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PRELIMINARY STUDY, ANALYSIS AND DESIGN FOR A POWER SWITCH FOR DIGITAL ENGINE ACTUATORS

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Pratt & Whitney Aircraft Group
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16. Abstract

Innovative control configurations using high temperature switches to operate actuator-driving solenoids were studied in this program, which addressed the impact on engine control system life cycle costs and reliability of electronic control unit (ECU) heat dissipation due to power conditioning and interface drivers. Various power supply and actuation schemes were investigated, including optical signal transmission and electronics on the actuator, engine-driven alternator, and inside the ECU. The use of a switching shunt power conditioner results in the most significant decrease in heat dissipation within the ECU. No overall control system reliability improvement is projected by the use of remote high temperature switches for solenoid drivers.

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A. SUMMARY

The object of this program was to study innovative control configurations using high temperature switches to reduce Electronic Control Unit (ECU) heat load. These switches would operate solenoids that drive engine actuators. If the power supply and solenoid drivers could be mounted external to the ECU, a significant heat reduction could occur, and hence, reliability would improve.

A baseline control system using solenoid-driven actuators and a conventional internal dissipating shunt power supply was established for trade-off against alternative system configurations. Five power supply variations and ten actuation schemes were investigated. These schemes included electronics on the actuator, alternator and inside the ECU. The investigation encouraged the use of optics wherever practical.

The use of a switching shunt power conditioner instead of the baseline dissipative shunt conditioner resulted in the most significant decrease in heat dissipation within the ECU. The switching shunt regulator short circuits excessive alternator power. This power supply uses conventional silicon technology and can, therefore, be incorporated into the ECU without a high technology component development program. A secondary improvement in heat dissipation and reliability can be obtained by mounting the power supply at the alternator, but this additional benefit may not be worth the cost and risk of the required development program for the high temperature components.

No overall control system reliability improvement is projected by the use of remote high temperature switches for solenoid drivers. Remote switches would result in higher Life Cycle Cost (LCC) and development costs than the baseline system with internal switching. A system of optically-activated switches would provide good EMI immunity; however, higher LCC and high technology risk significantly reduces the desirability of this approach.

B. INTRODUCTION

Studies at Pratt & Whitney Aircraft indicate that considerable savings in development, procurement and maintenance cost can be obtained by the use of digital electronic controllers for gas turbine engines. Advanced engine requirements can result in a complex hydromechanical control with undesirable control weight and complexity. Digital electronic control hardware is not affected by complex control algorithms. Modifications to the control, to reflect new engine requirements or modifications, are usually handled by inexpensive software changes. Even new engines can frequently be accommodated with a combination of new software and minimal hardware changes. The electronic control's ability to perform automatic troubleshooting through self-test, coupled with less expensive replacement parts, can result in reduced maintenance cost. The ease with which redundancy can be achieved in electronic systems will reduce total system failure and in-flight shutdowns to numbers less than the current hydromechanical systems. But, while redundancy improves system reliability, it also adds complexity, with attendant maintenance, weight, and cost penalties. To minimize these penalties, the major emphasis in control system development must be to achieve maximum reliability and maintainability at the component and subsystem level.

The NASA Digital Output Interface (DOI) program (NAS3-19898) determined that Life Cycle Cost (LCC) and reliability of the control output interface could be improved by replacing conventional analog-type interface and effectors with digitally compatible solenoids. The use of solenoids with their relatively high power requirements results in a significant burden on the power conditioning circuit, which is normally located in the electronic control unit. Increased power conditioning results in increased heat dissipation, which in turn elevates junction temperatures and reduces reliability of the electronic control unit.

This program addressed the impact on control system life cycle cost and reliability of electronic control heat dissipation due to power conditioning and interface drivers. The major elements of the control system were broken down into building blocks that could be modified and substituted into a baseline system. Hamilton Standard Division was contracted to provide sufficient design evaluation on the building blocks to generate numbers for cost, weight, and reliability. The building blocks were configured into nine control systems that were evaluated for reliability and total cost of ownership (Life Cycle Cost).

