equipment or service requirements.

The requirements discussed in this section formed the basis for the clearance sensor screening and evaluations discussed in Section 4.3.

TABLE 4.2-I
CLOSED-LOOP CLEARANCE SENSOR PERFORMANCE REQUIREMENTS

COMPRESSOR REQUIREMENTS

Rotor Speed	500-19000 rpm
No. of Blades	40-75
Blade Thickness	1.01 - 0.177cm (0.40- 0.070 in)
Blade Material	Titanium (Front Stages) NI STL (Rear Stages)
Seal Material	NI CR Sponge
Clearance	0.038 cm (0.015 in) (open-loop experience) 0.020 cm (0.008 in) (closed-loop goal)
Axial Movement	0.317 cm (0.125 in)
Accuracy	+ 0.002 cm (0.001 in)
Response	1.0 sec., Max.

HIGH-PRESSURE TURBINE REQUIREMENTS

Rotor Speed	500-19000 rpm
No. of Blades	40-70
Blade Thickness	0.5 cm (0.2- 0.3 in)
Blade Material	SIC GRIT IN NI STL
Clearance	0.033 cm (0.013 in) (open-loop experience) 0.017 cm (0.007 in) (closed-loop goal)
Axial Movement	0.381 cm (0.150- 0.200 in)
Accuracy	+ 0.001
Response	1.0 sec., Max.

LOW-PRESSURE TURBINE REQUIREMENTS

Rotor Speed	900-7500 rpm
No. of Blades	N/A -Blade tips are shrouded
Blade Thickness	0.02- 0.03 in. knife-edge
Blade Material	NI STL
Seal Material	NI STL
Clearance	0.050 cm (0.020 in) (open-loop experience) 0.025 cm (0.010 in) (closed-loop goal)
Axial Movement	0.300- 0.400 in.
Accuracy	+ 0.002 cm (0.001 in)
Response	1 sec., Max.

4.3 CLEARANCE SENSOR SCREENING AND EVALUATIONS

Work conducted under the Energy Efficient Engine Technology Benifit/Cost Study (Ref. 4.3.1) indicated that a closed-loop clearance control system, which continuously monitors blade tip clearance, could provide further improvment of 0.75 to 1.0 percent in cruise TSFC over open-loop systems as well as potential reductions in fuel consumption during climb and descent. Approximately one-half of the potential improvement derives from the high-pressure turbine. The principal criteria for screening sensor candidates were defined as follows:

1) must meet flight engine weight, complexity and maintainability requirements;

2) must be compatible in size with current laser proximity probes (approximately 1.2 cm [0.5 in.] dia);

3) must be tolerant to contaminants on the probe face;

4) must be capable of functioning under rub conditions at temperatures up to 1538°(2800°F);

5) must maintain clearance within ± 0.002 cm (0.001 in.) with a response time of 1.0 second or less;

6) must maintain clearance measurement accuracy over a range of blade tip thicknesses from 0.05 cm (0.02 in.) to 0.76 cm (0.3 in.).

4.3.1 Matrix of Potential Candidates

A survey of potential blade clearance sensing techniques yielded the following candidate sensor types: 1) touch, 2) eddy current, 3) reluctance, 4) x-ray, 5) capacitance, 6) optical, 7) microwave and 8) fluidic.

The touch probe concept shown in Figure 4.3.1-1 includes a translating button which invades the gaspath to contact a rotating blade tip to determine its radial location. The eddy current probe concept depicted in Figure 4.3.1-2 includes an electric circuit to provide an alternating current through a coil which enduces an eddy current through the blades as an indication of the clearance. The reluctance probe, Figure 4.3.1-3, is an electromagnetic circuit which includes a two-pole magnet and the blades, which together create a closed circuit which has varying reluctance dependent on the spacing.

The x-ray probe, Figure 4.3.1-4, includes a source and detector (receiver) to project across the clearance region between the blade tips and outer air seal for measuring running clearance. The capacitance probe, Figure 4.3.1-5, is based on measuring the capacitance between a fixed primary plate and the rotating blades as a secondary plate to identify the clearance. The advanced optical probe, Figure 4.3.1-6, illuminates a window between the blade tip plane and an abradible stop to determine the running clearances.

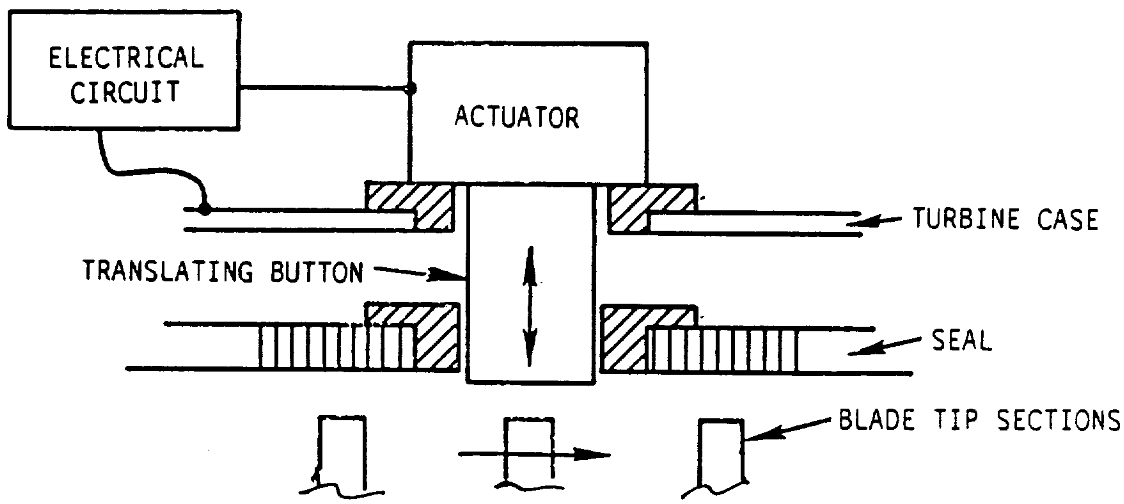


Figure 4.3.1-1 Touch Probe Schematic

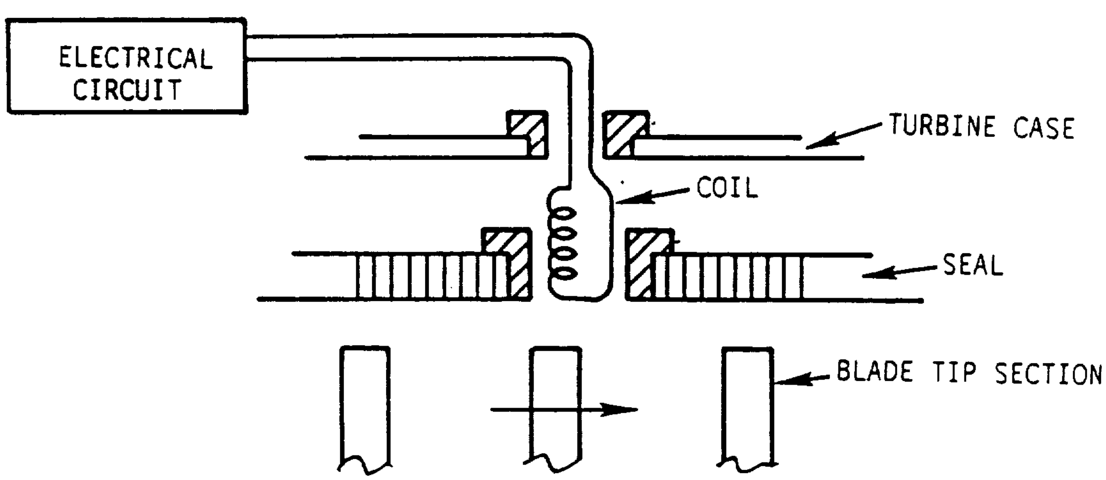


Figure 4.3.1-2 Eddy Current Probe Concept

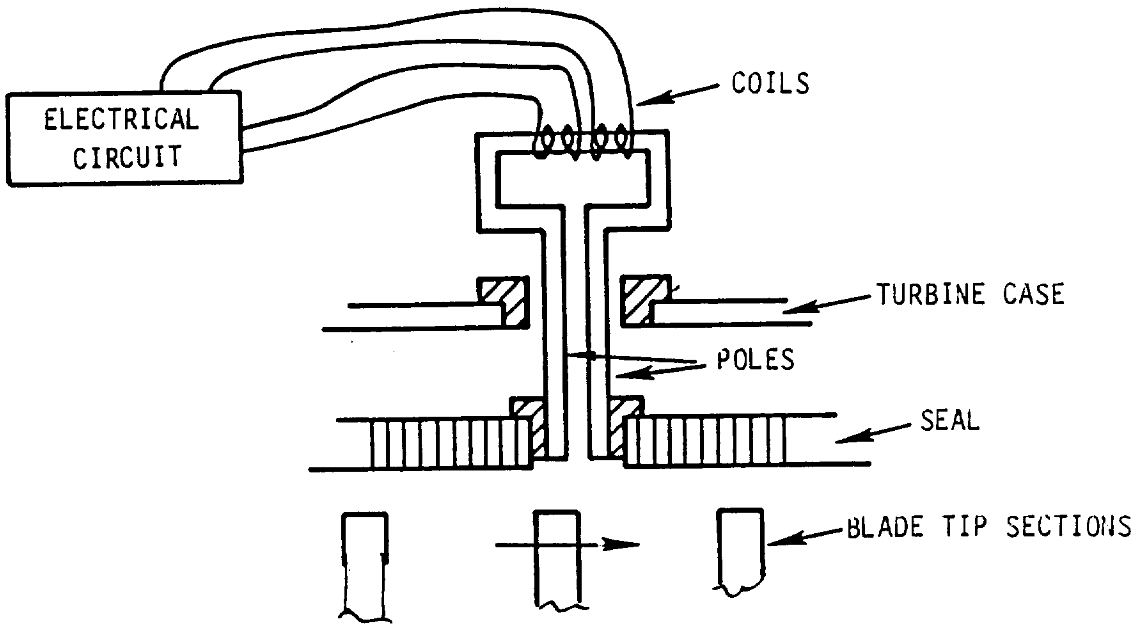


Figure 4.3.1-3 Reluctance Probe Concept

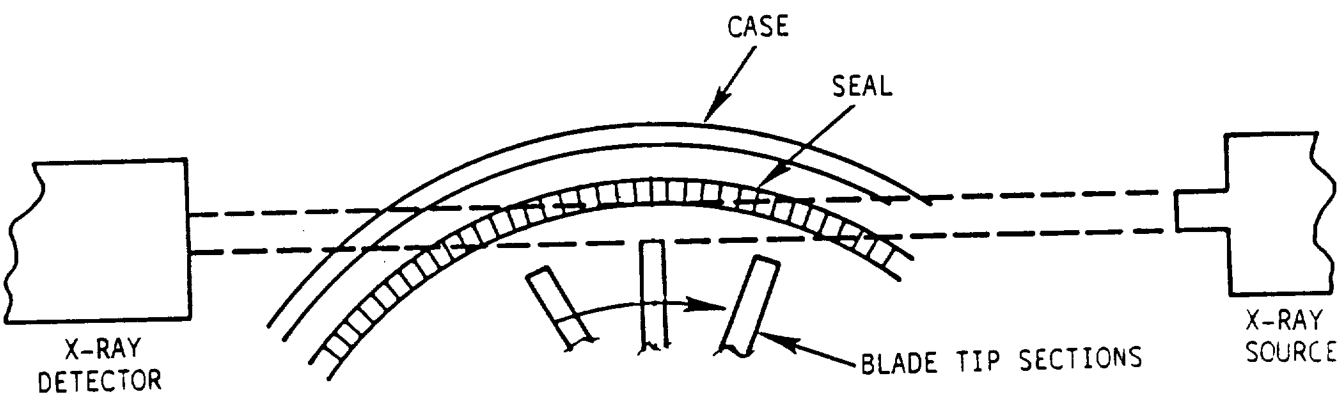


Figure 4.3.1-4 X-Ray Probe Concept

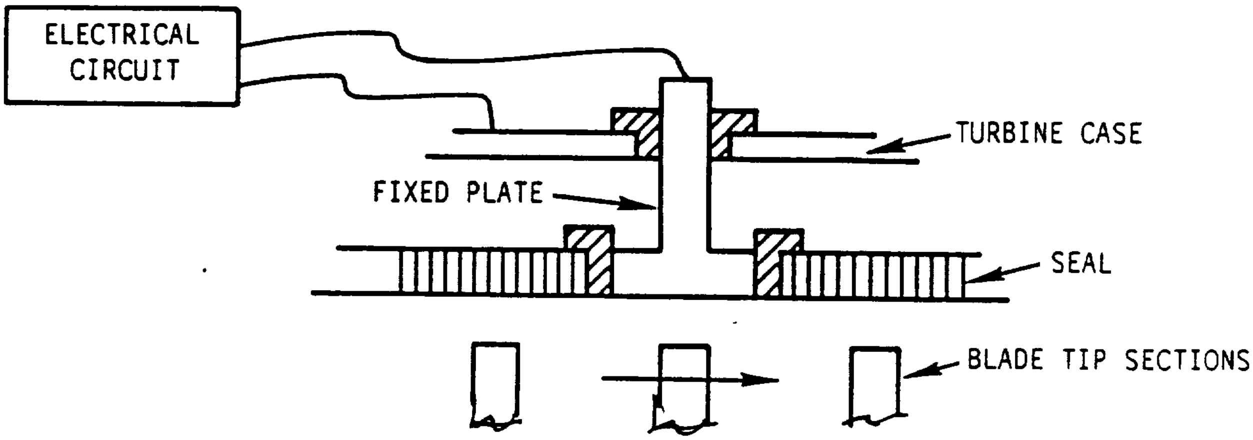


Figure 4.3.1-5 Capacitance Probe Concept

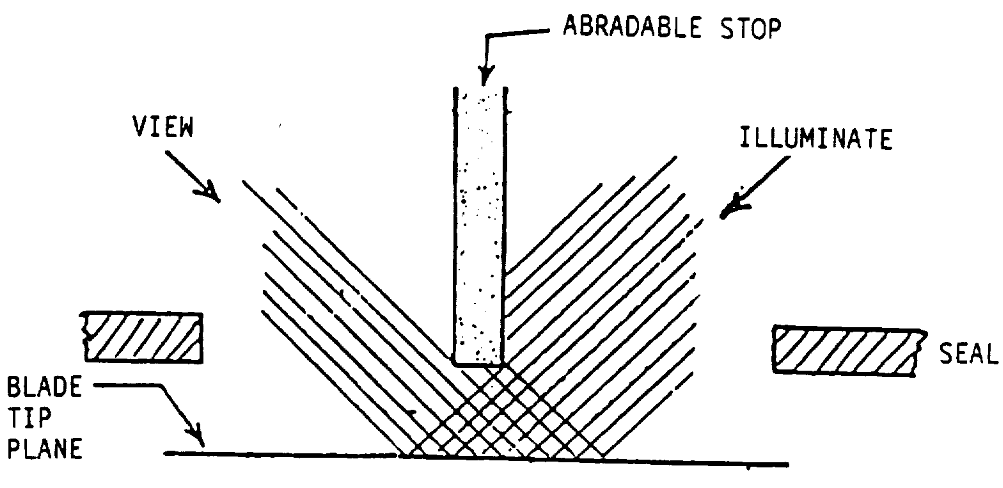


Figure 4.3.1-6 Optical Clearance Sensor Concept

The microwave probe concept shown in Figure 4.3.1-7 provides clearance measurement by matching a known electrical input frequency to a resonant frequency in a microwave probe cavity. The final candidate, a fluidic probe concept, is shown in Figure 4.3.1-8. Clearence measurement is a calculated function of a nozzle flow area in a pressure-balanced and flow-metered bridge system.

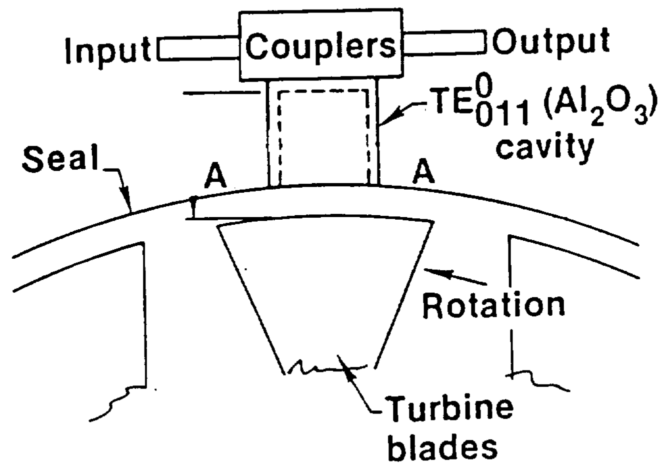


Figure 4.3.1-7 Microwave Probe Concept

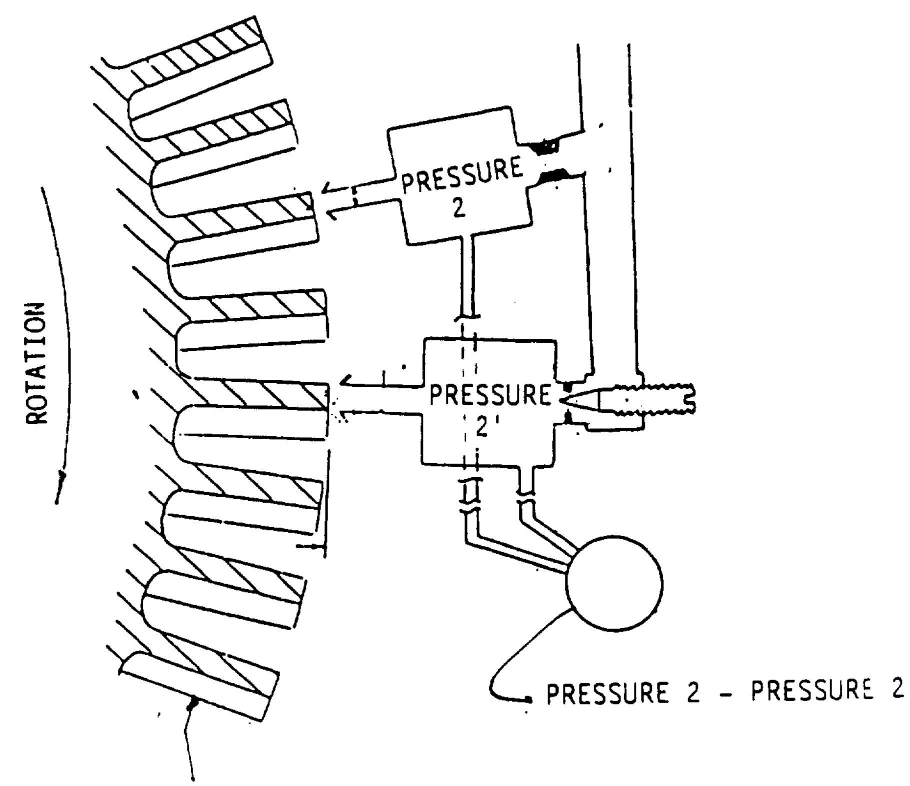


Figure 4.3.1-8 Fluidic Probe Concept

4.3.2 Probe Concept Screening

A screening process narrowed the candidates from eight down to three: 1) optical, 2) microwave, and 3) fluidic. The touch probe was determined to be nonviable since it is difficult to automate the translating button, it senses the longest blade only, it does not directly measure the running clearance, and requires current to be passed through engine bearings. The eddy current probe was eliminated because of the need to place electric circuit elements in a hot turbine environment, the variability of high temperature magnetic properties, and an indirect indication of running clearance. The reluctance probe is not considered viable because of poor signal quality and service, electric circuit elements exposed to the hot gaspath, variability of high temperature magnetic properties, and the requirement for magnetic, abradable probes. The x-ray probe, although an effective clearance measurement device, requires large and heavy components with high electric power input.

The capacitive probe, while promising, will require the development of an abradable, conductive sensor plate, very high temperature insulators, and a technique for filtering electrical noise generated within the engine. The effects of sensor tip contaminants (molten particulates for example) also need to be investigated.

Optical, microwave, and fluidic probes were judged to show sufficient promise to merit further more detailed study. The optical sensors could measure actual clearance since the optical output is proportional to the window size between the abradable stop and the blade tips. Delicate optics can also be set back in recesses from the hot gaspath.

The microwave probe provides direct clearance measurement by frequency matching. The fluidic probe also provides direct clearance measurement by pressure balancing as discussed earlier.

4.3.3 Refined Definitions - Optical, Microwave, and Fluidic Systems

A refined optical clearance sensing system was conceived for further study and evaluation. The system, shown in Figure 4.3.3-1, includes a light source and detector power and pneumatic sources, a micro-processor/memory/buffer system, and necessary optics. The optical sensor employs a relatively thin optical stop which abrades along with the outer air seal such that the blade-to-stop clearance is always the same as the blade-to-seal clearance of interest. When light is obliquely incident on a blade tip from one side of the stop, the stop casts a shadow on the blade tip and controls (in proportion to the clearance) the amount of tip illumination viewable from the non-illuminated side of the stop. The stop can be momentarily retracted by a simple pneumatic actuator to permit viewing the full unshadowed illumination, which can be used as a reference for subsequent shadowed measurements. Automatic compensation is thereby provided for changes in blade reflectivity, source intensity, optical loss etc.

Evaluation of this system led to the following conclusions regarding viability: 1) direct clearance measurement capability; 2) low contamination sensitivity; 3) readily multiplexible; 4) low cost light source with low power requirement; 5) automatically compensates for reflecting and degradation; 6) probably acceptable for compressor and low-pressure turbine applications; and 7) questionable for high-pressure turbine applications (erosion sensitivity and background light).

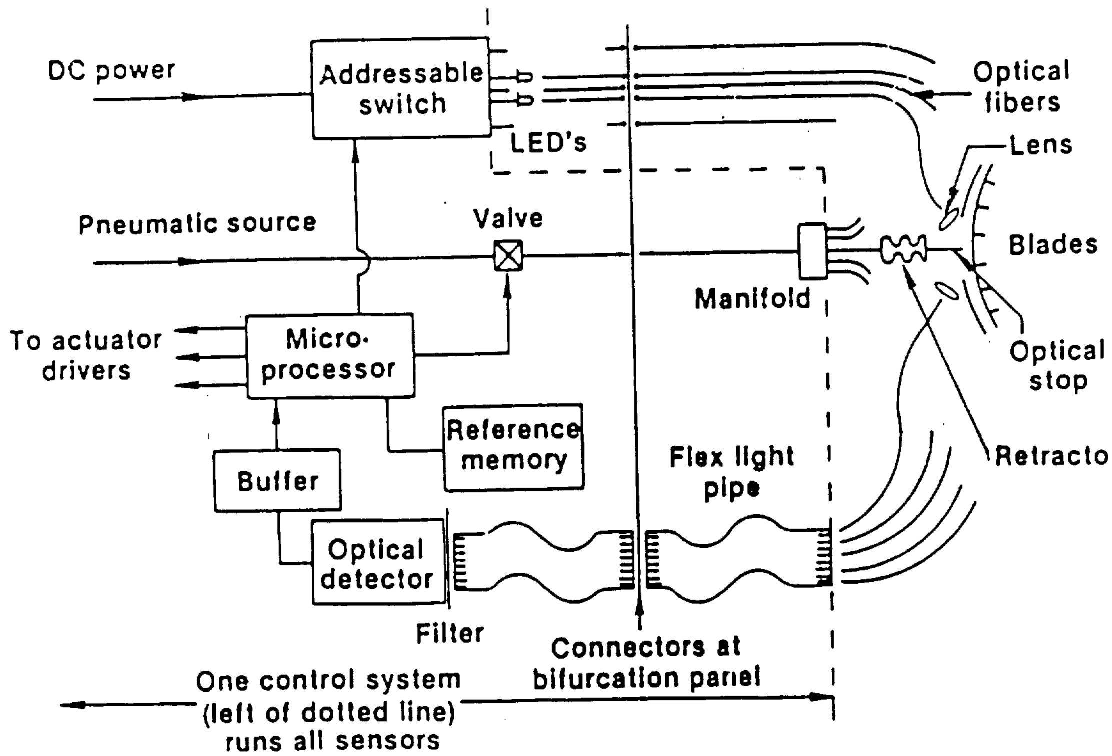


Figure 4.3.3-1 Optical Clearance Sensor System

The refined definition of the microwave sensor system, shown schematically in Figure 4.3.3-2, includes a microwave source, a detector, and signal processor in addition to the sensor head. Clearance measurement is achieved by matching a known electrical input frequency to a resonent frequency in the microwave probe cavity where the frequency is a function of the clearance between the sensor probe face and the passing blade tips. The system was determined to be suitable for the high temperature high pressure turbine application, assuming verification of probe face contamination tolerance and 2800°F operating capability, without dielectric property deterioration.