C. THE POWER SWITCH CONCEPT

Current electronic engine control (EEC) unit designs, such as shown schematically in Figure 1, require analog circuitry for both input and output analog-type devices. This circuitry imposes a need for relatively precise power regulation, which, in turn, contributes to the parts count and complexity of the power conditioning circuitry. Power conditioning circuitry is conventionally incorporated in the electronic control unit to avoid electromagnetic interference (EMI) problems and to isolate this circuitry from vibration and excessive heat.

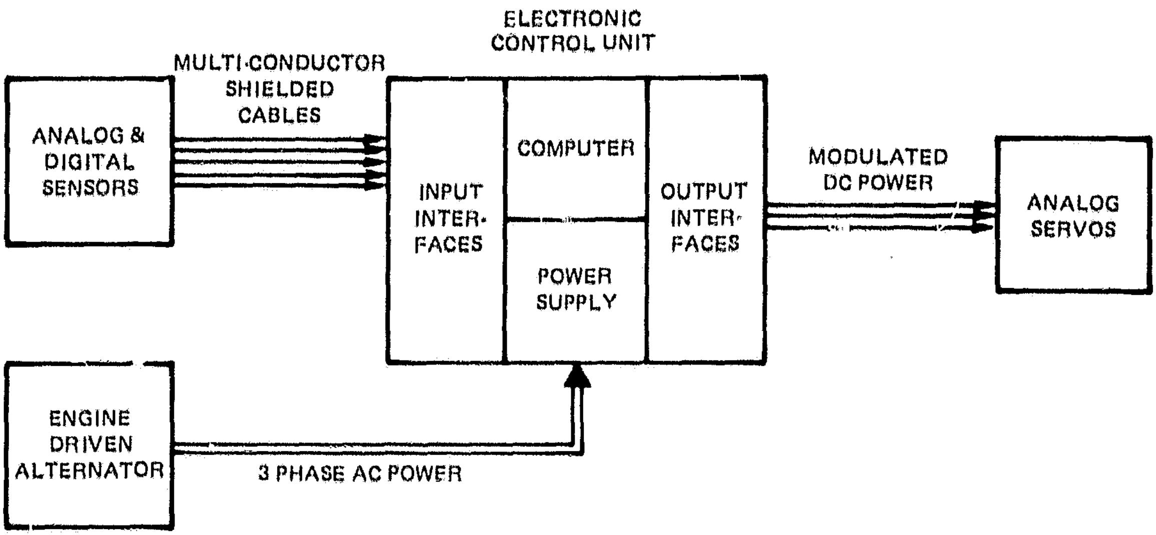

Figure 1 Current Electronic Control System Design Practice

A trade study of output interface devices, conducted under the NASA Digital Output Interface (DOI) program[1] (NASA Contract NAS3-19898) indicated that solenoids may have reliability and life cycle cost (LCC) benefits over conventional electromechanical devices, such as torque motors. Solenoid interface devices, such as described in Appendix A, do not require the fine voltage regulation that such devices as torque motors do. This should simplify power conditioning circuitry and improve electronic control unit reliability. However, solenoids require more power to operate than torque motors (15 watts versus 0.1 watt), and this has a detrimental impact on the power conditioning circuitry.

With a conventional permanent magnet alternator, which is a constant current device, excess power available from the alternator must be accommodated by the power conditioning circuitry. The engine-driven alternator must be sized to accommodate the worst case operating condition (all actuation systems active). As a result, the alternator must have an even higher power output for a system with solenoid interfaces. During steady state operation, however, there may be no active actuation systems, in which case the only power required is that to operate the electronics, and perhaps two or three discretes. This can result in the excess power being dissipated as heat in the electronic control unit, with a resulting decrease in its reliability.

With the power switch concept, shown schematically in Figure 2, a portion of the power conditioning circuitry and the solenoid switches are moved out of the electronic control unit to eliminate internal dissipation of any excess power. To implement this concept, a high current level (on the order of 1 amp) switch is required, which can operate reliably in the environment external to the electronic control unit (for example, mounted on the actuator itself). The switch may be either electrically or optically activated, the latter approach being immune to EMI. High temperature electronic components may also be required for an external conditioning unit.

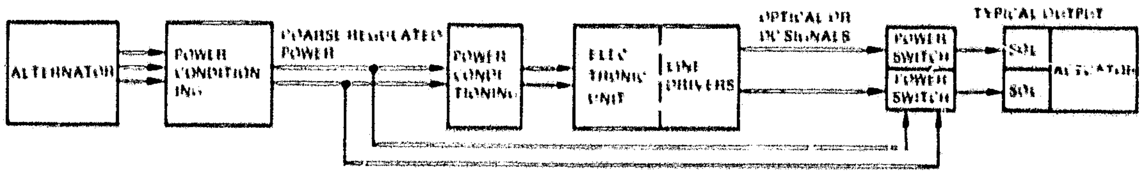

Figure 2 Concept for Removing Power Dissipation from the Electronic Unit

Silicon switches, which can be used inside the electronic control unit, cannot function in the high temperature environment of 162°C found at actuator locations. A gallium arsenide (GaAs) switch developed by the United Technologies Research Center has been demonstrated to have the capability to switch up to 1 amp current at 200°C(2). Details of this power switch are described in Section D.3.d of this report. High temperature electronic components may also be required for an external power conditioning unit.

D. ANALYSIS OF THE POWER SWITCH CONCEPT

The objective of this program was to determine a control system configuration making use of GaAs power switches to remove power dissipation elements from the electronic control unit, thereby resulting in a system with improved reliability and life cycle cost (LCC).

LCC represents the total cost of ownership for a system during that system's useful life. For an aircraft application, the useful life of the system must be the same as that of the aircraft. LCC includes acquisition cost of the system plus spares, cost of labor and material for repairs, and the cost of fuel required to carry the weight of the system over its useful life.

The methodology used to select a control system configuration consisted of the following steps:

1) The control system was targeted for inclusion on a high technology engine that would be in prototype in the mid 1980's and in full production in the late 1980's. To this end, it was decided that the E^3 engine presently being studied under NASA Contract NAS3 20646 (Energy Efficient Engine, Component Development and Integration Program), would be a suitable vehicle for establishing baseline control requirements. Control system requirements are discussed in Section D.1.

2) A baseline control system design, based on component technology developed under the Navy/Pratt & Whitney Aircraft FADEC (Full Authority Digital Electronic Control program N00019-76-C-0422)[4], was developed to permit LCC and reliability trade studies. The baseline control system is described in Section D.2.

3) Building blocks were established for common elements of potential system configurations, such as alternator, cables, power switches, etc. Cost, weight and reliability were determined for each building block. Building block data are presented in Section D.3.

4) A matrix of alternative system configurations for relocating or reducing power dissipation in the electronic control unit was derived to be traded against the baseline system to establish the optimum configuration. Five power conditioning schemes and ten power switch schemes were traded off for life cycle cost. These schemes are discussed in Section E and F.

5) Utilizing the building block information, trade studies were conducted to determine the LCC and reliability for each system. The results of the trade studies are presented in Section G.

6) LCC results were evaluated to determine the best candidate control system configuration or configurations. Recommended programs, discussed in Section I, were then defined for more detailed evaluation of these configurations.

D.1 ENGINE CONTROL SYSTEM REQUIREMENTS

Control system requirements are based on a commercial high technology high bypass fan engine that would be in development during the early 1980's and in full production in the mid to late 1980's. The engine is similar to that being developed under the E^3 program. Basic requirements in terms of outputs and inputs are shown in Figure 3 and discussed in the following paragraphs.