Refined definition of the fluidic sensor system, shown in Figure 4.3.3-3, includes the fluidic sensor, transducer, and a stepper motor to balance the pneumatic "bridge". The stepper motor is driven to adjust the control area to a position to produce a given difference between P_2 and P_2'. The control area is directly correlateable with clearance. While the system was determined to be a viable candidate for high pressure turbine environments, there is concern over molten particulate matter large enough to plug the sensor tip flow orifices and create false clearance indications.

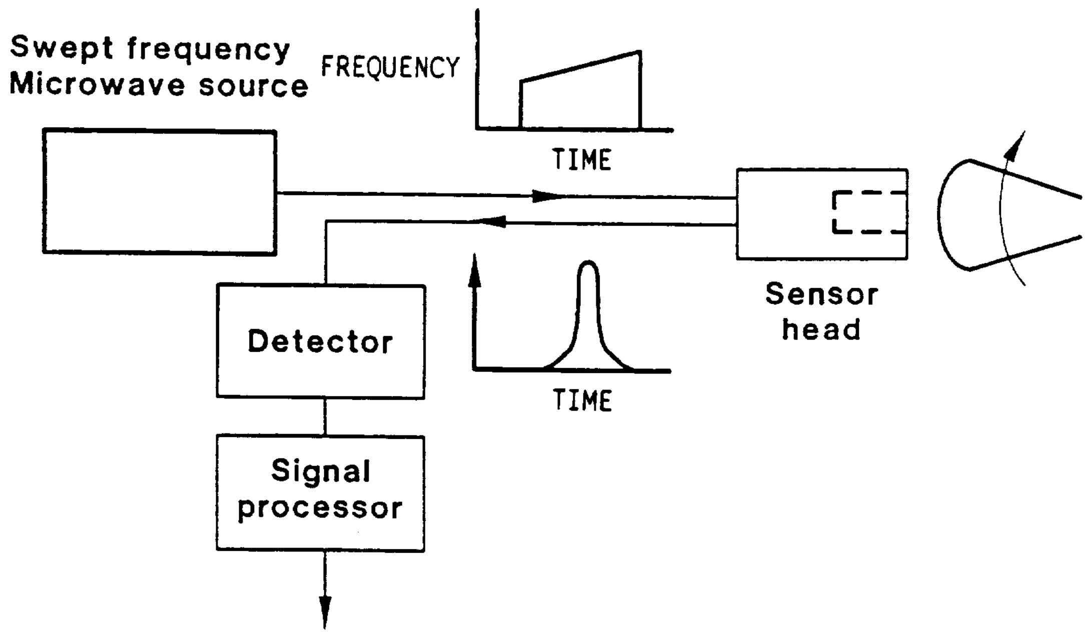


Figure 4.3.3-2 Microwave Clearance Sensor System

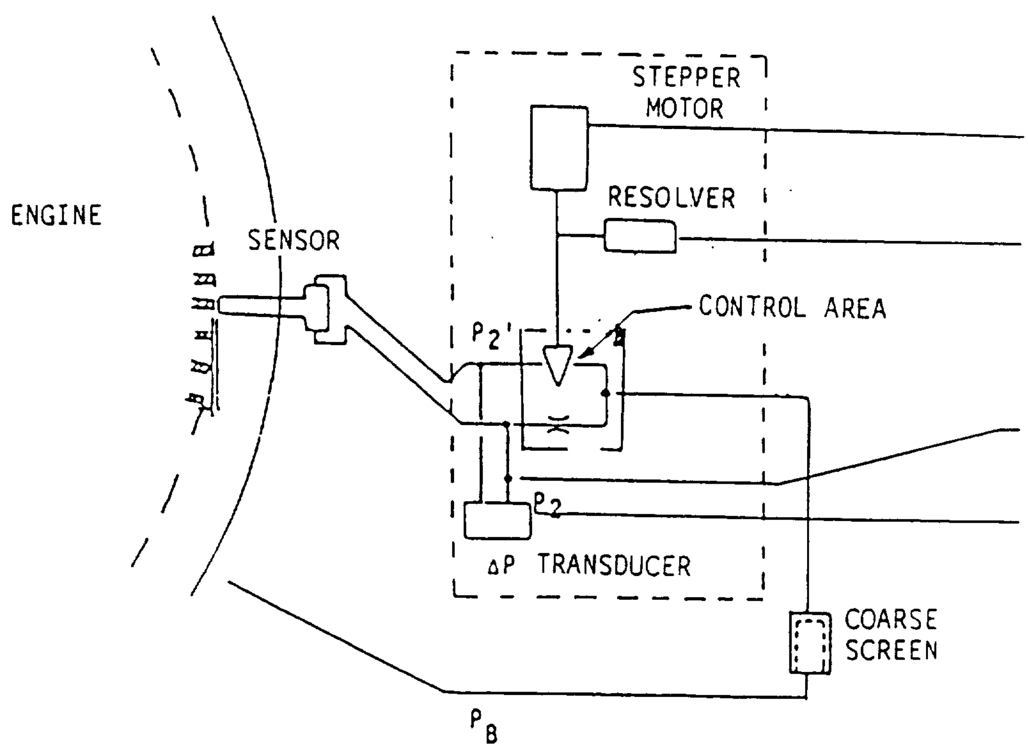


Figure 4.3.3-3 Fluidic Clearance Sensor System

4.4 SENSOR TIP ABRADABILITY TESTS

Both the microwave and fluidic sensor probe faces can be provided with an abradable surface compatible with the ceramics used in high-pressure turbine outer airseals. For the fluidic sensor, this surface material was zirconia whereas the microwave sensor used a porous alumina cap over a dense alumina cavity filler. The latter was necessary to preserve the dielectric characteristics of the microwave sensor probe cavity. These configurations are shown in schematic cross-section and as mounted in a turbine outer airseal segment for rub tests in Figure 4.4-1.

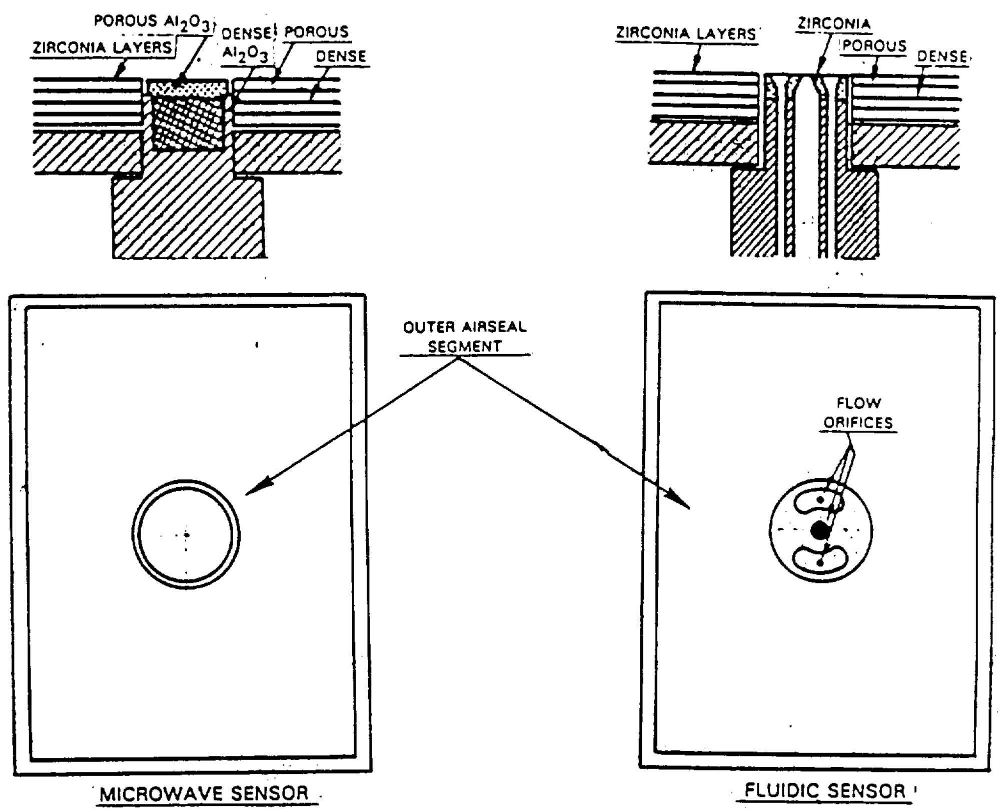


Figure 4.4-1 Samples of Sensor Specimens as Configured for Rub Tests

Hot rub tests of the fluidic sensor tip indicated a need for investigation of alternate sensor tip configurations. Under conditions of 2250°F surface temperature and a rub depth of 0.063 cm (0.025 in.), significant cracking and mechanical failure of the ceramic tip cap was observed, particularly in the area surrounding the flow orifices and the kidney-shaped plenums. Direction of rub was changed with no noticeable improvement. Reducing the size of the plenums also did not eliminate the problem.

Early rub tests of the microwave sensor tip indicated some spalling and mechanical failures near the edge regions of the tip cap. These were eliminated by modifying the bonding surface geometry at the interface between the dense and porous alumina layers. Rub repeatability tests confirmed satisfactory results. Additional testing was subsequently conducted in a hot rub turbine simulation test rig to assess the ability of the microwave sensor to measure clearance over a range of temperatures. During these tests a useable clearance signal was produced up to 2600°F, when the test was terminated because of thermal failure of a portion of the rig structure. It appeared, however, that the sensor could have continued to produce useable signals at higher temperatures.

4.5 APPLICATION STUDY AND BENEFITS ANALYSIS

The sensor screening activities previously described, along with results from the sensor tip abradability tests, indicated that the microwave and fluidic sensors were the most promising candidates for high-pressure turbine applications. A study was subsequently conducted to quantify the mission fuel burn benefits associated with utilization of these sensor devices in a closed-loop active clearance control system. Specific objectives of the study were to (1) compare the fluidic and microwave sensors in a high-pressure turbine application, (2) evaluate a "Thermal-only" vs. a combined "Thermal/Mechanical" actuation system, (3) determine the benefits of closed-loop active clearance control over all segments of the flight path, from take-off to landing and (4) investigate the benefits of utilizing closed-loop active clearance control clearance deterioration recovery.

4.5.1 Study Ground Rules

The engine selected for this evaluation was the Maximum Efficiency Energy Efficient Engine (ME^4) described in Ref. (1). It employs a two-stage high-pressure turbine similar to those utilized in the most advanced modern day turbofan engines with open-loop active clearance control systems. It's open-loop running clearances could therefore be expected to be similar to those encountered in current engine experience.

Two aircraft missions were selected for the evaluation: a short-range (400 N.M. Typical Range) 150 passenger domestic twinjet and a long-range (2000 N.M. Typical Range) 440 passenger international trijet. These missions represent significant differences in the fuel burn profiles, as shown in Figure 4.5-1. These profiles highlight the mission segments where additional clearance control could be expected to show a benefit.

The clearance histories utilized in the study are depicted in Figures 4.5-2 and 4.5-3 and are representative of modern two-stage high-pressure turbines employing open-loop active clearance control. Figure 4.5-2 shows the clearance inprovement relative to actual experience, that was assumed to be achieveable in the climb and cruise portion of the flight profile, by utilizing a closed-loop clearance control system in conjunction with thermal actuation. For purposes of the study, 0.0190 cm (0.0075 in) was considered to be the practical limit for clearance closure. Thermal actuation would have little effect in the takeoff and early climb phases of the mission profile because the short time interval precludes case response to the available cooling air. In the descent phase, there is simply insufficient cooling air available at descent power settings.

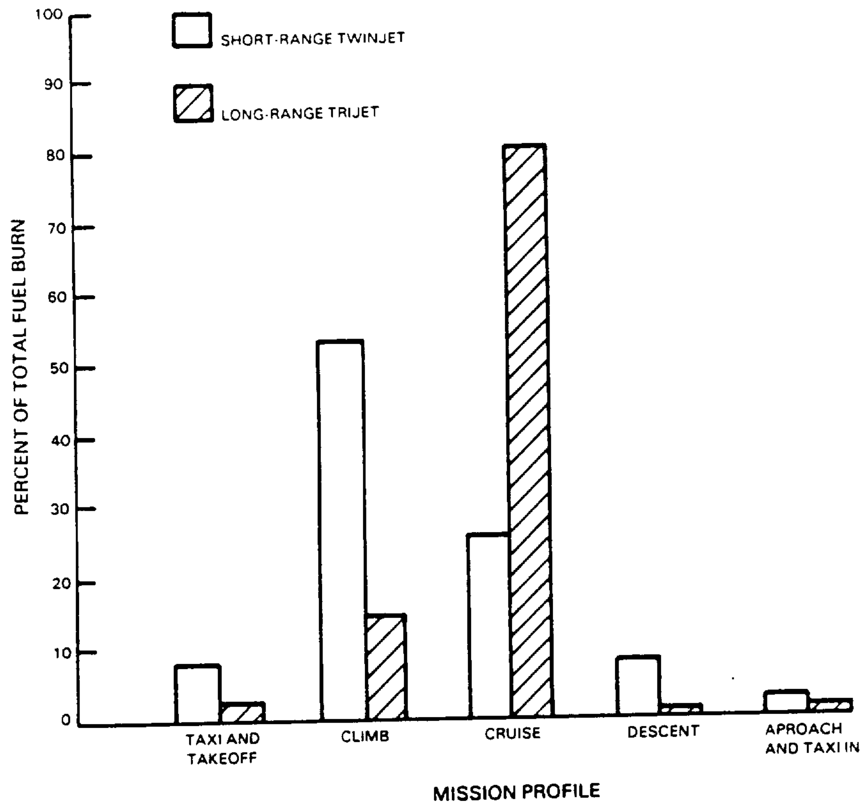


Figure 4.5-1 Fuel Burn Profiles for Selected Missions

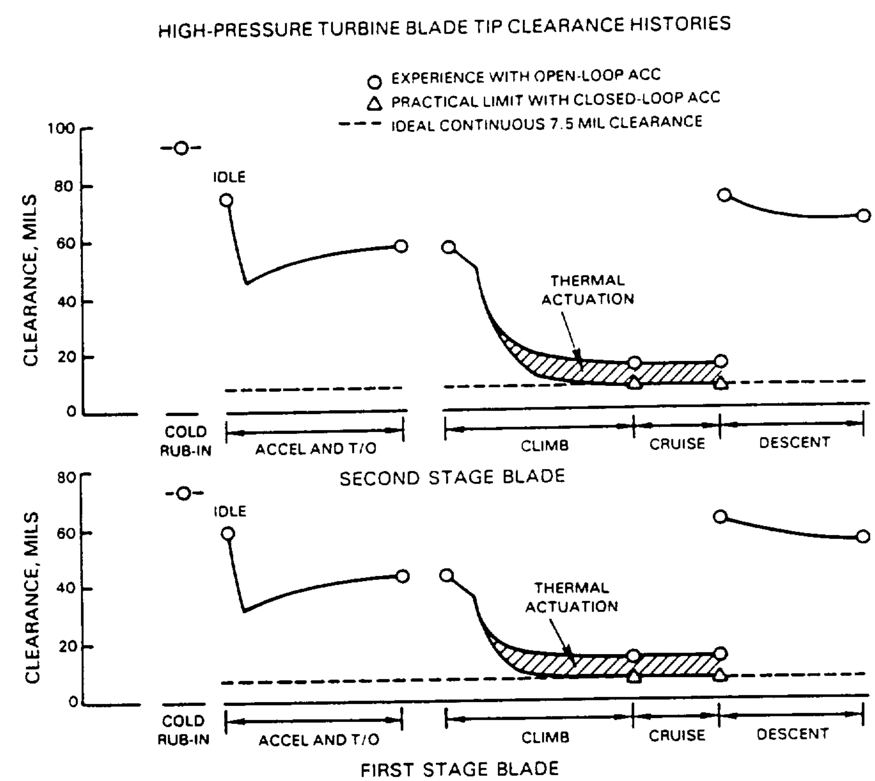


Figure 4.5-2 Two-Stage High-Pressure Turbine Showing Potential Added Clearance Closure with Closed-Loop Thermal Actuation Only

Figure 4.5-3 shows the added clearance improvement assumed possible in the takeoff, early climb and descent portions of the mission profile with the addition of the mechanical actuation system described in Section 4.5.2-1. The lower limit in these portions of the profile is set by the desire to minimize rubs due to gravitational, gyroscopic and gust load deflections (see Ref.1).

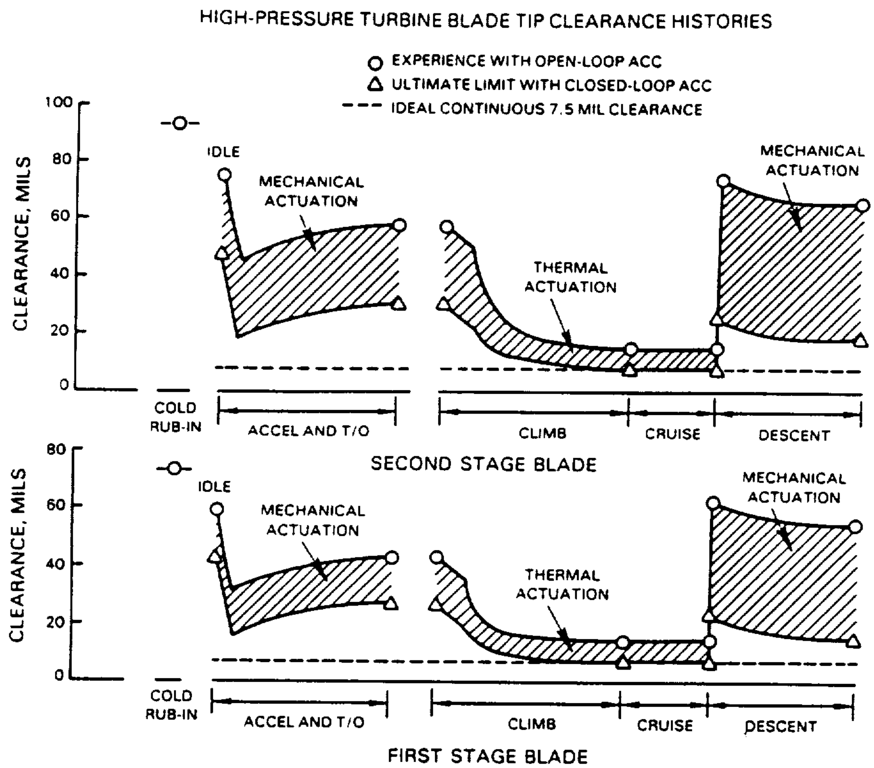


Figure 4.5-3 Two-Stage High-Pressure Turbine Showing Potential Added Clearance Closure with a Combined Thermal/Mechanical Closed-Loop ACC System

Because the fludic sensor requires a small amount of compressor air for its operation, it imposes a slight performance penalty on the engine. The magnitude of the penalty is a function of the number of sensors required to accurately monitor clearance in the turbine. For this study it was assumed that four sensors, one located in each circumferential quadrant of the turbine case, would be required as a minimum. The performance penalty for this number was on the order of a 0.025 percent increase in TSFC.

To investigate the benefits of clearance deterioration recovery, it was assumed that the study engine would have the same deterioration characteristic as the Energy Efficient Engine Flight Propulsion System described in Ref. (2) (Energy Efficient Engine Flight Propulsion System Preliminary Analysis and Design Report). This characteristic is shown in Figure 4.5-4, which identifies the performance recovery possible with high-pressure turbine clearance recovery.

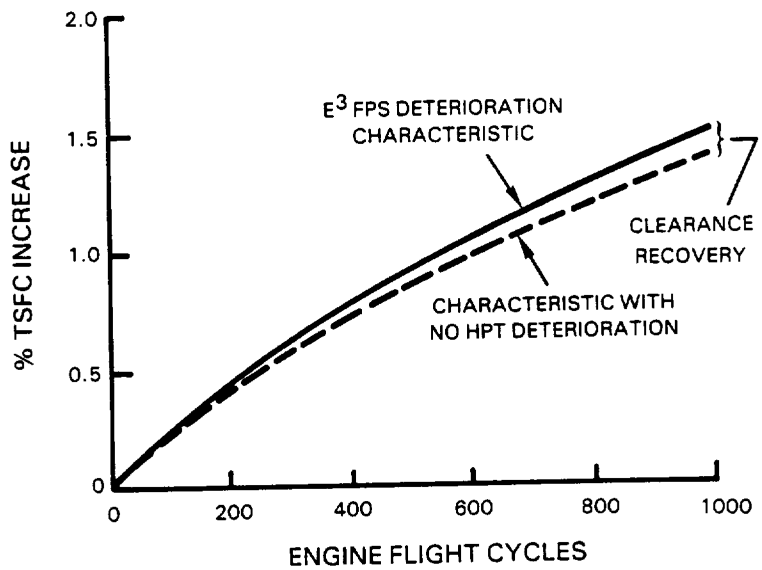


Figure 4.5-4 Potential High-Pressure Turbine Clearance Deterioration Recoverable with Closed-Loop ACC

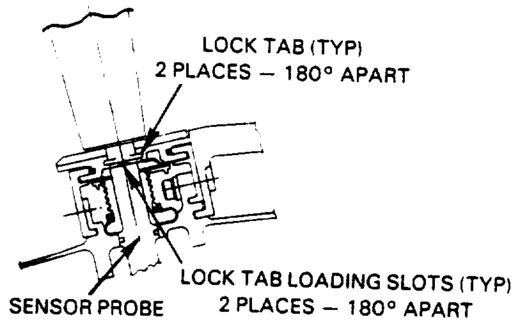
4.5.2 High-Pressure Turbine Closed-Loop Active Clearance Control System Definition

In order to conduct a meaningful mission analysis, it was necessary to provide a system definition that would permit a reasonably accurate installed weight assessment for the sensor types. The two major elements of the system are (1) the combined thermal/mechanical actuation devices necessary for clearance variation and (2) the closed-loop sensor system required to control the thermal/mechanical actuation devices such that the desired clearances are obtained. These elements are described in the following paragraphs.

4.5.2-1 Thermal/Mechanical Actuation System

The design of the thermal/mechanical actuation system was set by the requirements to provide (1) rapid turbine blade outer airseal radial movement for those conditions where thermal response might not be adequate, (2) the capability to 'fine-tune' the blade tip clearances during steady state or moderate transient conditions and (3) the capability to maintain case concentricity with respect to the blade tips while the case is undergoing differential pressure or thermal loads.

The conceptual design that evolved from these requirements combines a pressure-balanced thermal system with a two-position mechanical system; the latter was selected over a fully-modulated approach because it represented a simpler design. The pressure-balanced system is shown in Figure 4.5-5. The system divides the secondary airflow (cooling air) into two basic components to balance the pressure loads on the outer airseals. This balance is accomplished by internal manifolds and bellows-type conduits which maintain the pressurized airflow necessary for cooling the segments. The pressure in the cavity formed at the turbine case, seal rail supports and outer seal segments is modulated through a valve to balance the system. Figure 4.5-5 also shows how either sensor probe would be installed in the outer airseal segment.