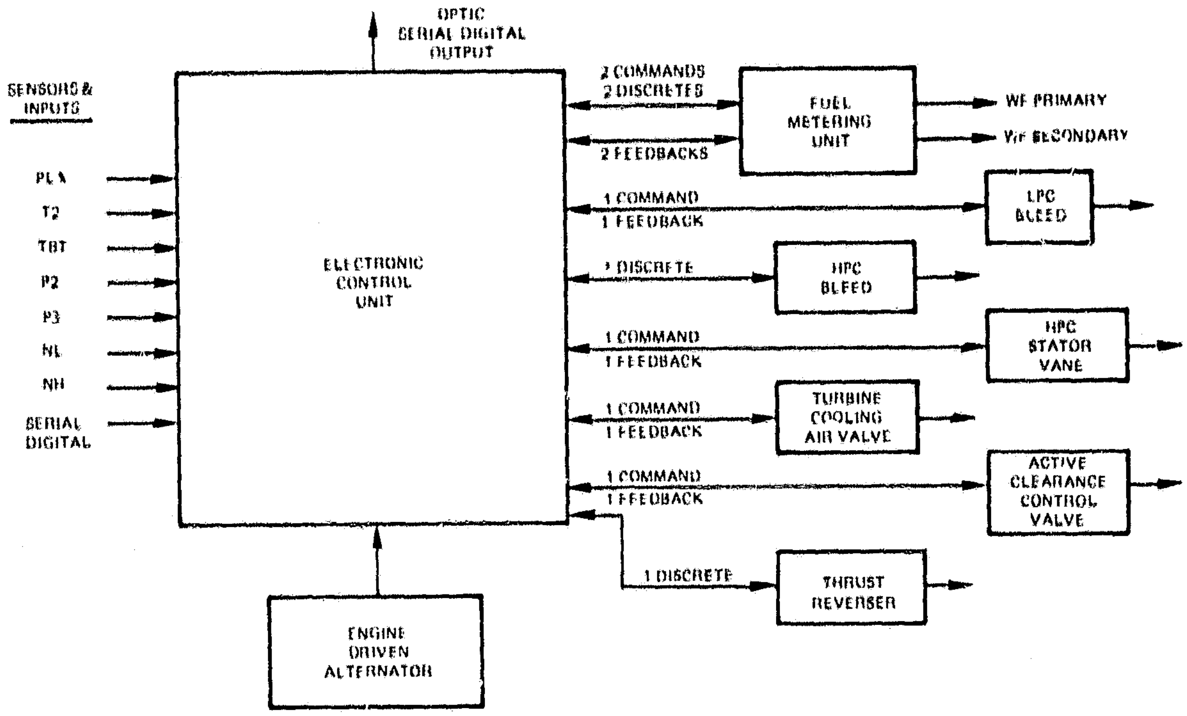

Figure 3 Hypothetical Control System Requirements

This engine requires two separate modulated fuel flows for a low emissions burner as well as modulated high compressor stator vanes and modulated inter-compressor bleeds. Six discrete functions: pilot fuel valve on/off, main fuel valve on/off, start bleed, turbine cooling, active clearance, and thrust reverser, are also required. The inputs to the control are: power lever angle (redundant), engine inlet temperature, turbine blade temperature, engine inlet pressure, burner pressure, engine exhaust pressure, high and low rotor speed, and serial data information from the airframe such as altitude, Mach number and possible backup parameters.

To assess the effect of control component location, control and actuator locations were assumed for a conceptual high bypass fan engine. Locations and distances for various control components are shown in Figure 4.

Environmental requirements which the system must meet are discussed in Appendix B.