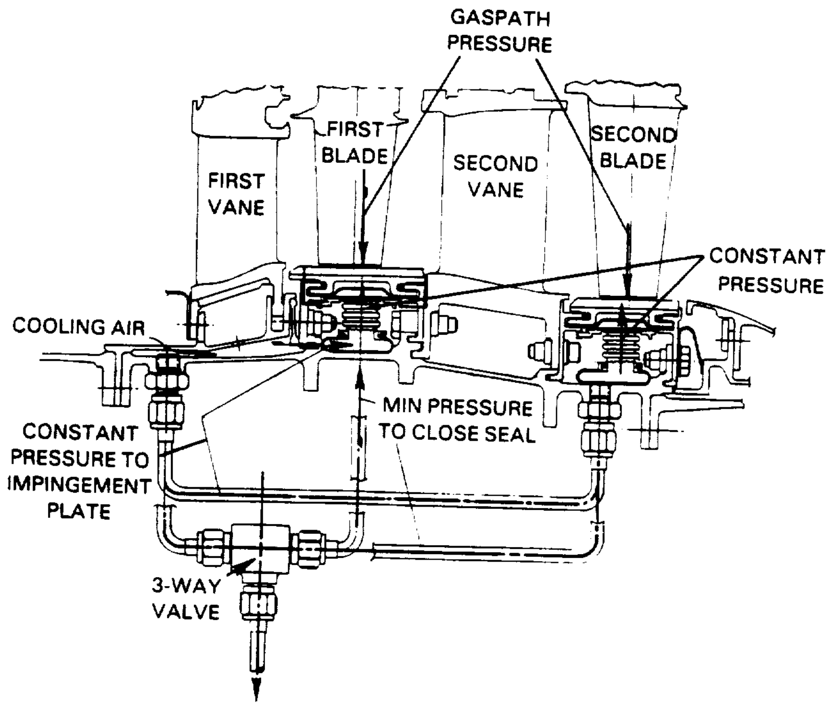


Figure 4.5-5 Pressure Balanced Thermal Actuation System

The two-position mechanical system, shown in Figure 4.5-6, incorporates a 'brake band' which encircles the seal segments. The primary function of the brake band is to provide positive seating of the seal segments while minimizing actuation loads. The band is centered by lugs on the band which engage slots on the support rails. Attachment hooks on the seal segments provide a positive connection to the brake band. Pressurizing the band actuators causes the band to contract, reducing the clearances between the outer airseal support lugs and the support rails.

The final element in the actuator system design is the case round-up feature shown in Figure 4.5-7. The system shown comprises segmented airflow manifolds, fully modulated through valves and integrated with the thermal system described previously. The sensor probes define the blade tip proximity to the case in each quadrant and provide the data necessary to define the impingement airflow split between manifold segments for the rounding-up process.

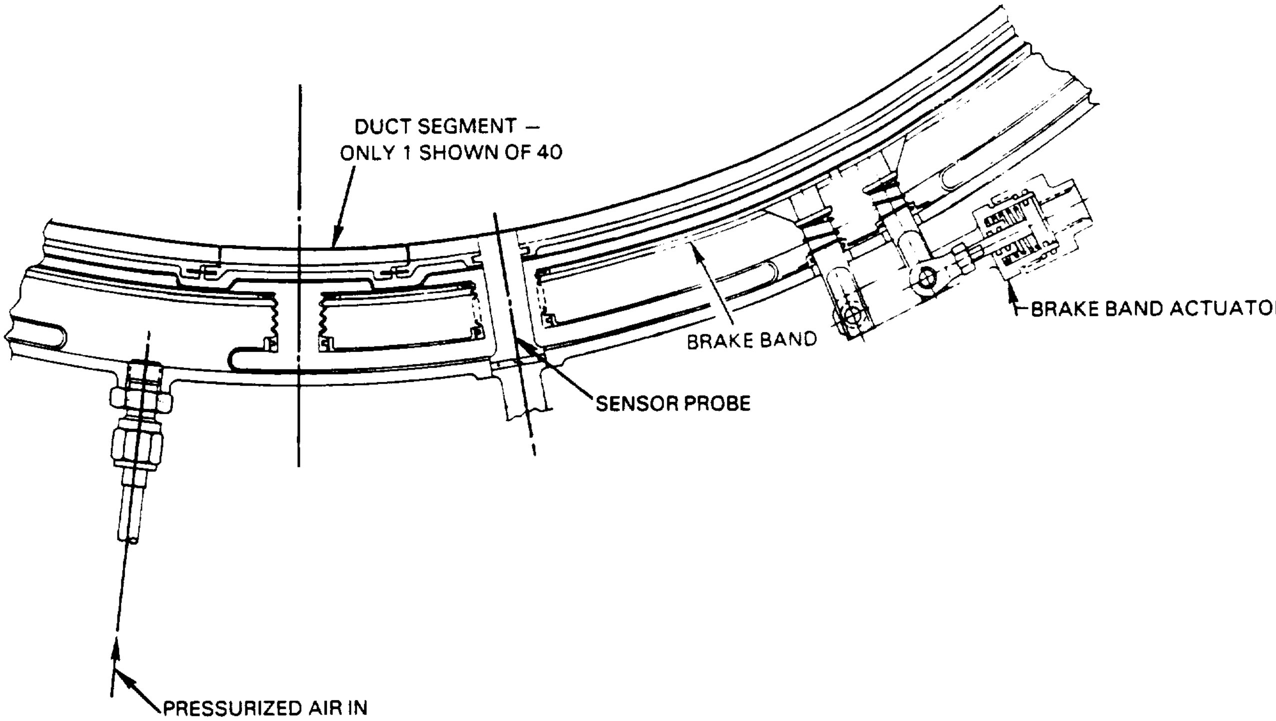


Figure 4.5-6 Two-Position "Brake-Band" for Clearance Closure

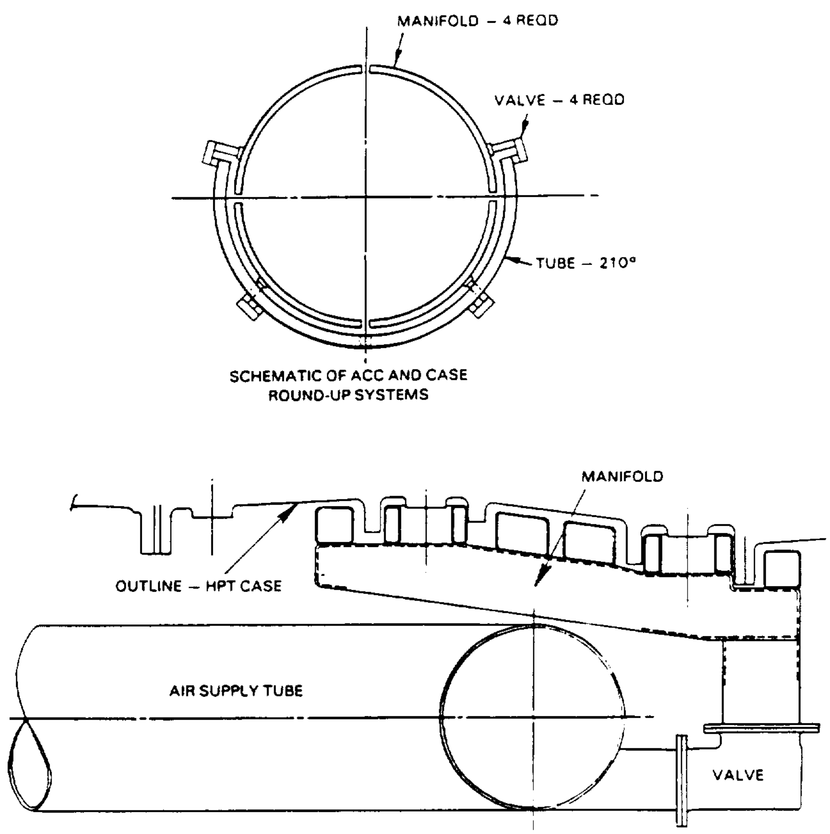
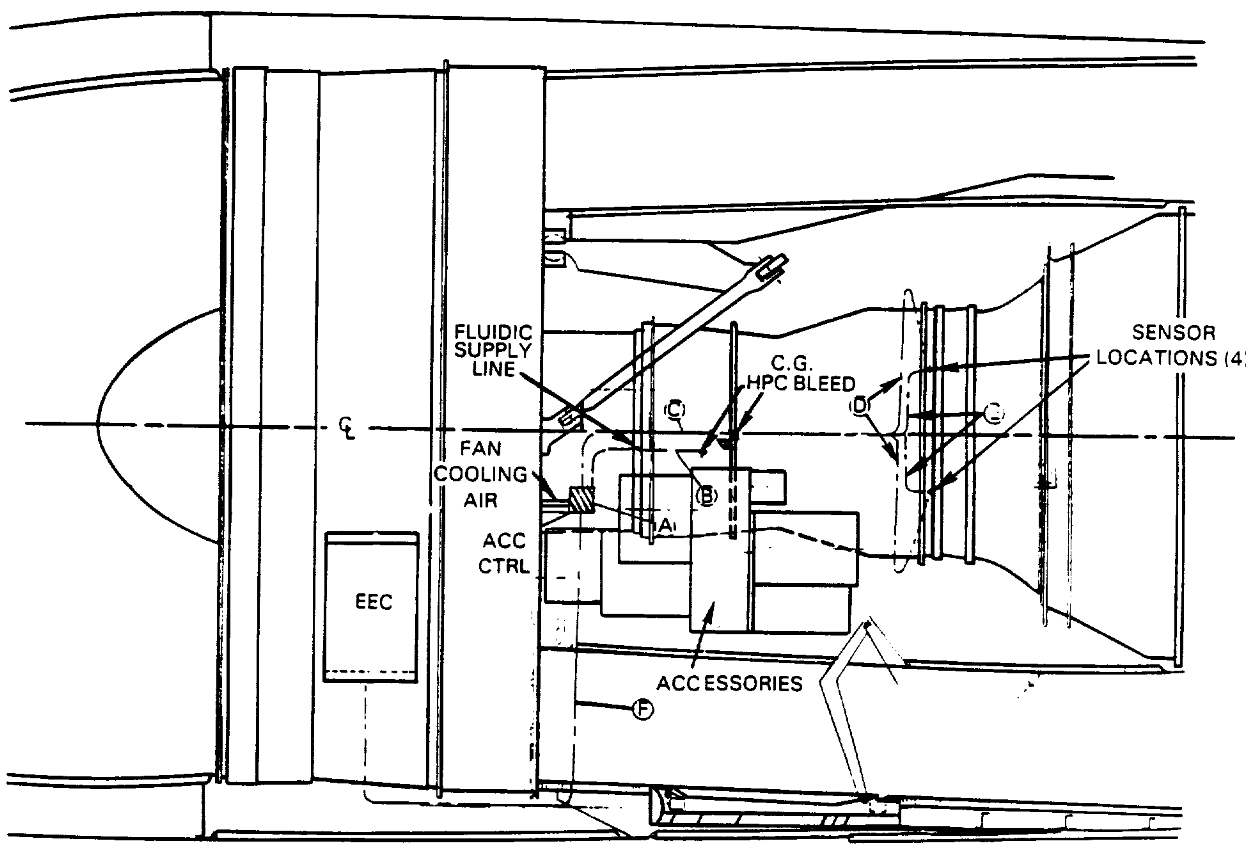


Figure 4.5-7 Case Round-Up Feature of the Thermal Actuation System

4.5.2.2 Closed-Loop Sensor System

The closed-loop sensor system comprises the elements of the total clearance control system that are necessary to insure that the thermal/mechanical system provides the required clearance control. The system is shown schematically in Figure 4.5-8 as installed on the engine. Its components are the clearance sensor (probes) mounted in the turbine case; the wave guides (microwave) or air supply lines (fluidic) connecting the sensors to the controller box; the controller box, which receives clearance signals from the sensors, feeds these signals to the control logic in the electronic engine control and provides actuation signals to the valves controlling air distribution; and the connector cable between the controller box and the electronic engine control. The fluidic system requires an additional air supply line from a suitable high-pressure compressor bleed location to the controller box. Microwave sensor wave guides and fluidic sensor air supply lines are representative of conventionally fabricated parts.



(A) CONTROLLER BOX
(B) HIGH-PRESSURE COMPRESSOR BLEED AIR SUPPLY LINE
(C) WAVE GUIDE/AIR SUPPLY LINES
(D) WAVE GUIDE/AIR SUPPLY LINES
(E) WAVE GUIDE/AIR SUPPLY LINES
(F) CONNECTOR CABLE BETWEEN CONTROLLER BOX AND ELECTRONIC ENGINE CONTROL (EEC)

Figure 4.5-8 Schematic of Closed-Loop Sensor System Installation on the Maximum Efficiency Energy Efficient Engine

4.5.2-3 Closed-Loop Active Clearance Control System Weight

The estimated weights for the systems described in sections 4.5.2-1 and 4.5.2-2 are summarized in Table 4.5-1. The weights shown are preliminary estimates based on the conceptual nature of the design studies, and represent weight added to the engine relative to a conventional open-loop clearance control system. The fluidic system is slightly heavier than the microwave system because its controller box contains step motors (compared to simple electronic circuit boards); there are twice as many air supply lines as wave guides; the connector cables between the controller box and the electronic engine control require significantly more wires; and there is the added requirement for a compressor bleed air supply line. Even so, the total weight difference is only in the order of 10 percent.

TABLE 4.5-I
ESTIMATED CLOSED-LOOP ACTIVE CLEARANCE CONTROL SYSTEM WEIGHT

System Component	Fluidic Sensor	Microwave Sensor
Thermal/Mechanical Actuation, kg (Lbs)	35.6 (78.5)	35.6 (78.5)
Closed-Loop Sensor, kg (Lbs)	15.1 (33.5)	10.4 (23.0)
Total Weight, kg (lbs)	50.8 (112.0)	46.0 (101.5)

4.5.3 Mission Analysis Results

Application of the study ground rules and closed-loop active clearance control system definition to mission analyses yielded the results shown in Figures 4.5-9 through 4.5-12.

Figures 4.5-9 and 4.5-10 compare the mission fuel burn savings, over each segment of the mission profile, between the combined thermal/mechanical actuation system and the thermal-only actuation system. The clearance sensor used for this particular comparison was the microwave. As expected, the fuel burn benefit of the combined system is greater than the thermal-only system due to the added fuel saved during takeoff, descent and approach through use of mechanical actuation. This benefit is more pronounced in the short-range twinjet application because of the fuel burn profile (see Figure 4.5-1). However, when the added weight of the closed-loop active clearance control systems is included in the analysis, the advantage of the combined system is considerably reduced for the short-range mission and disappears altogether for the long-range mission. If first cost and maintenance cost were added to the analysis, the advantage of the combined system in the short-range mission would be further eroded and might disappear altogether. Therefore, the additional weight, cost, and complexity of the mechanical actuation system incorporated in this study does not appear to be justified. The remaining analyses were conducted using the thermal-only actuation system.

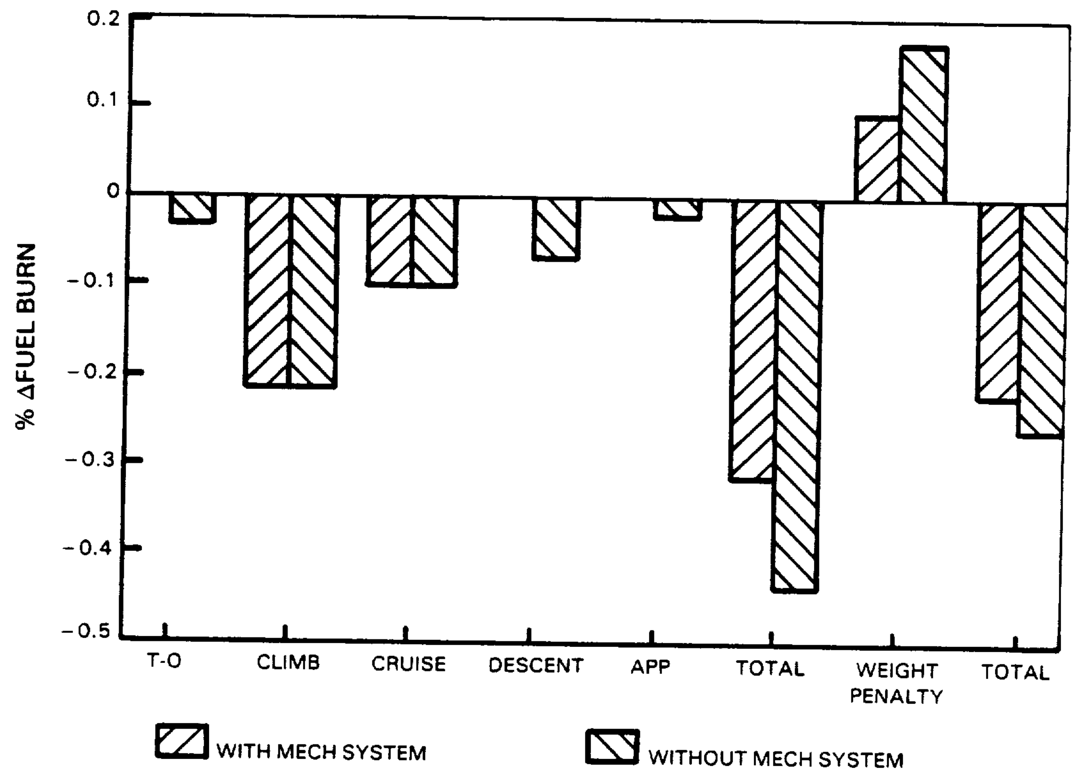


Figure 4.5-9 Closed-Loop ACC System Mission Fuel Burn Benefit; Small Twin at 400 N.M.

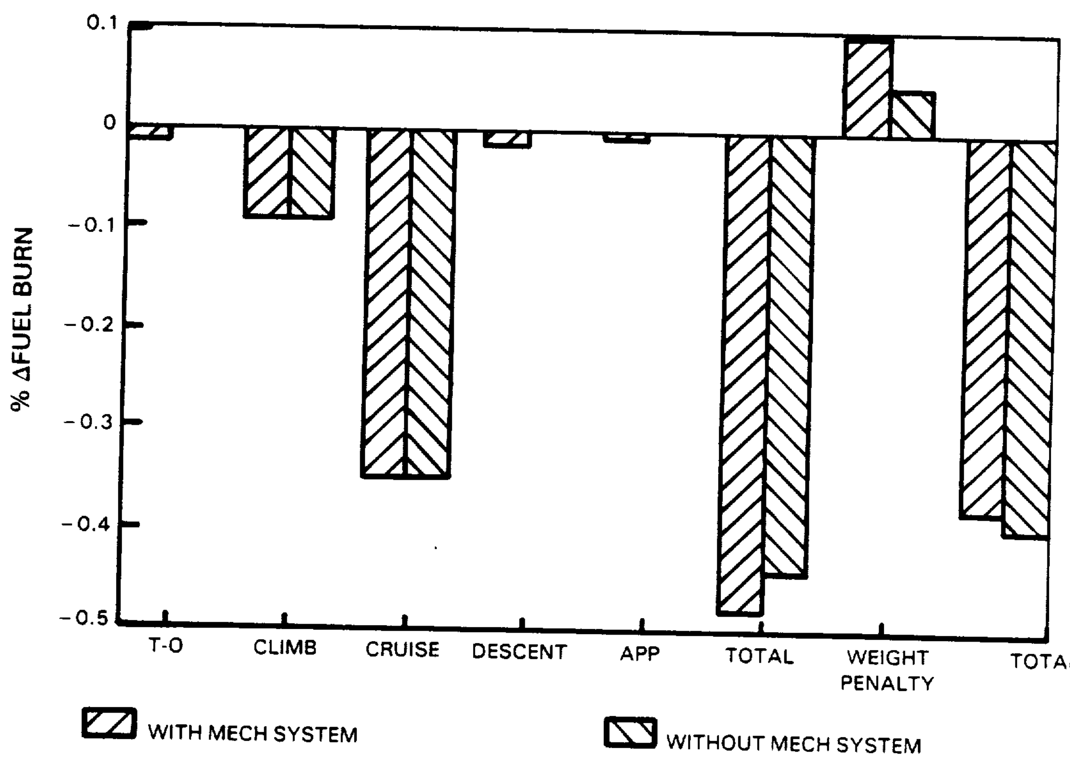


Figure 4.5-10 Closed-Loop ACC System Mission Fuel Burn Benefit; 440 Pax Trijet at 2000 N.M.

Figure 4.5-11 compares the mission fuel burn savings achieved with closed-loop ACC system when either a fluidic or microwave clearance sensor are incorporated in a thermal actuation system. As expected, the heavier weight and performance penalty associated with the fluidic system give the advantage to the microwave sensor in both mission applications.

The final element of the mission analysis was to investigate the benefits of utilizing closed-loop ACC for clearance deterioration recovery. The assumption here was that the sensor would 'sense' clearance increases caused by inadvertent blade tip rubs and continually compensate for these throughout the life cycle of the engine so that the design clearance was maintained. Results of this analysis are summarized in Figure 4.5-12 for a nominal engine life of 4000 cycles before removal for scheduled maintenance. As indicated, significant fuel burn savings can be obtained through deterioration recovery in the high-pressure turbine alone. This form of benefit should also be obtainable in high-pressure compressor and low-pressure turbine applications and may, in fact, be the principle benefit for those applications.

It remains now to work toward verification of these projected benefits. This will require continued sensor and control system development and operational testing, as well as development of a case design criteria to minimize case deflections due to thermal and mechanical loads. This effort was outside the scope of the present study.

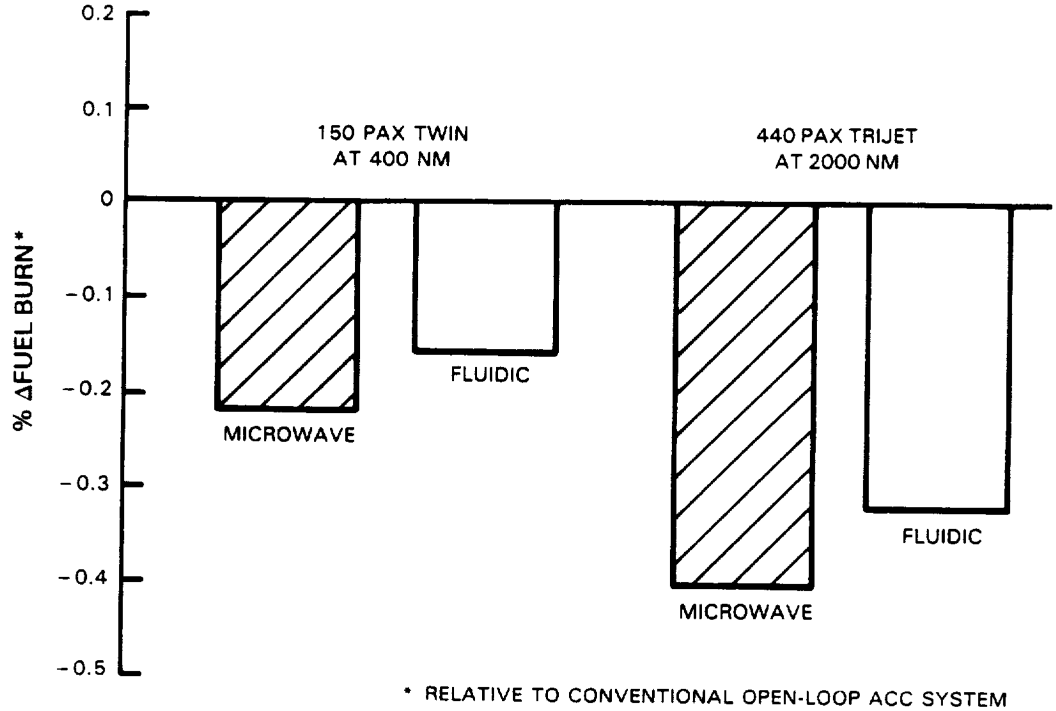


Figure 4.5-11 Energy Efficient Engine ACC Study - Sensor Comparison

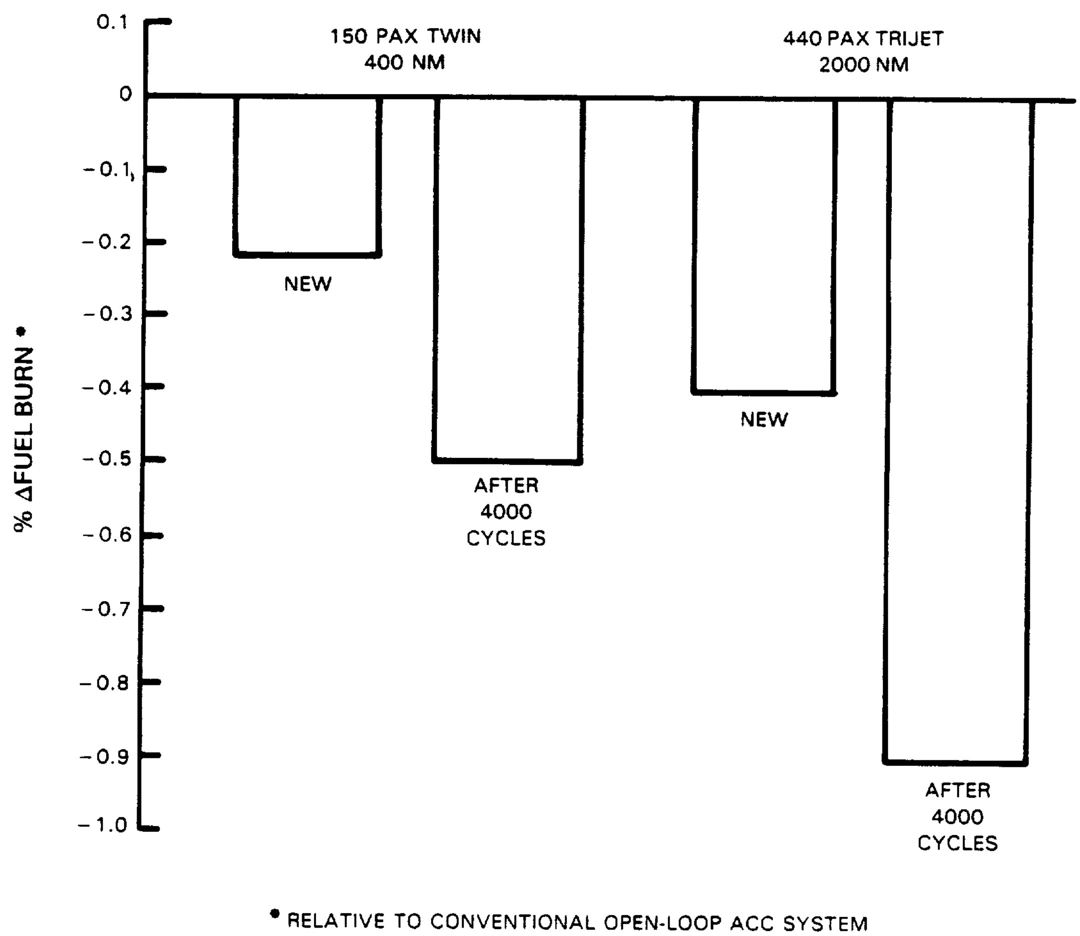


Figure 4.5-12 Energy Efficient Engine ACC Study - Effect of Deterioration Recovery

SECTION 5.0

RECOMMENDED TECHNOLOGY PROGRAMS

Critical advanced control technologies have been identified that will require R&D type programs. These technologies in addition to providing better performance minimize control costs and weight and improve reliability. The necessary programs, including overall system demonstration, are outlined in this section.

5.1 OPTICAL PROXIMITY SENSOR

Objective

Develop the present experimental test optical proximity sensor into a production unit.

Advantages

- o Increased engine performance by maintaining ideal clearance by active clearance control
- o Prevention of performance loss due to seal rub during transients

Approach

- o Develop compact light weight light source to replace present laser
- o Develop fused end type fiber ends to eliminate cooling requirements
- o Develop simplified detector to replace present complex diode array

12 Months

  - o Design of sensor - 6 months
  - o Fabrication and calibration - 6 months
  - o Engine test - 6 months

5.2 OPTICAL PYROMETER

Objective

Develop the present experimental test optical pyrometer into a flight unit. Development would include electronics for signal conditioning but not for data reduction.

Advantages

- o Increased engine life by preventing turbine over-temperature through direct measurement of turbine blade temperature
- o Detect incipient turbine failures resulting from hot spots

Approach

- o Design flight hardware - 6 months
- o Fabricate flight hardware and calibrate - 6 months
- o Endurance testing on engine - 6 months
- o Redesign flight hardware based on above test - 3 months
- o Fabrication and test - 3 months
- o Final testing on engine - 6 months

5.3 GaAs SWITCH DEVELOPMENT

Objective

- o Develop the present experimental high temperature GaAs switch.

Advantages

- o Removes high power dissipating semiconductor switches from control
- o Permits preliminary power regulation to be performed on alternator rather than on inside of control box

Approach

- o Fabrication of test units - 5 months
- o Implementation and evaluation of passivation - 12 months
- o Selection of best passivation technique
- o Fabrication of passivated switches - 7 months
- o Life test passivated switches - 3 months
- o Bench test on control bench test - 6 months
- o Engine test - 6 months

5.4 GaAs PHOTO SWITCH

Objective

- o Develop a high temperature GaAs switch that can be activated by a remote light source.

Advantages

- o Removes large heat dissipating switches from control box, placing them on controlled device.
- o Eliminates EMI problems by using fiber-optic cables instead of electrical lines.

Approach

- o Design and build a hybrid two-stage photo switch - 7 months
- o Test and evaluation of first generation switch - 2 months
- o Design and build second generation hybrid photo diode - 3 months
- o Design and build monolithic chip - 8 months
- o Test and evaluation of hybrid and monolithic chips - 4 months
- o Bench test breadboard control - 6 months
- o Engine test - 6 months

5.5 GaAs DIODE PROTECTION

Objective

- o Develop a high temperature diode.

Advantages

- o Provides switch protection against counter EMF during solenoid disengagement
- o Diode protection can be located on switched device, thereby reducing heat inside control

Approach

- o Design and fabrication of junction - 6 months
- o Design and fabrication of Schottky barrier diodes - 14 months
- o Evaluation of above diodes - 10 months
- o Redesign of best technology - 4 months
- o Final fabrication - 5 months
- o 1000-hour life test - 5 months
- o Bench test on control - 6 months
- o Engine test on dummy load - 6 months

5.6 HIGH TEMPERATURE GaAs RECTIFIER

Objective

- Develop a high temperature rectifier

Advantages

- Increased power supply reliability through development of high temperature rectifiers
- Increased control reliability by mounting rectifiers on alternator, thereby removing heat load from inside electronic control box

Approach

- Design the candidate rectifier types (Schottky barrier junction, abrupt P-N junction, and graded P-N junction) - 7 months
- Fabricate above diodes - 5 months
- Mount and test - 6 months
- Burn-in and evaluate - 6 months
- Test on engine - 6 months

5.7 VARIABLE SPEED DRIVE FOR FIXED DISPLACEMENT FUEL PUMP

Objective

- Develop a variable speed pump drive that is lightweight, reliable, and efficient (low temperature rise in both fuel and transmission).

Advantages

- Reduces fuel temperature rise because pump speed is matched to fuel demand
- Reduces control hardware because metering would be performed by pump rather than with separate metering and bypass valves.

Approach

- Design and test breadboard hardware, consisting of J-85 engine pump and F100 fuel pump clutch - 6 months
- Test above with electrohydraulic interface for dynamic response - 6 months
- Design and fabricate barstock pump; this portion of program would be effected only if there is a commitment to a production engine - 12 months

5.8 SHEDDING VORTEX FLOW METER

Objective

Develop a vortex flow meter compatable with the high response rates necessary for minor loop fuel flow control.

Advantages

- o No moving parts
- o Frequency output compatable with digital electronics
- o High level of accuracy
- o High frequency device for fast response

Approach

- o Vortex generator profile development - 4 months
- o Prototype flow meter design - 5 months
- o Fabrication - 2 months
- o Performance evaluation - 3 months
- o Contamination testing - 4 months
- o Bench test under simulated engine conditions - 6 months
- o Engine testing - 6 months

5.9 SOLID STATE PRESSURE TRANSDUCERS

Objective

- o Develop of Surface Acoustic Wave Sensor into a production unit

Advantages

- o Increases accuracy over present sensors (0.1%)
- o Increases response
- o Reduced size, weight, and production cost
- o Frequency output is digitally compatible
- o Increased reliability (10,000 hr MTBF goal)
- o Low power consumption

Approach

- o High-Q oscillator structure development - 7 months
- o Hybrid circuit development - 10 months
- o All quartz design, fabrication, and test - 12 months
- o Test SAW oscillators hybrid electronics package - 8 months
- o Evaluate sensors - 4 months
- o Test sensors on control bench test - 6 months
- o Test sensors on engine - 6 months

5.10 OPTICAL DISPLACEMENT ENCODER

Objective

Develop the present optical displacement encoder into a flightworthy production unit.

Advantages

- o Position output is direct digital word
- o Operates in high temperature environment
- o Low cost in production
- o Low interface cost
- o Can be easily multiplexed

Approach

- o Design third generation breadboard
- o Fabricate breadboard - 6 months
- o Test
- o Design barstock unit
- o Fabricate barstock unit - 6 months
- o Test unit
- o Bench test unit under simulated engine conditions - 6 months
- o Engine mounted test (passive) - 6 months

5.11 PIEZOELECTRIC JET PIPE EFFECTOR

Objective

Develop a piezoelectric jet pipe effector to replace present day torque motor.

Advantages

- o Increases reliability by replacing the numerous forms of fine gauge wire in a torque motor with the infinite number of parallel paths of the piezoelectric element
- o Reduced weight
- o Low current draw
- o Reduced production cost (relative to torque motor)
- o Digitally compatable

Approach

- o Design unit - 7 months
- o Fabrication - 4 months
- o Evaluate performance - 3 months
- o Endurance testing - 6 months
- o Bench testing under simulated engine conditions - 6 months
- o Engine mounting while operating into dummy load - 6 months

5.12 AIR COOLING

Objective

- o Development of techniques for air cooling electronic package

Advantages

- o Eliminates fire hazard associated with fuel cooling
- o Reduces weight by eliminating fire bulkheads, double-walled tubing, struts, etc. necessitated by running fuel cooling lines to the control

Approach

- o Analytical study of prospective cooling schemes - 6 months
- o Design electronic control box - 6 months
- o Fabricate box - 3 months
- o Test (bench) - 6 months
- o Engine test - 6 months

5.13 FIBER OPTIC CABLING

Objective

- o Develop low cost durable fiber optic cabling and connectors

Advantage

- o Reduces cost and weight because present systems frequently result in overkill
- o Increases reliability by reducing fiber breakage

Approach

- o Survey fiber optic cable suppliers for hardware that will satisfy engine requirements - 6 months
- o Test cables and connectors - 6 months
- o Develop new designs based on above test - 12 months

5.14 ENERGY EFFICIENT ENGINE TECHNOLOGY DEMONSTRATION

Objective

- o To coordinate and demonstrate advanced elements of the Energy Efficient Engine control system.

Advantages

- o Demonstrate new technology elements
- o Demonstrate overall concept on engine test

Approach

- o Design and analytical effort (includes software) - 12 months
- o Fabricate breadboard unit - 12 months
- o Closed loop bench test - 6 months
- o Engine test - 12 months

5.15 SAFETY FUELS

For a number of years, the aircraft industry has been interested in the use of safety fuels for improved fire safety in the event of crash. These safety fuels, by reducing fuel misting when fuel tanks or fuel lines break, reduce the possibility of explosion and fire. Although safety fuels were not considered in the Energy Efficient Engine study, R&D programs are recommended for determining the suitability and practicability of safety fuels for turbine engines and fuel systems. Some suggested program areas for control systems are:

- o Determine optimum fuel injection method
- o Heat transfer characteristics for engine-mounted heat exchangers
- o Design modifications required to maintain fuel system performance equivalent to that attained with present day fuels
- o Long-term effects of safety fuels on fuel system components
- o Fuel system revisions required to maintain engine starting, performance, and altitude relight capability.

REFERENCE

1. Gray, D. E. and Gardner, W. B., "Energy Efficient Engine Program - Technology Benefit/Cost Study", NASA CR-174766, October 1983.

2. Gardner, W. B., et al, "Energy Efficient Engine - Flight Propulsion System Preliminary Analysis and Design Report", NASA CR-159487, April, 1979.

APPENDIX A

ABBREVIATIONS

APPENDIX A
ABBREVIATIONS

ACC	Active clearance control
A/D	Analog to digital
ARINC	Aeronautical Radio Incorporated (standard format for serial data channel)
CCD	Change coupled device
C-MOS	Complementry metal oxide simiconductor
CPU	Central processing unit
D/A	Digital to analog
D-MOS	Diffused metal oxide semiconductor
DOI	Digital oxide interface
EA-ROM	Electrically alterable read only memory
EEC	Electronic engine control
EGT	Exhaust gas temperature
EMI	Electromagnetic interface
F/B	Feedback
GaAs	Gallium arsenide
GEODE	Generalized electro-optic displacement encoder
H.P.	High pressure
IGV	Inlet guide vane
I^2L	Integrated interjection logic
I/O	Input/output
JFET	Junction field effect transistor
LED	Light emitting diode
L.P.	Low pressure

ABBREVIATIONS (Cont'd.)

LSI	Large scale integration
LVDT	Linear voltage differential transformer
MOS	Metal oxide semiconductor
MSI	Medium scale integration
MTBF	Mean time between failures
MTBUR	Mean time between unscheduled removal
N_H	High rotor speed in RPM
N_L	Low rotor speed in RPM
N-MOS	Negative metal oxide semiconductor
P	Total pressure
P_2, P_2'	Pressures within fluidic clearance sensor
ΔP	Difference between P_2 and P_2'
PLA	Power lever angle
P-MOS	Positive metal oxide semiconductor
P-ROM	Programable read only memory
Ps	Pressure, static
RAM	Random access memory
ROM	Read only memory
SAW	Surface acoustic wave
S/C	Signal conditioning
SLS	Sea level static
SOS/C-MOS	Silicon on saphire complementry metal oxide semiconductor
SS	Steady state
SSI	Small scale integration

ABBREVIATIONS (Cont'd.)

SVA	Stator vane angle
T	Total pressure
TBT	To be determined
TBO	Time between overhaul
$TE^{\circ}_{011}(Al_2O_3)$	Dielectric Aluminum Oxide Packed Powder Filler
Ts	Temperature, static
TTL also T^2L	Transistor-transistor logic (also called bi-polor)
UV-ROM	Ultra violet read only memory
VLSI	Very large scale integration
V-MOS	"V" metal oxide semiconductor
W-FEP	Pilot fuel flow

APPENDIX B

LOGIC DIAGRAMS

APPENDIX B

LOGIC DIAGRAMS

Appendix B contains logic diagrams and the weighted scores for each selected component. Most of the matricies were derived by one of the three vendors. Where both Bendix and Hamilton Standard Division considered the same component but computed different scores, both matrices are presented with the second or alternate being designated (A).

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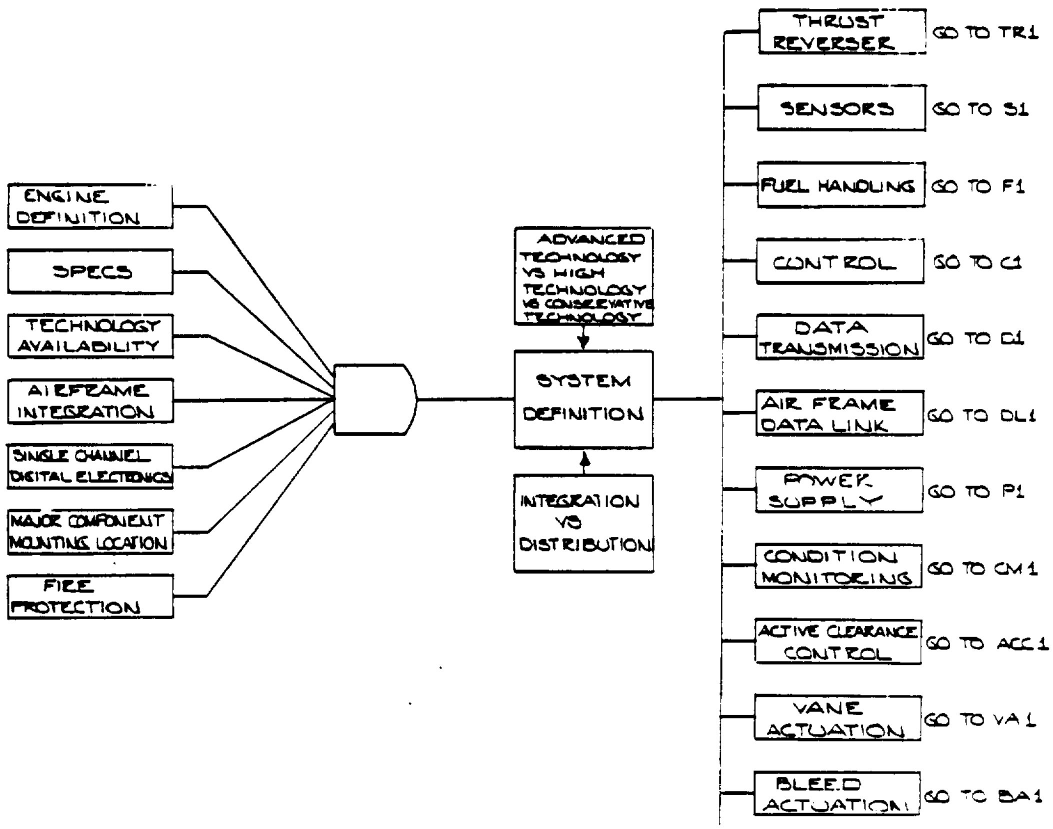

Figure B-1 Control System Decision Logic Diagram

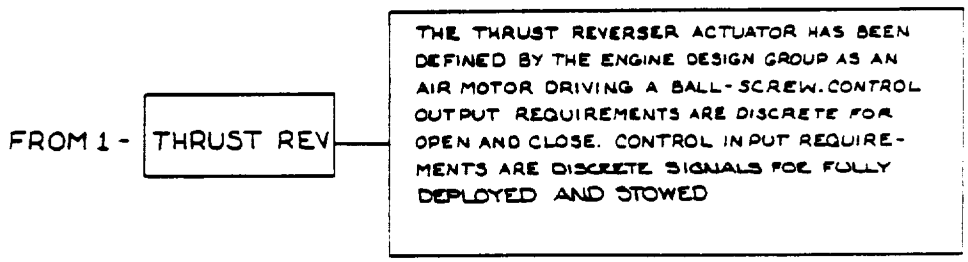

Figure B-2 Control System Decision Logic Diagram TR1

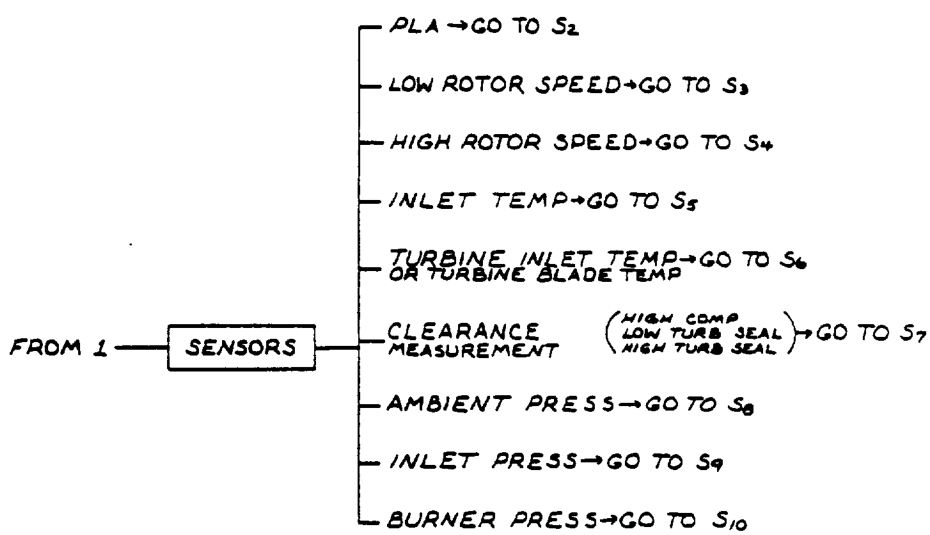

Figure B-3 Control System Decision Logic Diagram S1

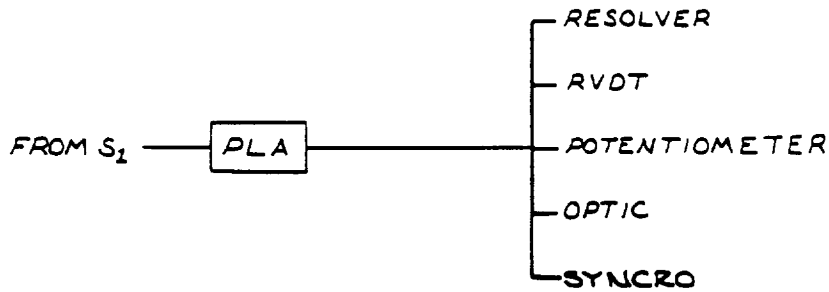

Figure B-4 Control System Decision Logic Diagram S2

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
RESOLVER	6	6	8	4	4	4			32
RVDT	6	6	2	4	2	4			24
POTENTIOMETER	8	8	2	2	4	4			28
OPTICAL ENCODER	8	6	8	4	8	3			37
SYNCRO	6	6	8	4	2	4			30

Figure B-5 Decision Matrix for S2 (PLA Sensor)

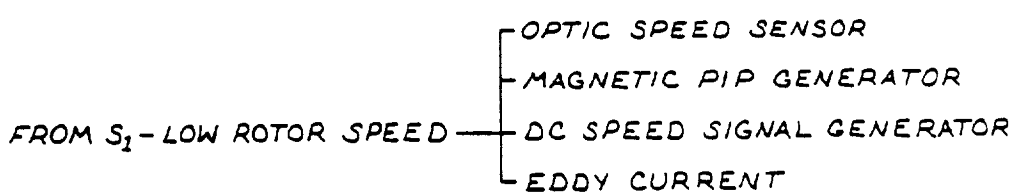

Figure B-6 Control System Decision Logic Diagram S3

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
OPTIC SPEED SENSOR	4	6	6	3	6	3			28
MAGNETIC PIP GENERATOR	4	4	4	4	6	4			26
DC SIGNAL GENERATOR	ELIMINATED-NOISE AND ACCURACY								
EDDY CURRENT	4	4	4	4	6	4			26

Figure B-7 Decision Matrix for S3 (Low Rotor Speed Sensor)

FROM S_1-HIGH ROTOR SPEED —

- OPTIC SPEED
- MAGNETIC PIP GENERATOR
- DC SPEED SIGNAL GENERATOR
- EDDY CURRENT
- COUNT FROM OPTIC PROXIMITY PROBE
- COUNT FROM OPTICAL PYROMETER
- COUNT FROM ALTERNATOR

Figure B-8 Control System Decision Logic Diagram S4

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
OPTIC SPEED SENSOR	4	6	6	3	6	3			28
MAGNETIC PIP GENERATOR	4	4	4	4	6	4			26
DC SPEED SIGNAL GENERATOR	ELIMINATED-NOISE AND ACCURACY								
EDDY CURRENT	4	4	4	4	6	4			26
COUNT FROM OPTIC PROX. PROBE	NOT CONSIDERED								
COUNT FROM OPTICAL PYROMETER	ELIMINATED-NOT ACCURATE AT LOW TEMP.								
COUNT FROM ALTERNATOR	8	8	8	4	6	4			38

Figure B-9 Decision Matrix for S4 (High Rotor Speed Sensor)