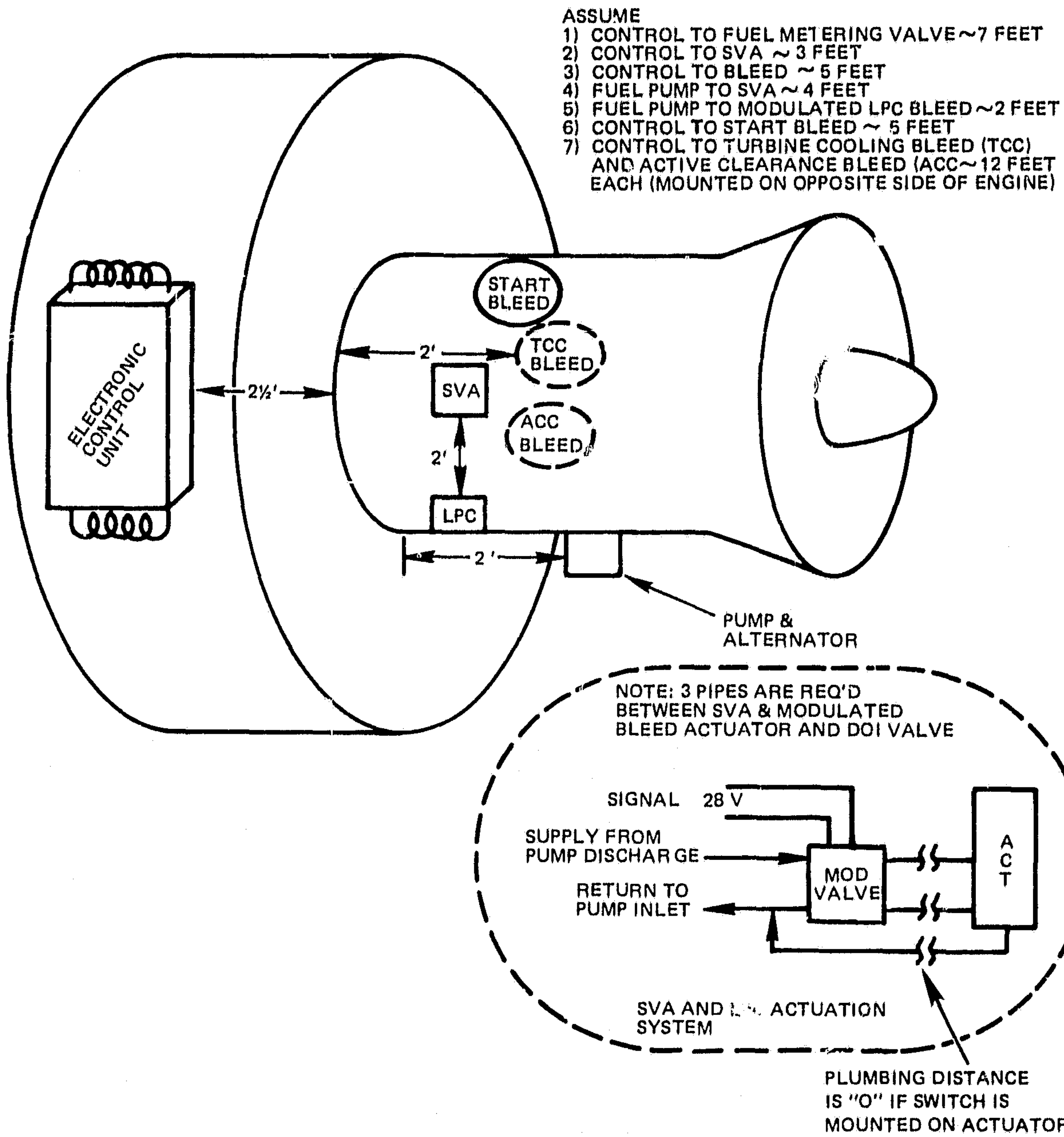

Figure 4 Location of Actuators on Engine, and Distances to Control

D.2 BASELINE CONTROL SYSTEM

To obtain realistic weighting of the cost, weight and reliability comparison studies associated with the alternative control system configurations, a "baseline" control system design was established comprising the following major component groups:

Electronic control unit (ECU)

Power conditioning circuitry

Engine driven alternator

Servo actuators for modulated outputs

Discrete control actuators

Interconnecting cabling

A simplified schematic of the baseline ECU hardware implementation is shown in Figure 5. Some of the more important features are summarized below.