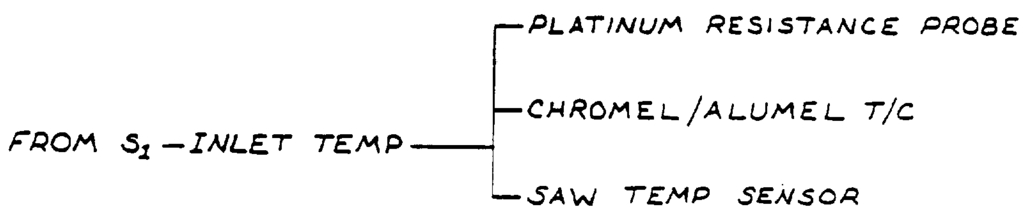

Figure B-10 Control System Decision Logic Diagram S5

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
PLATINUM RESISTANCE PROBE	6	6	6	4	4	4			30
C/A THERMOCOUPLE	4	6	6	4	2	4			26
SAW TEMP. SENSOR	6	6	6	4	6	2			30

Figure B-11 Decision Matrix for S5 (Inlet Temperature)

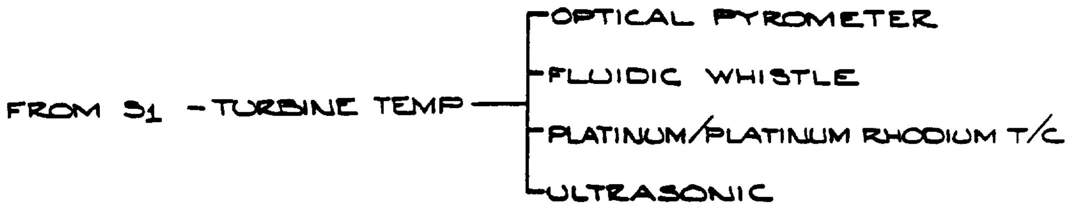

Figure B-12 Control System Decision Logic Diagram S6

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
OPTICAL PYROMETER	4	6	4	3	2	3			22
FLUIDIC WHISTLE	ELIMINATED - ACCURACY								
PLATINUM/PLATINUM RHODIUM T/C	2	2	4	1	2	2			13
ULTRASONIC	ELIMINATED								

Figure B-13 Decision Matrix for S6 (Turbine Temperature)

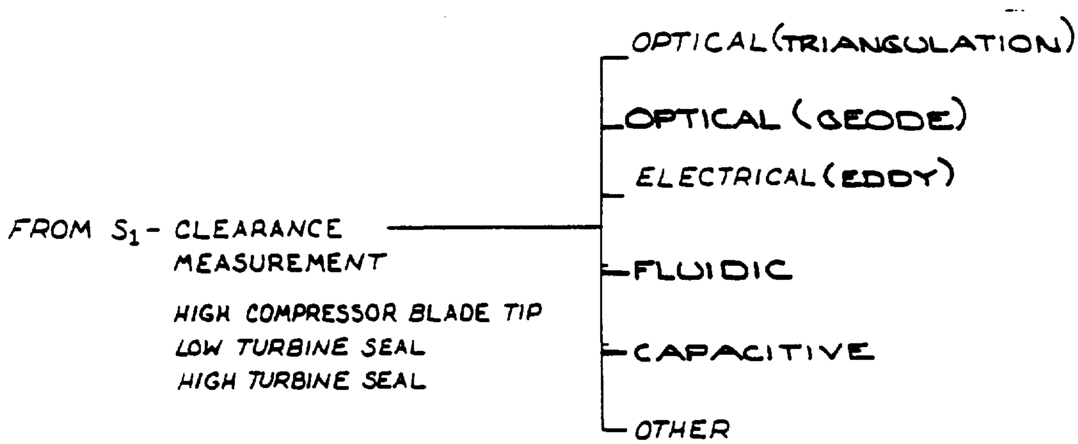

Figure B-14 Control System Decision Logic Diagram S7

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	ACCURACY		TOTAL
TRIANGULATING OPTIC	4	8	1.5	2	4	4	3	3	6		35.5
CAPACITANCE ELECTRICAL	8	8	.5	1	3	1	1	1	3		26.5
FLUIDIC	8	8	.5	2	1	1	4	4	0		28.5
EDDY CURRENT ELECTRICAL	8	8	0	3	2	1	0	0	1.5		23.5
GENERALIZED ELECTRO-OPTIC DISTANCE ENCODER (GEODE)	6	8	1.5	2	4	0	3	3	1.5		29

Figure B-15 Decision Matrix for S7 (Proximity Sensor)

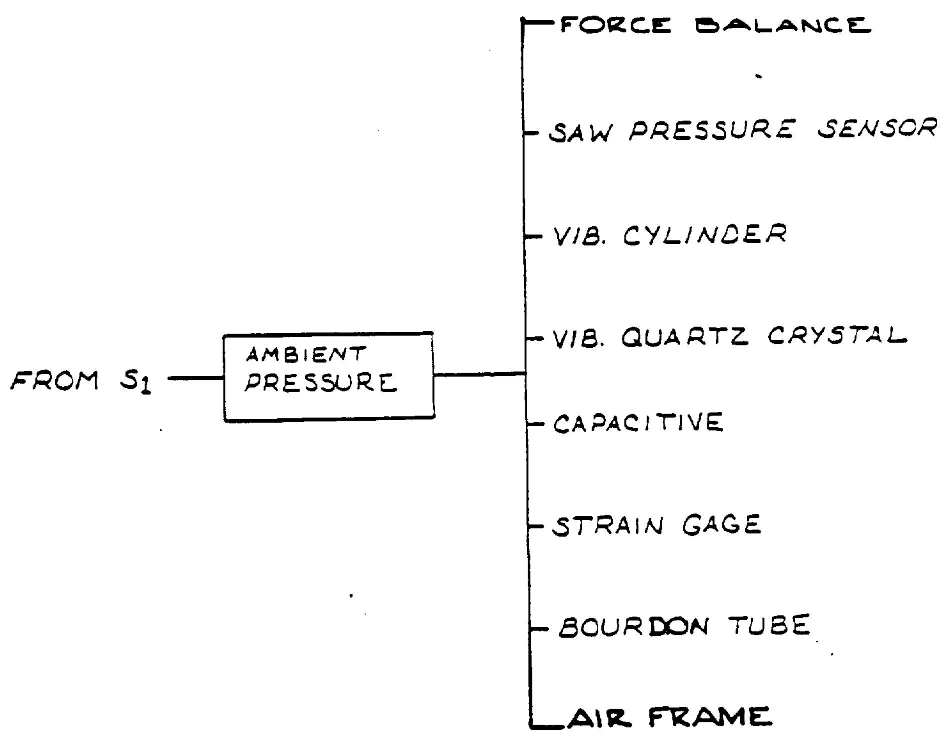

Figure B-16 Control System Decision Logic Diagram S8

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SAW PRESSURE	8	6	6	4	4	3			31
VIBRATING CYLINDER	6	4	6	4	4	4			28
VIBRATING QUARTZ XTAL	2	4	6	4	4	4			24
CAPACITIVE	ELIMINATED - ACCURACY								
STRAIN GAGE	ELIMINATED - ACCURACY								
BOURDON TUBE	ELIMINATED - ACCURACY								
FORCE BALANCE	4	2	2	4	2	4			18
FROM AIR FRAME	NOT COVERED UNDER GROUND RULES								

Figure B-17 Decision Matrix for S8 (Ambient Pressure Transducer)

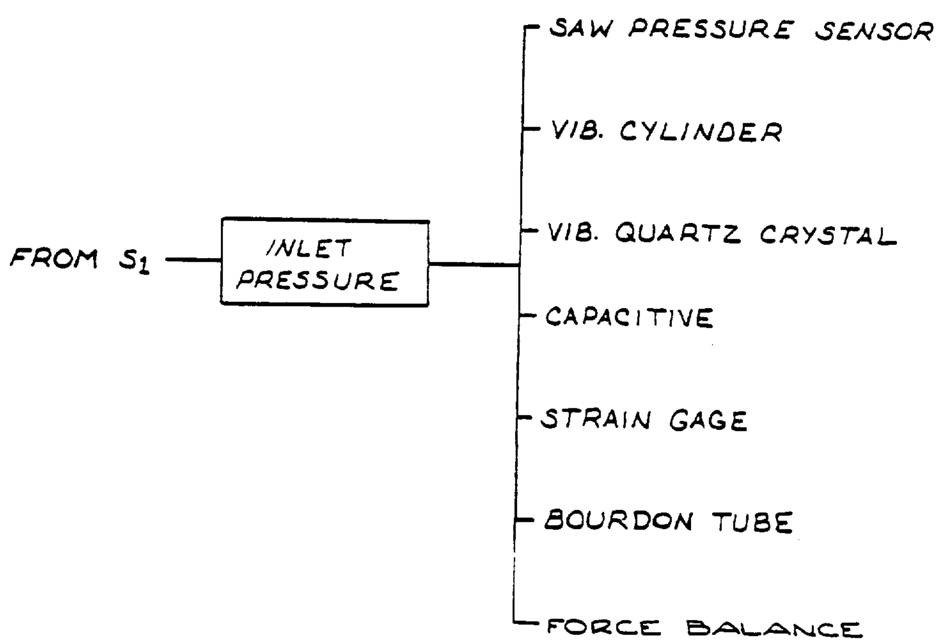

Figure B-18 Control System Decision Logic Diagram S9

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SAW PRESSURE X DUCER	8	6	6	4	4	3			31
VIBRATING CYLINDER	6	4	6	4	4	4			28
VIBRATING QUARTZ XTAL	2	4	6	4	4	4			24
CAPACITIVE	ELIMINATED - ACCURACY								
STRAIN GAGE	ELIMINATED - ACCURACY								
BOURDON TUBE	ELIMINATED - ACCURACY								
FORCE BALANCE	4	2	2	4	2	4			18

Figure B-19 Decision Matrix for S9 (Inlet Pressure Sensor)

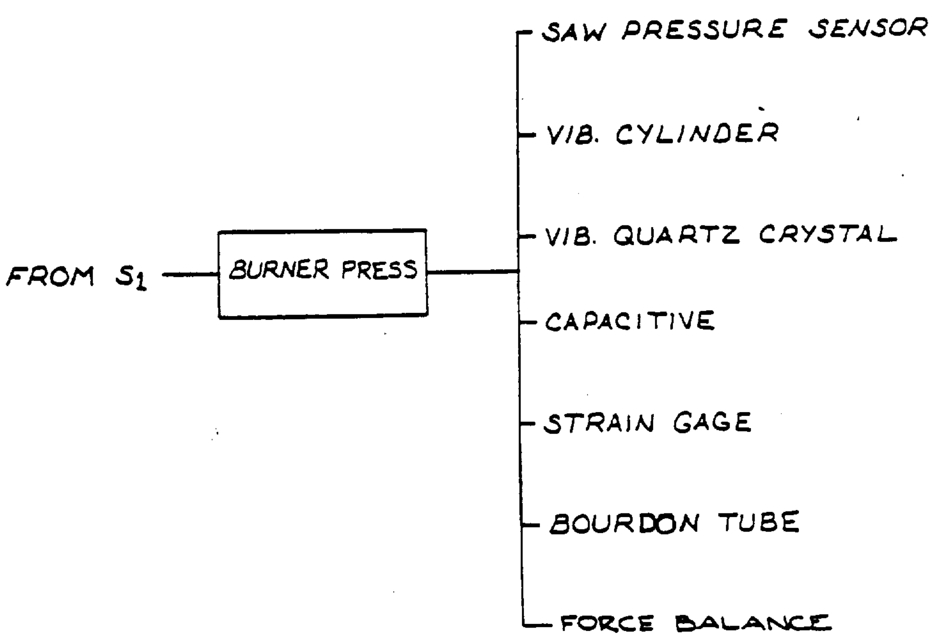

Figure B-20 Control System Decision Logic Diagram S10

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SAW PRESSURE X DUCER	8	6	6	4	4	3			31
VIBRATING CYLINDER	6	4	6	4	4	4			28
VIBRATING QUARTZ XTAL	2	4	6	4	4	4			24
CAPACITIVE	ELIMINATED - ACCURACY								
STRAIN GAGE	ELIMINATED - ACCURACY								
BOURDON TUBE	ELIMINATED - ACCURACY								
FORCE BALANCE	4	2	2	4	2	4			18

Figure B-21 Decision Matrix for S10 (Burner Pressure Sensor)

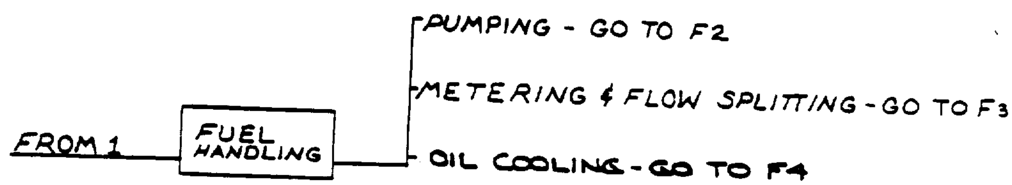

Figure B-22 Control System Decision Logic Diagram F1

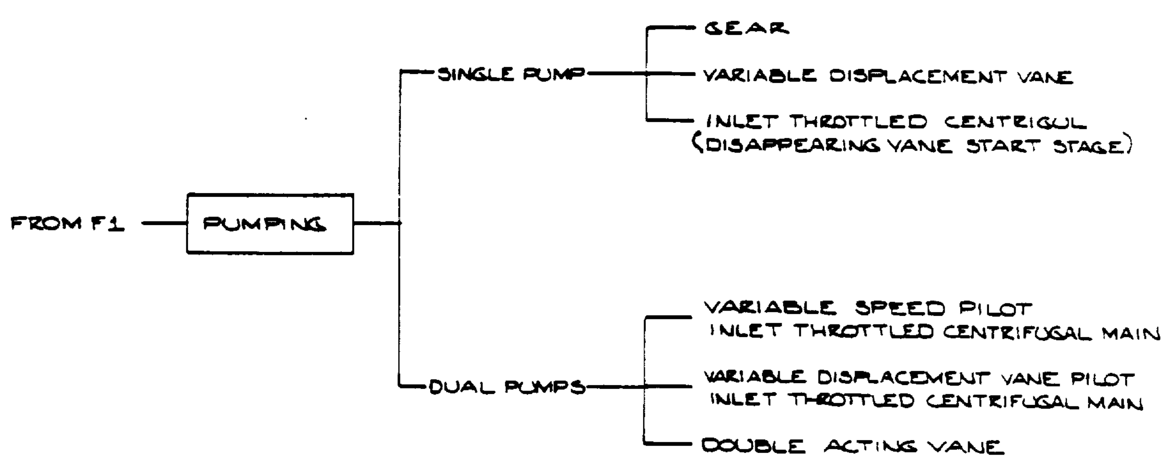

Figure B-23 Control System Decision Logic Diagram F2

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		COST	WEIGHT	RELIABILITY	MAINTAINABILITY (MOUNTING)	SIZE	TIME BETWEEN OVERHAULS	TEMPERATURE RISE	EFFECT ON CONTROL	TOTAL
SINGLE PUMPS	GEAR	2.0	.81	1.89	.50	.21	.50	.32	.25	6.48
SINGLE PUMPS	VARIABLE DISPLACEMENT VANE	.48	1.0	1.67	.50	.30	.20	.62	.50	5.27
SINGLE PUMPS	VAPOR CORE WITH STARTING VANES	1.38	2.38	1.82	.50	.61	.20	1.06	.50	8.45
	VARIABLE SPEED GEAR CENTRIFUGAL MAIN	1.38	2.0	2.0	.25	.50	.20	2.0	.50	8.83
	VARIABLE DISPLACEMENT VANE CENTRIFUGAL MAIN	.63	1.80	1.67	.25	.33	.20	1.80	.50	7.18
	DOUBLE ACTING VANE	.43	1.6	1.4	.50	.23	.20	1.06	.50	5.92

Figure B-24 Decision Matrix for F2 (Pumping)

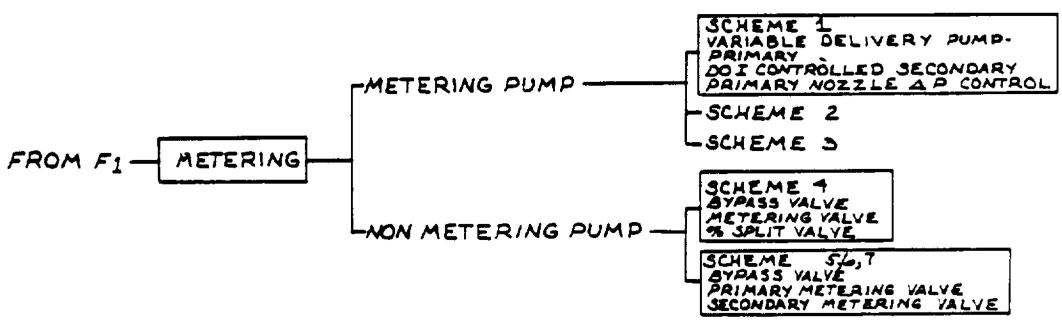


Figure B-25 Control System Logic Diagram F3 - Seven schemes for metering fuel flow were initially considered, as shown in Figures B-25c to B25h. The final pumping schemes evolved from overall system studies and are shown in Figure B-25a.

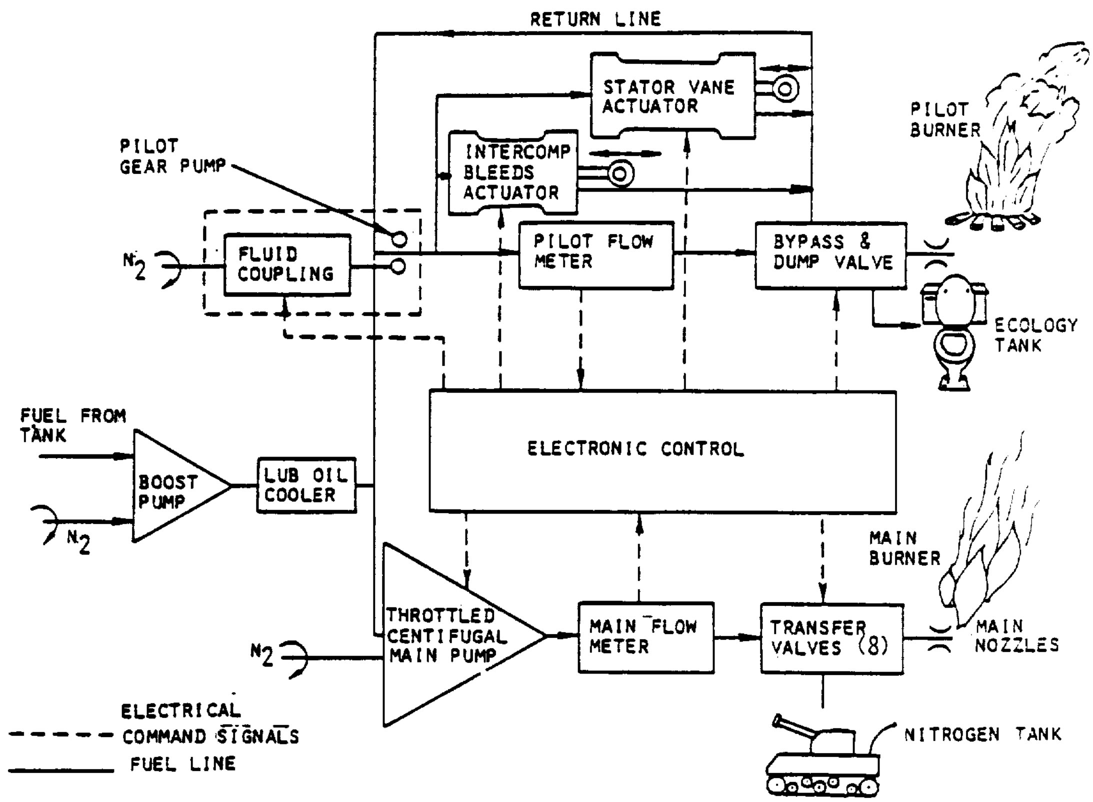
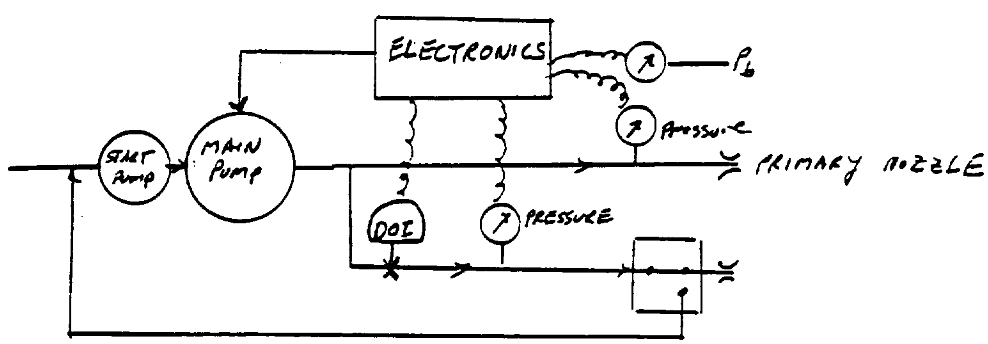


Figure B-25a Final Pumping Schemes Evolved From Overall System Studies



- FUEL FLOW METERED BY CONTROLLING NOZZLE ΔP
- ASSUME PRIMARY MANIFOLD PRESSURE ALWAYS > SECONDARY MANIFOLD
- RECIRCULATION FLOW USED TO BYPASS EXCESS START FLOW

Figure B-25b Scheme 1 for Metering Fuel Flow

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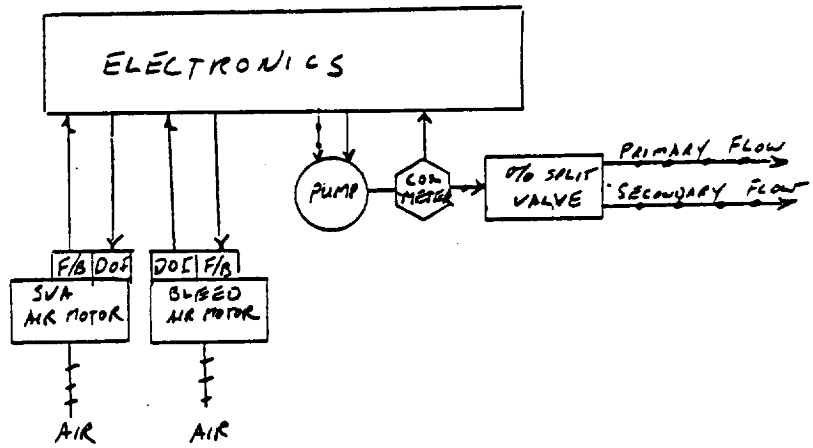
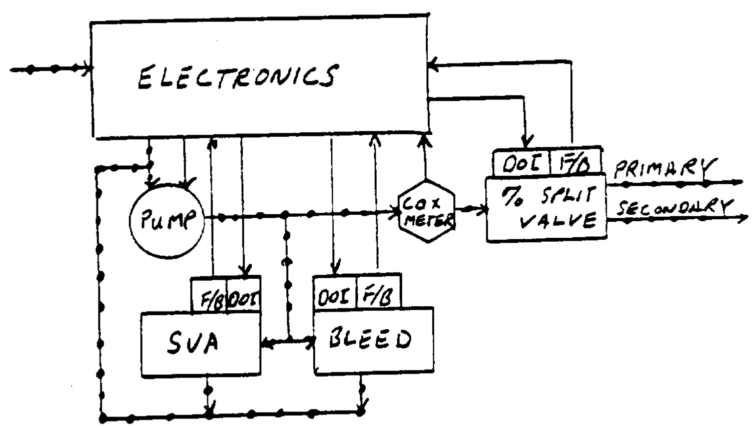


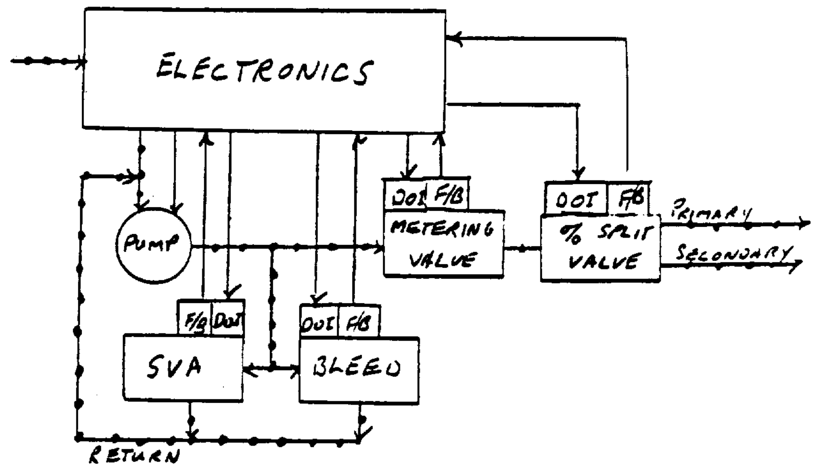
- PUMP USED FOR METERING
- COX METER USED FOR ACCEL/DECEL & LIMITING
- SECONDARY COOLING FLOW WILL AFFECT ACCEL/DECEL SCHEDULE

Figure B-25c Scheme 2 for Metering Fuel Flow



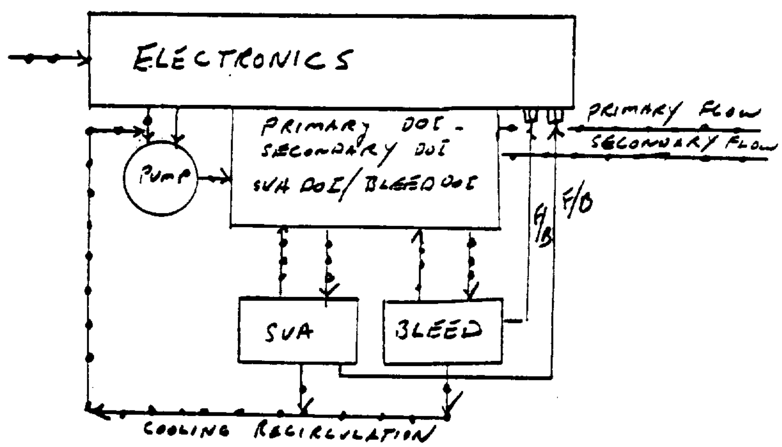
- PUMP METERS FLOW — NO METERING VALVE USED
- SVA & BLEED ACTUATION CAN CAUSE FUEL FLOW TRANSIENT
- COX METER USED ONLY FOR ACCEL/DECEL & LIMITING FUEL FLOW

Figure B-25d Scheme 3 for Metering Fuel Flow



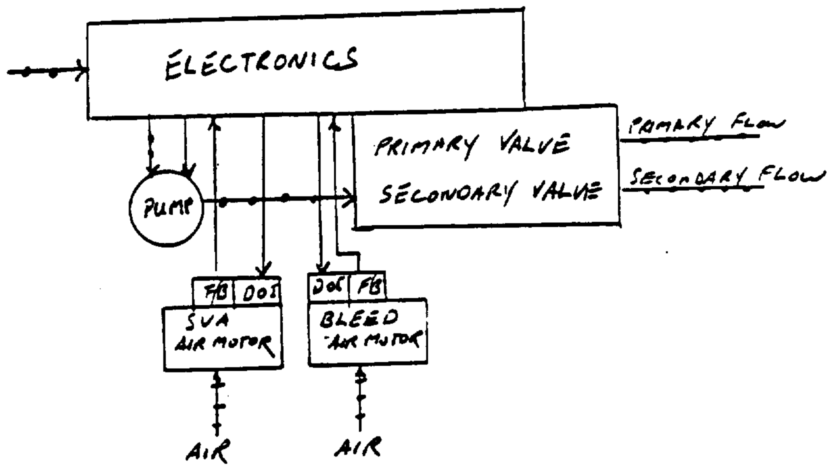
- PUMP NOT USED FOR METERING
- DISTRIBUTED SYSTEM SVA & BLEED CONTROL LOCATED ON ACTUATOR
- REQUIRES SEPERATE METERING FOR SECONDARY COOLING

Figure B-25e   Scheme 4 for Metering Fuel Flow



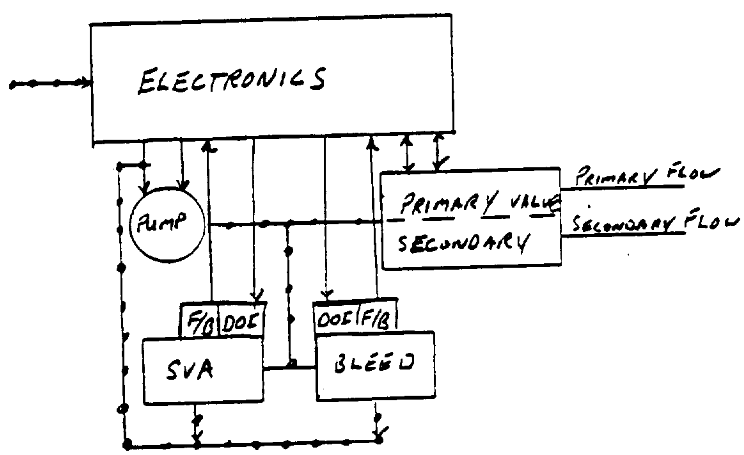
- SVA & BLEED CONTROL LOCATED ON FLOW BODY
- REQUIRES ACTUATOR COOLING LINE
- PUMP DOES NOT METER FLOW

Figure B-25f   Scheme 5 for Metering Fuel Flow



- PUMP NOT USED FOR METERING
- PROVIDES SECONDARY COOLING FLOW

Figure B-25g   Scheme 6 for Metering Fuel Flow



- DISTRIBUTED SYSTEM
- SVA & BLEED CONTROL LOCATED ON ACTUATOR
- ELECTRONICS MAY BE LOCATED ON FLOW BODY
- PUMP DOES NOT METER FLOW
- COULD PROVIDE UNMETERED FLOW FOR SECONDARY COOLING

Figure B-25h   Scheme 7 for Metering Fuel Flow

Figure B-26 Control System Decision Logic Diagram F4

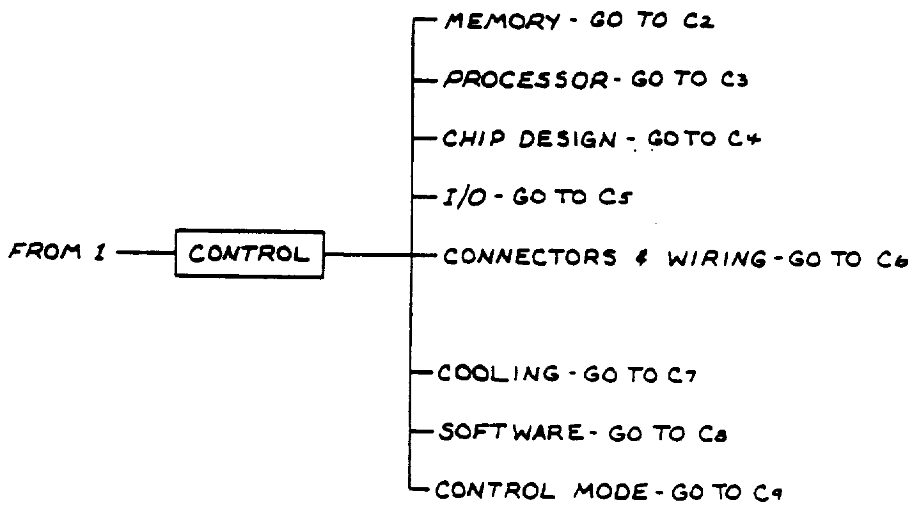


Figure B-27 Control System Decision Logic Diagram C1

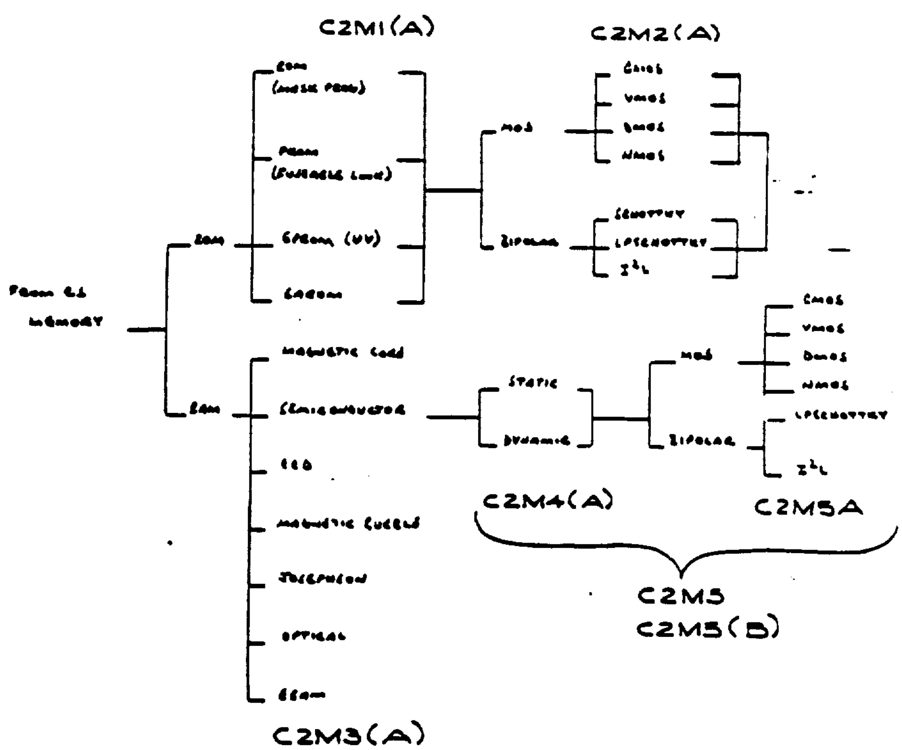


Figure B-28 Control System Decision Logic Diagram C2

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
ROM (MASK PROG)	2	6	3	2	2	2	2	3	4	4	2		32
PROM (FUSE LINK)	4	6	3	2	2	2	2	3	1	4	2		31
E PROM (UV)	6	6	3	2	2	2	1.5	3	4	4	4		37.5
EAROM	6	6	3	2	2	2	1.5	3	4	4	4		37.5

Figure B-29 C2M1M ROM Memory Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
ROM (MASK PROGRAM)	8	8	8	4	4	4			36
PROM (FUSE LINK)	8	6	8	4	8	4			38
EAROM	2	4	4	3	2	3			18
UVROM	4	4	4	3	6	2			23

Figure B-30 C2M1(A) ROM Memory Processor Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
CMOS	6	8	3	2	2	2	1.5	3	4	4	4		39.5
VMOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
D MOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
N MOS	8	8	3	2	2	2	1.5	3	4	4	3		40.5
SCHOTTKY	2	8	4	2	2	2	2	3	2	4	2		33
LPSCHOTTKY	6	8	4	2	2	2	2	3	3	4	3		39
I^2L	6	8	4	2	2	2	2	3	4	4	4		41

Figure B-31 C2M2 ROM Memory Processor Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
BI POLAR T^2L	2	2	4	4	2	4			18
L.P. SHOTTKY	4	4	4	3	4	4			23
I^2L	2	8	8	4	6	2			30
C-MOS	8	6	8	4	8	4			38
P-MOS	8	6	6	4	6	4			34
N-MOS	8	8	8	4	6	4			38

Figure B-32 C2M2(A) RAM Processor Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
MAGNETIC CORE	4	2	1	1.5	1	2	.5	1	2	1	1		17
SEMICONDUCTOR	8	8	4	1.5	2	2	1.5	3	4	4	4		42
CCD	4	8	4	1.5	2	2	1.5	3	4	1	4		35
MAGNETIC BUBBLE	6	8	4	1.5	2	2	1.5	3	4	1	4		37
JOSEPHSON *	2	2	4	1.5	2	1	.5	3	4	4	4		28
OPTICAL *	2	2	1	.5	1	2	.5	1	1	1	1		13
EBAM *	2	2	1	.5	1	2	.5	1	1	1	1		13

* NOT PRACTICAL FOR E3 APPLICATION

Figure B-33 C2M3 RAM Memory Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
STATIC C-MOS (NON REFRESHED)	8	6	8	4	8	4			38
STATIC N-MOS	8	8	8	4	6	4			38
STATIC T^2L BI POLAR	8	2	4	4	2	4			24
CHARGE COUPLED DEVICE	4	8	2	3	4	2			23
EAROM	4	4	4	4	6	3			25

Figure B-34 C2M3(A) RAM Memory Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY		SPEED	POWER		TOTAL
STATIC	8	8	4	2	2	2	2	4		4	4		40
DYNAMIC	8	8	3	1.5	1.5	2	2	4		4	4		38

Figure B-35 C2M4 RAM Memory Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
CMOS	6	8	3	2	2	2	1.5	3	4	4	4		39.5
V MOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
D MOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
NMOS	8	8	3	2	2	2	2	3	4	4	3		41
LPSCHOTTKY	6	8	4	2	2	2	2	3	3	4	2		38
I^2L	6	8	4	2	2	2	2	3	4	4	3		40

Figure B-36 C2M5 Static RAM Processor Matrix

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	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	AVAILABILITY	SPEED	POWER		TOTAL
VMOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
DMOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
NMOS	8	8	2	2	2	2	1.5	3	2	4	3		37.5

Figure B-37 C2M5 Dynamic RAM Matrix

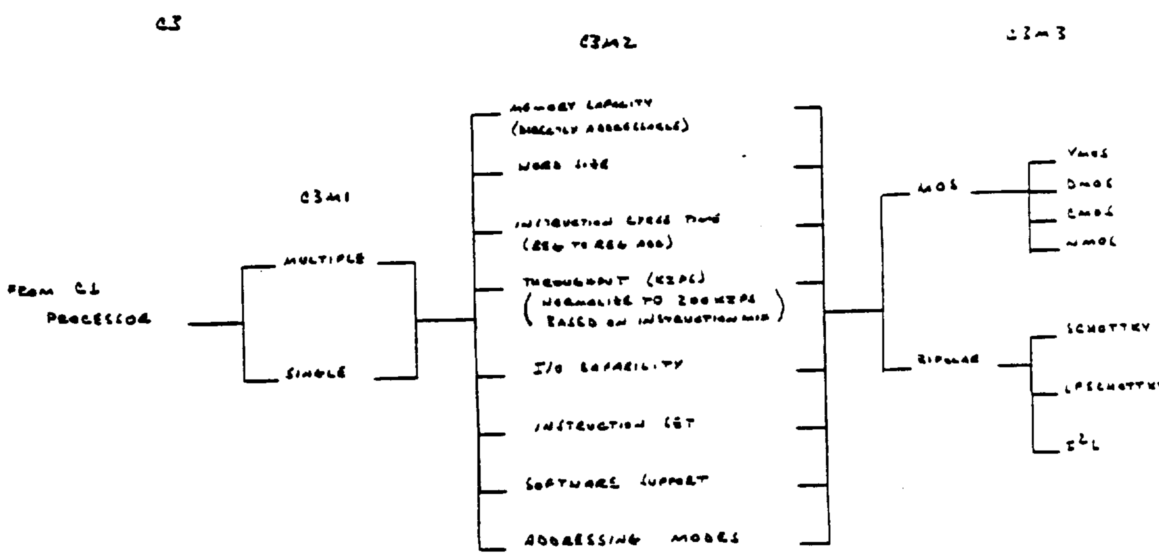


Figure B-38 Control System Decision Logic Diagram C3

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
SINGLE	8	8	3	1.5	2	2	2	4		4	4		38.5
MULTIPLE	8	6	4	1	2	2	2	4		4	3		36

Figure B-39 C3M1 Number of Processors Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
MICROPROGRAMMABLE	4	4	4	4	6	3			25
FIXED INSTRUCTION	6	6	6	3	6	4			31

Figure B-40 C3M1(A) Microprocessor Architecture Matrix

[redacted]

THESE TRADE OFFS TO BE DONE DURING DETAILED ANALYSIS WHEN REQUIREMENTS ARE MORE FULLY DEFINED.

Figure B-41 C3M2 Tradeoffs

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	AVAILABILITY	SPEED	POWER		TOTAL
C MOS	6	8	3	2	2	2	1.5	3	4	4	4		37.5
VMOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
DMOS	4	8	2	2	2	2	1.5	3	1	4	3		32.5
NMOS	8	8	3	2	2	2	1.5	3	4	4	3		40.5
SCHOTTKY	2	8	4	2	2	2	2	3	2	4	1		32
LPSCHOTTKY	6	8	4	2	2	2	2	3	3	4	2		38
I^2L	6	8	4	2	2	2	2	3	4	4	3		40

Figure B-42 C3M3 Microprocessor Technology Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SOS CMOS	8	8	6	4	8	4			38
LSI CMOS	8	6	6	4	8	4			36
N CHANNEL MOS	8	8	8	4	6	4			38
L.P. SCHOTTKY	4	4	4	3	6	4			25
I^2L	2	6	6	4	6	2			26
BI POLAR T^2L	2	2	6	4	2	4			20

Figure B-43 C3M3(A) Microprocessor Technology Matrix

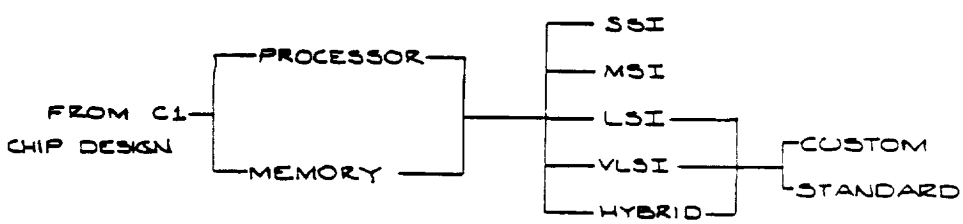


Figure B-44 Control System Decision Logic Diagram C4

		Cost	Weight	Reliability	Maintainability	Electronic Compatibility	Technology Readiness	Environmental Compatibility	Durability		Speed	Power		Total
	SSI	2	2	2	1.5	1.5	2	1.5	3		2	2		19.5
	MSI	2	2	2	1.5	1.5	2	1.5	3		2	2		19.5
STANDARD	LSI	6	6	3	1.5	1.5	2	1.5	3		2	3		29.5
	VLSI	8	8	2	1.5	1.5	2	1.5	3		2	3		32.5
	HYBRID	2	2	1	1	1.5	1	.5	2		2	3		16
CUSTOM	LSI	2	6	2	1	1.5	1.5	1.5	3		2	3		23.5
	VLSI	2	8	2	1	1.5	1.5	1.5	3		2	3		25.5
	HYBRID	2	2	1	1	1.5	1	.5	2		2	3		16

Figure B-45 C4M1 Processor Chip Design Matrix

		Cost	Weight	Reliability	Maintainability	Electronic Compatibility	Technology Readiness	Environmental Compatibility	Durability		Speed	Power		Total
	SSI	2	2	2	1.5	1.5	2	1.5	3		2	2		19.5
	MSI	2	2	2	1.5	1.5	2	1.5	3		2	2		19.5
STANDARD	LSI	6	6	3	1.5	1.5	2	1.5	3		2	3		29.5
	VLSI	8	8	2	1.5	1.5	2	1.5	3		2	3		32.5
	HYBRID	2	2	1	1	1.5	1	.5	2		2	3		16
CUSTOM	LSI	2	6	2	1	1.5	1.5	1.5	3		2	3		23.5
	VLSI	2	8	2	1	1.5	1.5	1.5	3		2	3		25.5
	HYBRID	2	2	1	1	1.5	1	.5	2		2	3		16

Figure B-46 C4M2 Memory Chip Design Matrix

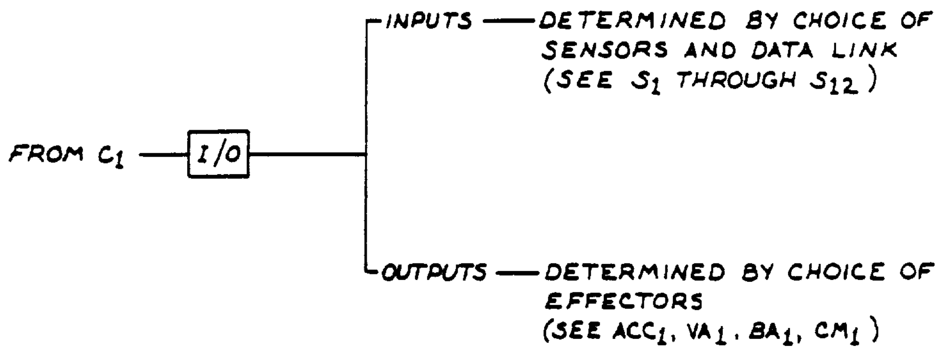


Figure B-47 Control System Decision Logic Diagram C5

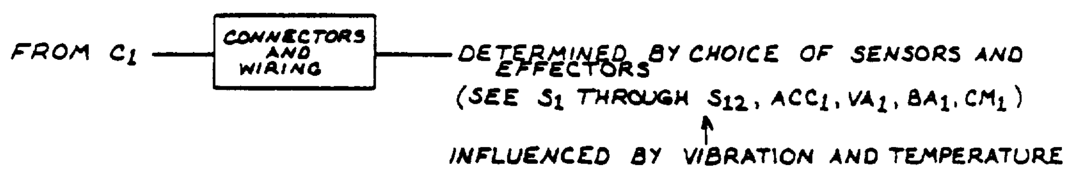


Figure B-48 Control System Decision Logic Diagram C6

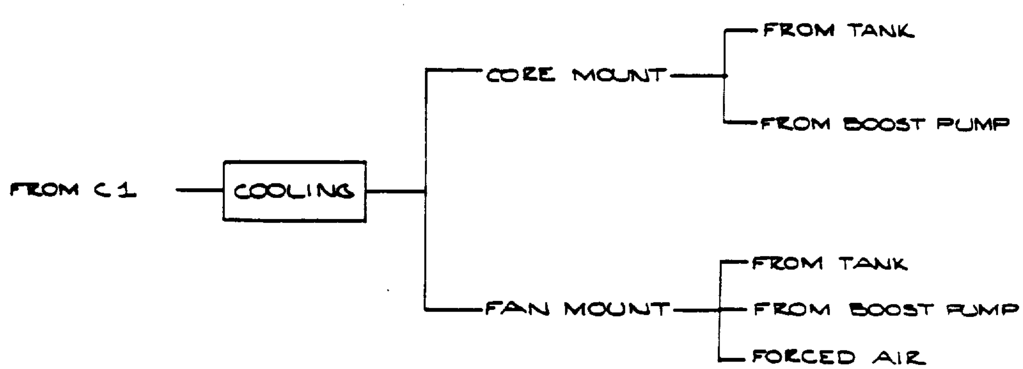
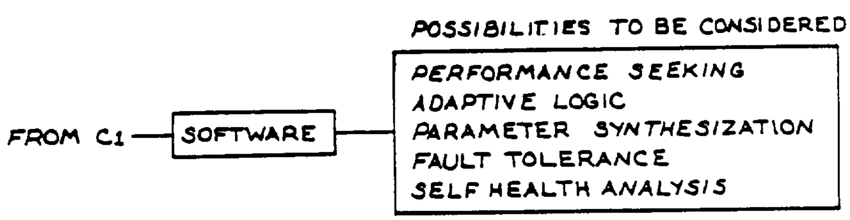


Figure B-49 Control System Decision Logic Diagram C7

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
AIR FRAME TANK COOLANT FUEL FAN CASE MOUNT	6	6	8	4	8	4			36
AIR FRAME TANK COOLANT FUEL CORE MOUNT	6	6	6	4	8	4			34
ENGINE BOOST PUMP COOLANT FUEL FAN CASE MOUNT	6	6	6	4	8	4			34
ENGINE BOOST PUMP COOLANT FUEL CORE MOUNT	6	6	4	4	8	4			32
FORCED AIR FAN DUCT MOUNT	8	8	4	3	4	2			29

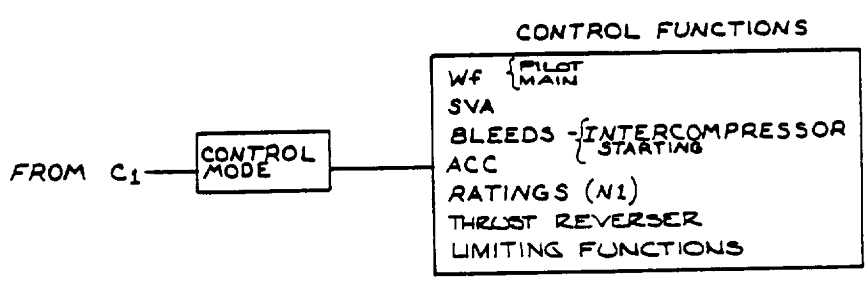
FORCED AIR COOLING WAS SELECTED DUE TO SUBSTANTIAL IMPACT ON ENGINE COST, WEIGHT, AND SAFETY

Figure B-50 C7M Control Cooling Matrix



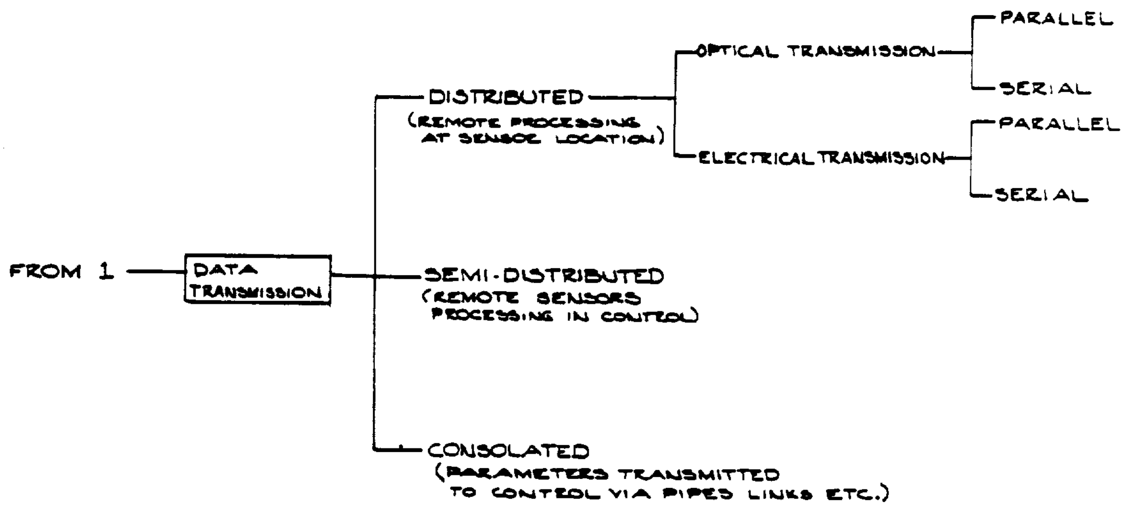
NOTE: DEVELOPMENT OF SOFTWARE IS BEYOND THE SCOPE OF THE PROGRAM; THEREFORE, NO TECHNICAL SELECTIONS WERE MADE.

Figure B-51 Control System Decision Logic Diagram C8



NOTE: THE CONTROL MODE IS SHOWN UNDER THE DESCRIPTION OF SELECTED E³ CONTROL SYSTEM IN SECTION OF THIS REPORT

Figure B-52 Control System Decision Logic Diagram C9



NOTE: THE VARIOUS SENSORS WERE INDIVIDUALLY CONSIDERED UNDER THE ABOVE THREE CATAGORIES AND, BASED ON ENGINEERING JUDGEMENT, WERE PLACED IN ONE CATEGORY. THE RESULTING SYSTEM IS A MIX OF THE THREE CATEGORIES.

Figure B-53 Control System Decision Logic Diagram D1

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH ORBITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
PARALLEL ELECTRICAL	4	4	2	4	8	4			26
PARALLEL OPTICAL	4	6	4	4	8	3			29
SERIAL ELECTRICAL	8	8	6	4	8	4			38
SERIAL OPTICAL	8	8	8	4	8	3			39

Figure B-54 Decision Matrix for D1M (Sensor Data Transmission)

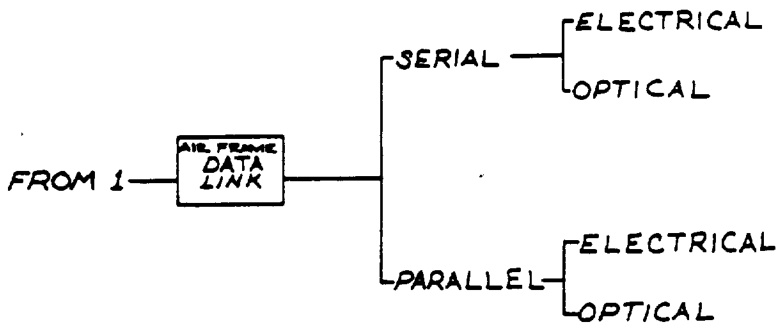


Figure B-55 Control System Decision Logic Diagram DL1

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
PARALLEL ELECTRICAL	4	4	2	4	8	4			26
PARALLEL OPTICAL	4	6	4	4	8	3			29
SERIAL ELECTRICAL	8	8	6	4	8	4			38
SERIAL OPTICAL	8	8	8	4	8	3			39

Figure B-56 Decision Matrix for DL1M (Data Link)

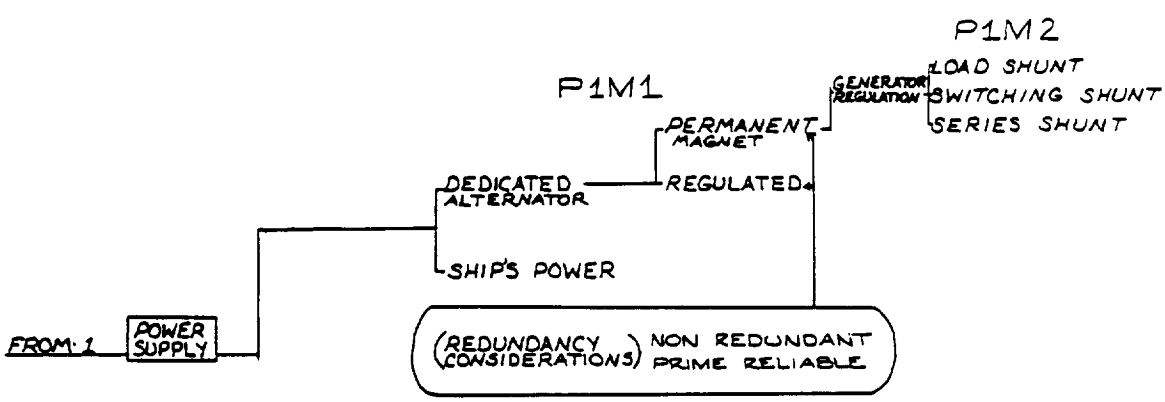


Figure B-57 Control System Decision Logic Diagram P1

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SHIPS POWER	2	8	2	1	2	4			19
DEDICATED PERMANENT MAGNET ALTERNATOR	8	8	8	4	6	4			38
DEDICATED CONTROLLABLE ALTERNATOR	6	6	6	3	6	4			31

Figure B-58 P1M1 Power Source Matrix

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
SERIES REGULATOR	8	6	6	3	6	4			33
SHUNT REGULATOR	8	8	8	3	8	4			39
SWITCHING REGULATOR	4	2	4	2	2	4			18

Figure B-59 P1M2 Power Source Matrix

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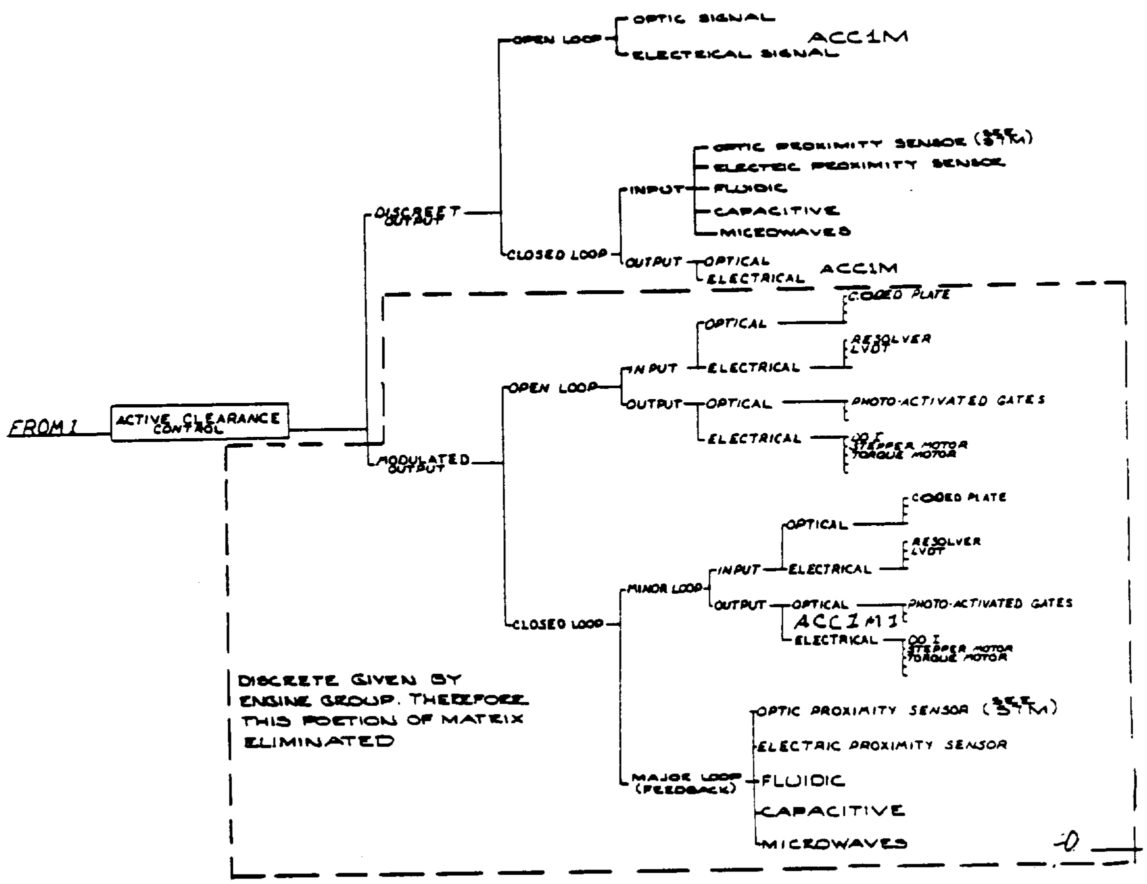

Figure B-60 Control System Decision Logic Diagram ACC1

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	ELECTRONIC COMPATIBILITY	TECHNOLOGY READINESS	ENVIRONMENTAL COMPATIBILITY	DURABILITY	SIZE/ORGANIZATION	SPEED	POWER		TOTAL
SILICON DRIVER	8	8	6	4	6	4							36
REMOTE GaAs DRIVER	8	8	8	4	8	3							39
REMOTE PHOTO GaAs DRIVER	8	8	8	4	8	2							38

Figure B-61 Decision Matrix for ACC11M (Discrete Actuator Signal)

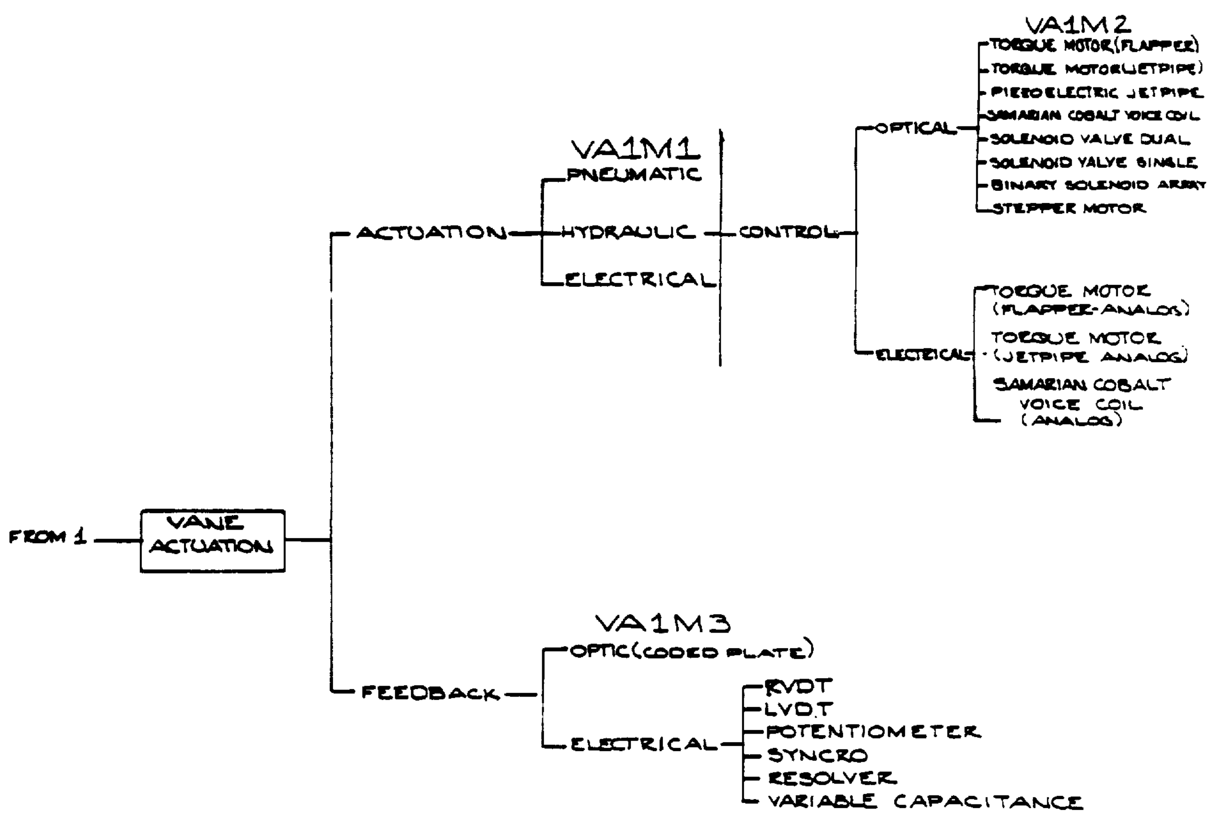

Figure B-62 Control System Decision Logic Diagram VA1

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	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
PNEUMATIC	ELIMINATED - INSUFFICIENT ACTUATING PRESSURE AT LIGHT OFF								
HYDRAULIC	SELECTED SYSTEM								
ELECTRICAL	ELIMINATED - IMPRACTICAL DUE TO POWER REQUIREMENTS & RESPONSE								

Figure B-63 Decision Matrix for VA1M1 (SVA Actuator)

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
TORQUE MOTOR (FLAPPER)**	4	6	6	4	8	4			3
TORQUE MOTOR (JET PIPE)**	4	6	8	4	8	4			34
PIEZOELECTRIC JETPIPE# (ANALOG)	6	6	8	4	8	2			34
SAMARIAN COBALT VOICE COIL **	8	6	8	4	6	1			33
SOLENOID VALVES (DUAL)*	6	6	8	3	8	3			34
SOLENOID VALVE (SINGLE)*	8	8	8	4	8	3			39
STEPPER MOTOR	4	4	4	4	4	4			24
BINARY SOLENOID ARRAY	4	2	4	2	6	1			19

* ANALOG VERSION OF THESE DEVICES AVERAGED 4 POINTS LOWER THAN THE TOTALS SHOWN

* DEVICES SHOWN USE REMOTE GAAS DRIVERS. SILICON DRIVERS WERE 4 POINTS LOWER AND REMOTE PHOTO GAAS DRIVERS WERE 1 ONE POINT LOWER DUE TO TECHNICAL READINESS

Figure B-64 Decision Matrix for VA1M2 (Effector Control Signal)

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
CODED PLATE (OPTICAL)	8	6	8	4	8	3			37
RVDT	6	6	2	4	2	4			24
RESOLVER	6	6	8	4	4	4			32
POTENTIOMETER	8	8	2	2	4	4			28
LVDT	6	8	2	4	2	4			26
SYNCRO	6	6	8	4	2	4			30
VARIABLE CAPACITANCE	4	6	4	4	2	3			23

Figure B-65 Decision Matrix for VA1M3 (Feedback)

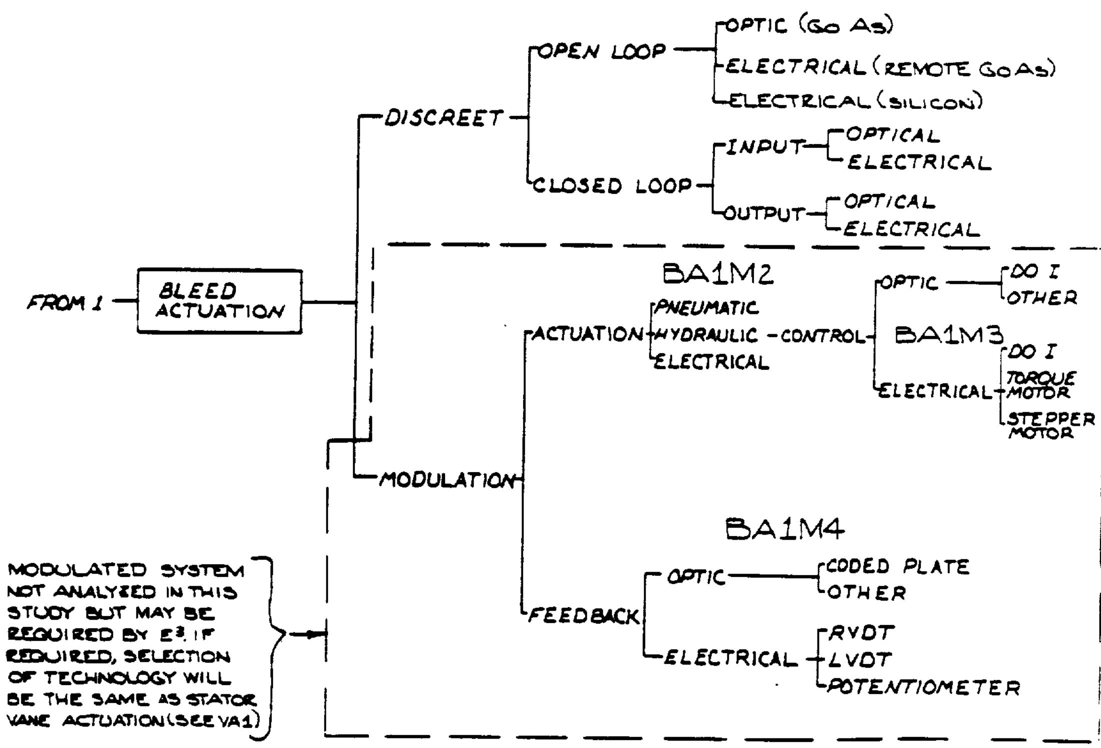

Figure B-66 Control System Decision Logic Diagram BA1

	COST	WEIGHT	RELIABILITY	MAINTAINABILITY	COMPATIBILITY WITH DIGITAL ELECTRONIC CONTROL	TECHNOLOGY READINESS			TOTAL
OPTIC (REMOTE GaAs)	8	8	8	4	8	2			38
ELECTRIC (REMOTE GaAs)	8	8	8	4	8	3			39
ELECTRICAL SILICON	8	8	6	4	6	4			36

Figure B-67 Decision Matrix for BAIM (Bleed Actuator Discrete)

APPENDIX C

MEMO: ENERGY EFFICIENT ENGINE CONTROL SYSTEM
COST AND WEIGHT COMPARISONS WITH
JT9D BASELINE

[redacted]

PRATT & WHITNEY AIRCRAFT GROUP

Internal Correspondence

To John Bissett

From R. E. Babineau Ext. 7665

Subject Energy Efficient Engine Control System Cost & Weight Comparisons with 9D Baseline

August 1, 1978

cc: W. B. Gardner
D. Gray
J. Kuhlberg
R. Owens
H. Zickwolf

The Control Preliminary Definition work plan calls for quantification of control system cost, weight and reliability, and comparison of these values to the "state of the art". The control system for the current JT9D engine has been established as the baseline system for comparison. There are substantial dif- ferences in the control system requirements, which result in non-common, and therefore non-comparable, system elements; i.e., the high efficiency burner requires a substantially different metered fuel flow system than JT9D. In order to provide a meaningful comparison, these elements, as listed below, will not be included:

Non-Common Elements

Thrust reverser actuator and feedbacks
Purge System
  Nitrogen tank
  Ecology tank
  Purge and transfer valve
HP compressor case cooling
HP cooling air solenoid
Optical proximity sensor
Optical pyrometer

A comparison of system plumbing and wiring was not included in the study. Plumbing and wiring is dependent on detailed system design, engine design, the number of control system elements required, and other factors beyond the scope of this study.

Cost and weight comparisons of the control system elements which are common to the two systems, or comparable, are shown in the attached tables. Please convert the total Δ's into Δ DOC and Δ fuel usage for the Energy Efficient Engine.

R.E. Babineau

R. E. Babineau

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ENERGY EFFICIENT ENGINE
CONTROL SYSTEM PRELIMINARY DEFINITION
WEIGHT COMPARISON

Control System Component	JT9D Baseline System Weight kg (lb)	EEE System Weight kg (lb)	Weight kg (lb)	Comments
Fuel pump	21.04 (46.75)	8.55 (19)	-12.49 (27.75)	9D includes filter
Fuel control	16.38 (36.4)	6.89**(15.3)	-9.49 (21.1)	
T_{T2}	0.68 (1.5)	0	-0.68 (1.5)	E^3-data from aircraft
Altitude	- -	0	0	E^3-data from aircraft; 9D-not required
Mn	- -	0	0	E^3-data from aircraft; 9D-not required
Vane Control & Modulating Bleed Control	10.8 (24.0)	0	-10.8 (24.0)	E^3-function of electronic box
Start Bleed Solenoid	0.86 (1.9)	0.68 (1.5)	-0.18 (0.4)	E^3-2-stage valve
Start Bleed Control	1.31 (2.9)	0	-1.31 (2.9)	
Stator Vane Actuator	2.16 (4.8)	2.16 (4.8)	0	
LPC Bleed Actuator	1.66 (3.7)	1.66 (3.7)	0	
Turbine Cooling Barometric Match	0.45 (1.0)	0	-0.45 (1.0)	E^3-function of element box
Turbine Case Cooling Valve	3.15 (7.0)	1.80 (4)	-1.35 (3.0)	
HP Compressor Case Cooling Valve	- -	5.40*(12)	- -	Not comparable-not a 9D engine function
Turbine Cooling Air Solenoid	0.86 (1.9)	0.68 (1.5)	-0.19 (0.4)	E^3-2 Stage Valve
HP Air Cooling Solenoid	- -	0.68*(1.5)	- -	Not comparable-not a 9D engine function
Air/Fuel Heater	5.63 (12.5)	0	-5.63 (12.5)	Eliminated in E^3 system
Fuel De-Icing Valve	1.62 (3.6)	0	-1.62 (3.6)	Eliminated in E^3 system
Pressure Diff. Switch	0.27 (0.6)	0	-0.27 (0.6)	Eliminated in E^3 system
Pressurizing and Dump Valve	4.95 (11.0)	0	-4.95 (11.0)	Eliminated in E^3 system
Purge and Transfer Valve	- -	1.44* (3.2)	- -	Not comparable-special requirement of high efficiency burner
Cutoff and Bypass Valve	- -	0.45 (1.0)	+0.45 (1.0)	
Pump Control	- -	0.45 (1.0)	+0.45 (1.0)	Not required in 9D system
Pilot Flowmeter	- -	1.13 (2.5)	+1.13 (2.5)	Not required in 9D system
Main Flowmeter	- -	1.13 (2.5)	+1.13 (2.5)	Not required in 9D system
P_2	0	0.11 (0.25)	+0.11 (0.25)	Part of 9D control
P_3	0	0.23 (0.5)	+0.23 (0.5)	
SVA Feedback	1.26 (2.8)	0.05 (0.1)	+1.21 (2.7)	
Bleed Feedback	1.13*(2.5)	- -	- -	Not comparable-E^3 not modulated
N_t	0	0.45 (1.0)	+0.45 (1.0)	Not required in 9D system
Alternator	0	0.90 (2.0)	+0.90 (2.0)	Not required in 9D system
Critical Proximity Sensor	- -	- -*	- -	Not comparable-not a 9D engine requirement
Nitrogen Purge Tank and Valving	- -	- -	- -	Not comparable-not a 9D engine requirement
Ecology tank	- -	- -	- -	Even trade if required
Thrust reverser actuator and feedbacks	- -	Not Available*	- -	Not comparable-not a 9D engine requirement
TBT Optical Pyrometer	- -	- -*	- -	Not comparable-not a 9D engine requirement
Plumbing and Wiring	- -	- -	- -	Not compared-dependent on detailed system design, engine design, total function, and other factors beyond the scope of this study
TOTALS			-43.34 (96.3)	

* - Not traded; therefore, not included in total.
** - Weight is average of HSD and Bendix estimates.

ENERGY EFFICIENT ENGINE
CONTROL SYSTEM PRELIMINARY DEFINITION
COST COMPARISON - BASED ON 1978 DOLLARS

Control System Component	Cost From Baseline System Dollars	Comments
Fuel pump	+ 3000	90 includes filter
Fuel control	- 14500**	
T_{T2}	- 973	E^3-data from aircraft
Altitude	0	E^3-data from aircraft; 90-not required
Mn	0	E^3-data from aircraft; 90-not required
Vane Control & Modulating Bleed Control	- 18500	E^3-function of electronic box
Start Bleed Solenoid	+ 315	E^3-2-stage valve
Start Bleed Control	- 800	
Stator Vane Actuator	0	
LPC Bleed Actuator	0	
Turbine Cooling Barometric Match	- 154	E^3-function of electronic box
Turbine Case Cooling Valve	+ 85	
HP Compressor Case Cooling Valve	- -*	Not comparable-not a 90 engine function
Turbine Cooling Air Solenoid	+ 315	E^3-2 Stage Valve
HP Cooling Air Solenoid	- -*	Not comparable-not a 90 engine function
Air/Fuel Heater	- 2400	Eliminated in E^3 system
Fuel De-Icing Valve	- 2050	Eliminated in E^3 system
Pressure Diff. Switch	- 338	Eliminated in E^3 system
Pressurizing & Dump Valve	- 850	Eliminated in E^3 system
Purge and Transfer Valve	- -*	Not comparable-special requirement of Vorbix burner
Cutoff and Bypass VAlve	+ 400	
Pump Control	+ 400	Not req'd. in 90 system;
Pilot Flowmeter	+ 3000	Not required in 90 system
Main Flowmeter	+ 3000	Not required in 90 system
P_2	+ 100	Part of 90 control
P_3	+ 300	
SVA Feedback	+ 628	
Bleed Feedback	- -	Not comparable-E^3 not modulated
N_2	+ 300	Not required in 90 system
Alternator	+ 700	Not required in 90 system
Critical Proximity Sensor	- -*	Not comparable-not a 90 engine requirement
Nitrogen Purge Tank & Valving	- -	Not comparable-not a 90 engine requirement
Ecology Tank	- -	Even trade if required
Thrust Reverser Actuator and Feedbacks	- -*	Not comparable-not a 90 engine requirement
TBT Optical Pyrometer	- -*	Not comparable-not a 90 engine requirement
Plumbing and Wiring	- -	Not compared-dependent on detailed system design, engine design, total function and other factors beyond the scope of this study
TOTALS	- 28022 dollars	

NOTES: * - Not traded; therefore not included in total
**- Cost is average of HSD and Bendix estimates

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CONTROL SYSTEM BENEFITS TO
ENERGY EFFICIENT ENGINE
RELATIVE TO JT9D ENGINE

Δ WT = -43.34 kg (96.3 lbm)
Δ cost = 28,022 dollars

<u>Resulting Airplane Operating Benefits, P&WA Airplane*</u>

	% Fuel Burned		% Δ DOC	
	Tri.	Quad.	Tri.	Quad.
ΔWt = -43.34 kg/ENG	-0.08	-0.09	-0.05	-0.05
ΔCost = -28,022/ENG	-	-	-0.08	-0.08
Total %Δ	-0.08	-0.09	-0.013	-0.13

*Typical Mission, Trijet: 1300 km (700 n. mi.)
Quadjet: 3700 km (2000 n. mi.)

APPENDIX D

ENGINE DESIGN AND CONTROL SYSTEM CONCEPTUAL DESIGN SCHEMATICS

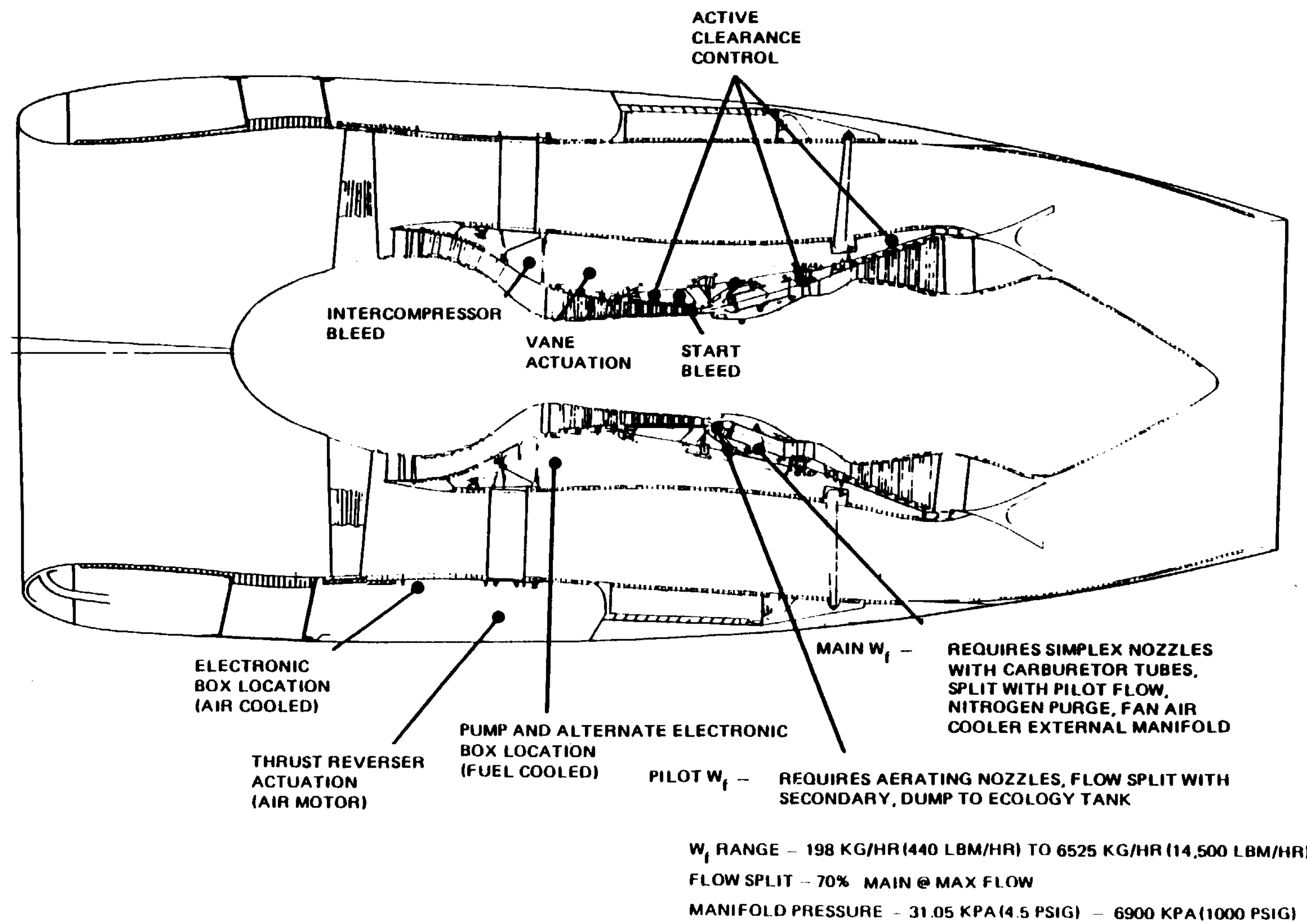

Figure D-1 Control Component Location and Parametric Information

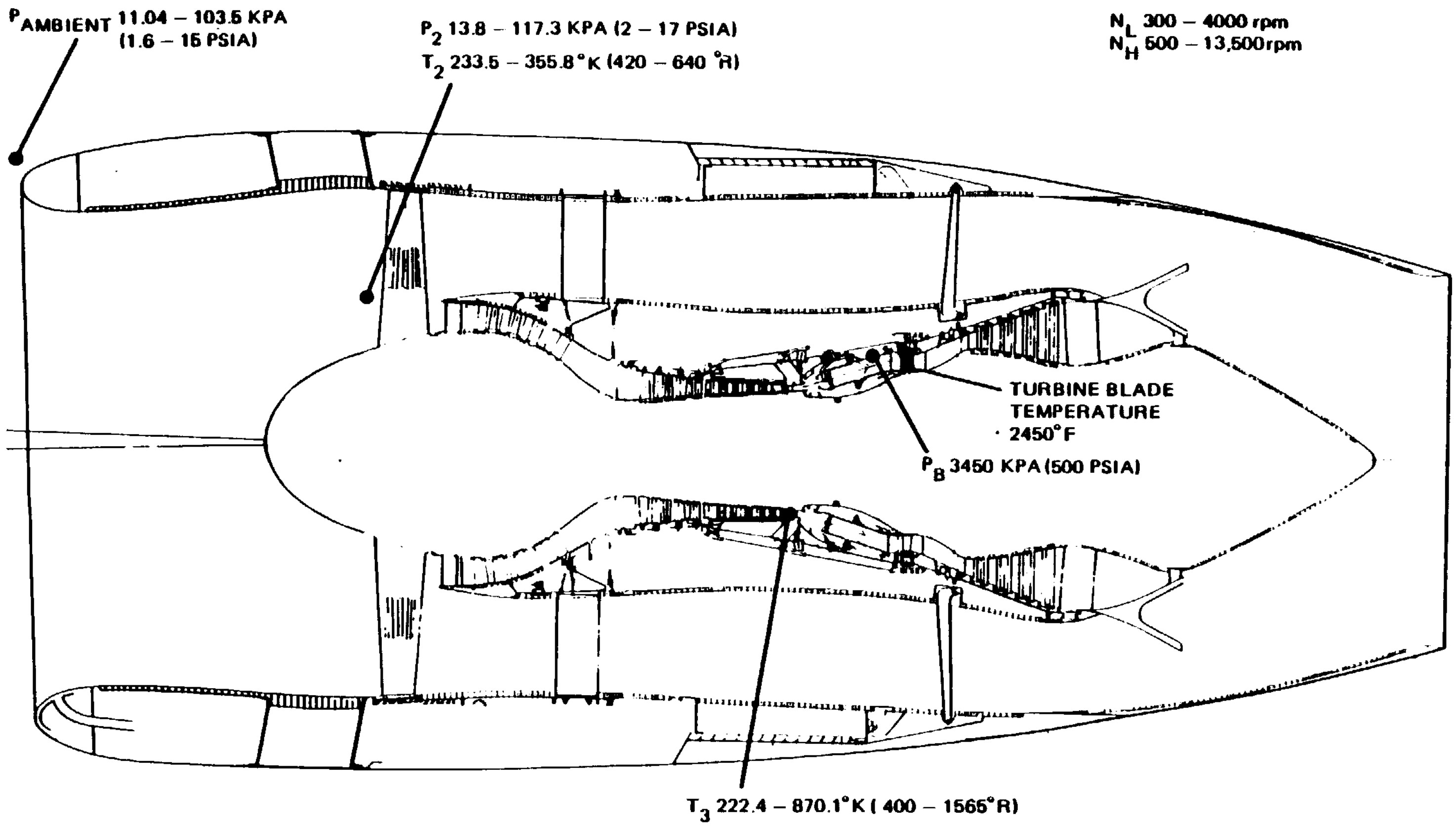

Figure D-2 Control System Sensor Location

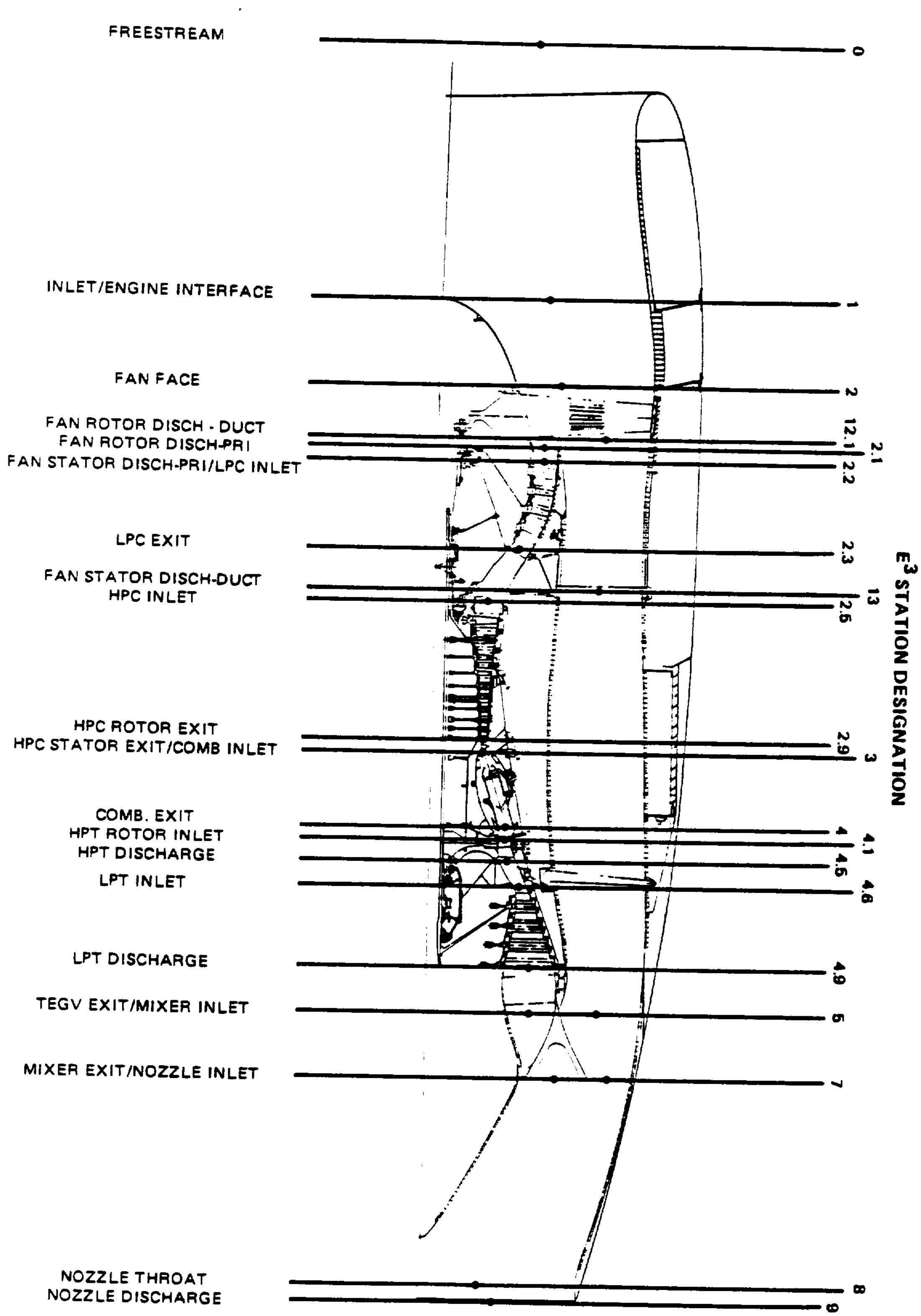

Figure D-3 Engine Station Designations

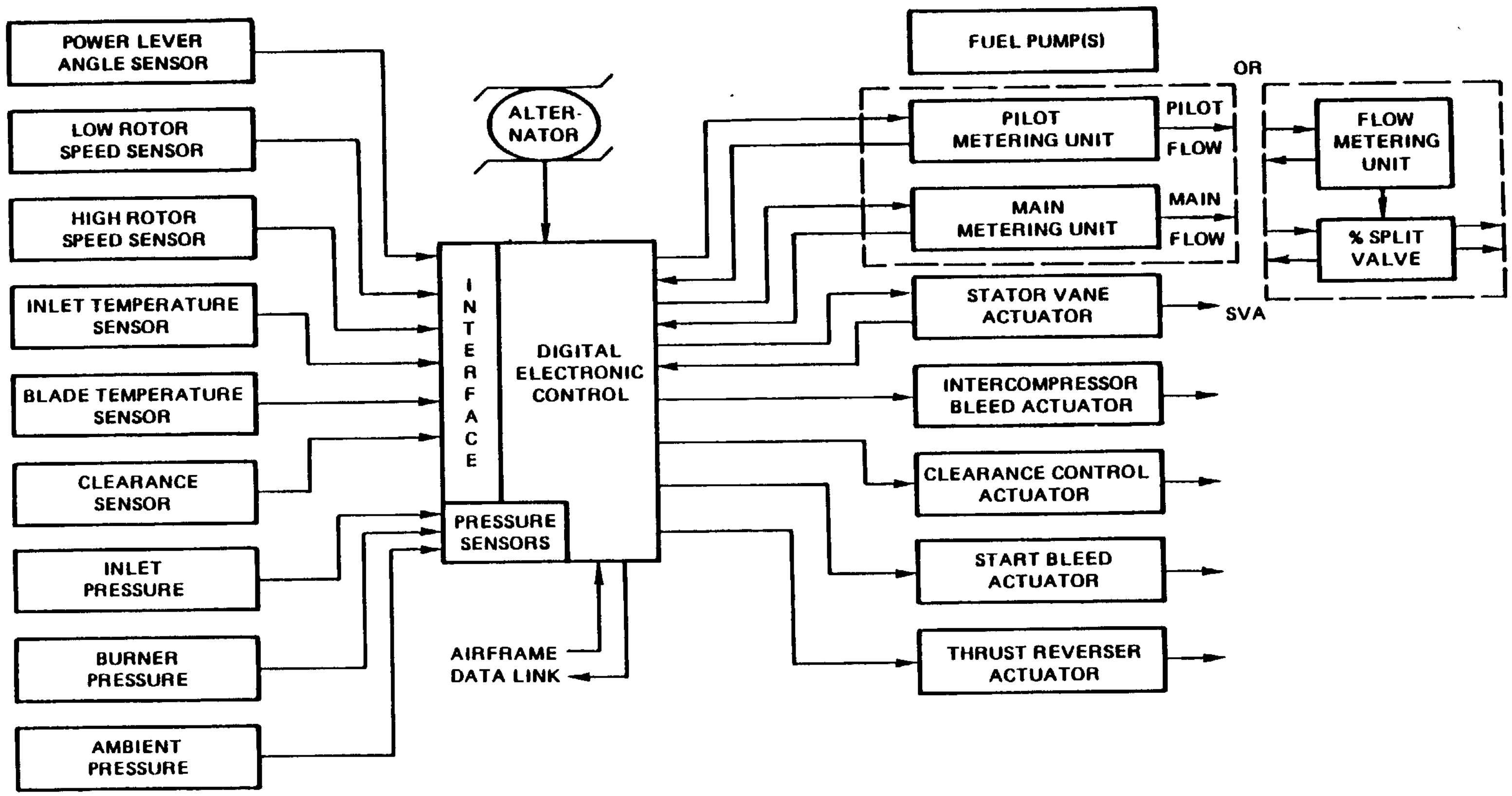

Figure D-4 Conceptual Diagram of Electronic Control

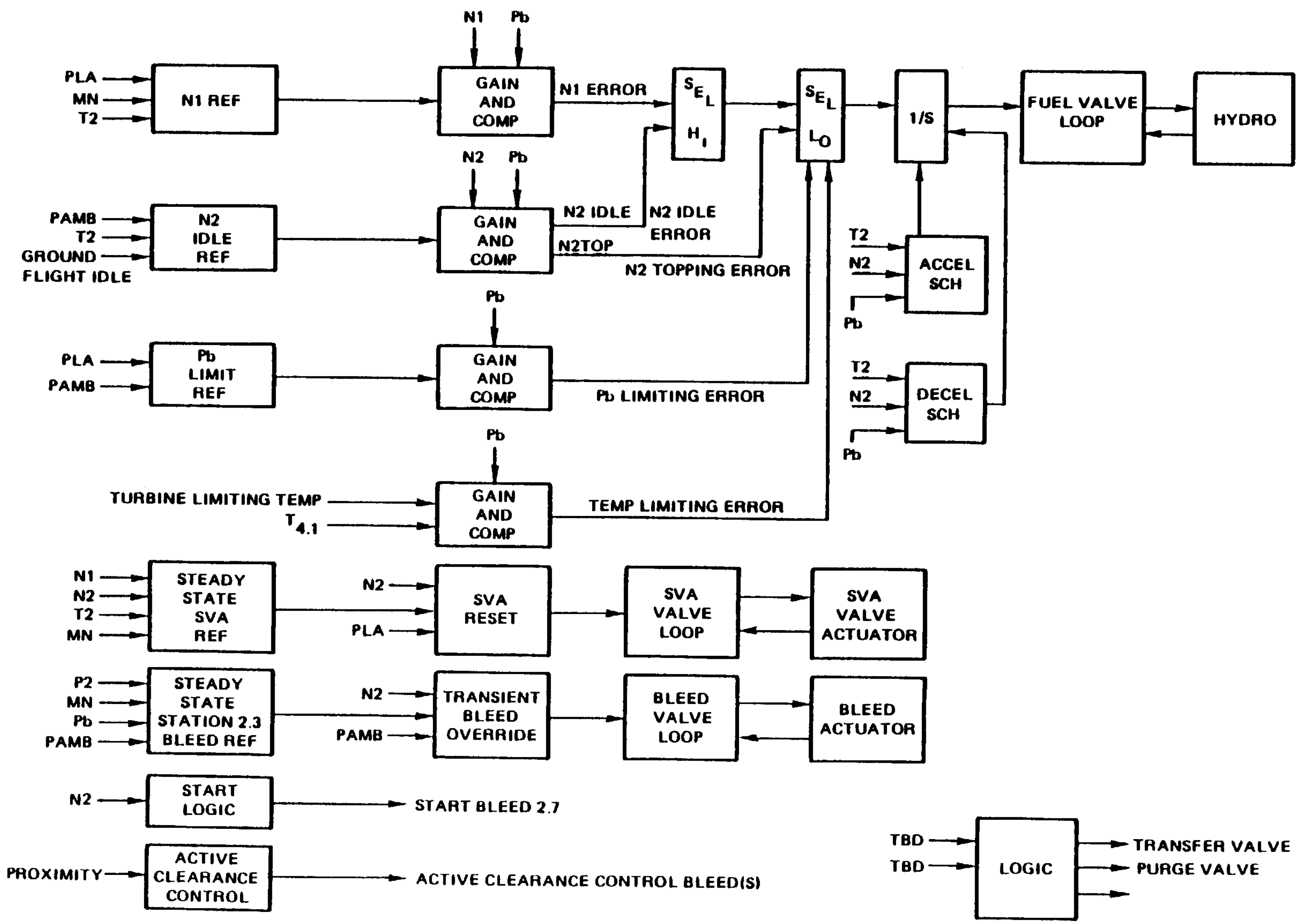

Figure D-5 Preliminary Control Mode

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