- Implementation of input interface circuitry and digital processor for the ECU was based upon advanced state-of-the-art (FADEC) technology. Sensor requirements were established from the E^3 program. Silicon drivers, for switching solenoid current, are located in the ECU.

- Power conditioning for the baseline control system is implemented with a dissipative shunt regulator for the 14 volt bus and series shunt regulators for the 5 and 10 volt supplies. All power conditioning circuitry is located internal to the ECU.

- The alternator is a single winding, three-phase, permanent magnet design.

- Output effectors for each of the four modulated outputs consist of two solenoids, one for the increase direction and one for the decrease direction. Position feedback from each servo actuator is achieved with a single prime reliable optic encoder. Stator vane and bleed actuation systems utilize a servo-amplifier stage between the solenoid valves and the actuator ram.

- Discrete outputs are implemented with servo assisted solenoids.

- All electrical cables are double shielded to prevent EMI problems. Optic cable is composed of seven fibers with each cable carrying one discrete signal.

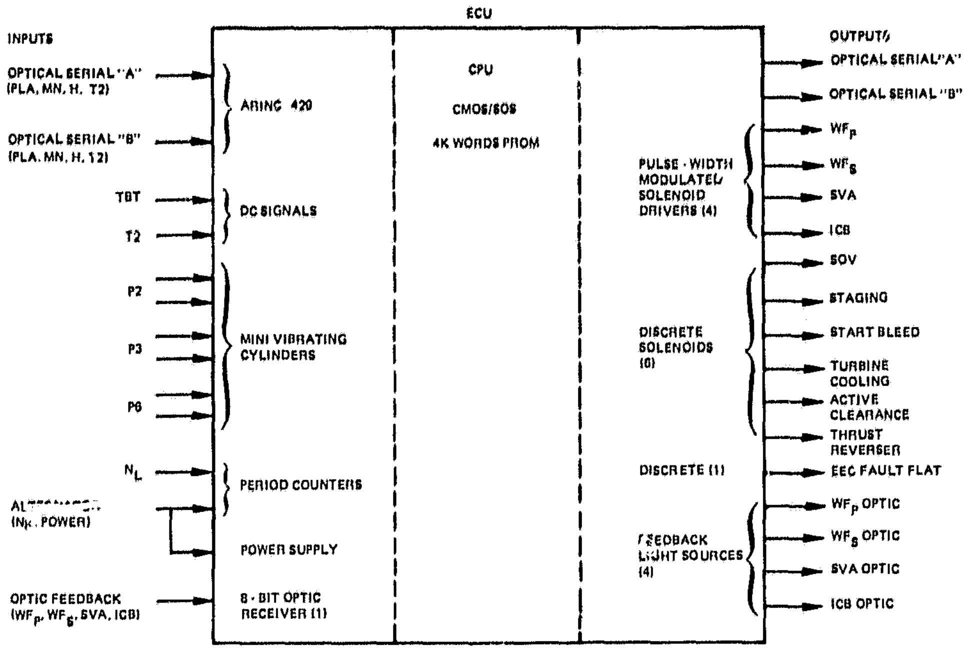

Figure 5 Baseline Control System

D.3 BUILDING BLOCKS

Examination of the potential alternative system configurations shows that, to a large extent, the hardware implementing them breaks down into particular functional "building blocks" which are located in different component areas for the various configurations. For example, the power switch is common to all schemes with only minor variations in the packaging/mechanical design detail. Therefore, much of the design definition in this area was applicable to all configurations.

Alternative configurations were evaluated using a building block basis as far as possible, so that overall system characteristics were obtained by accounting for the impact of additions to, deletions from, and changes to the baseline system design. The following building blocks were established for the trade studies of LCC and reliability:

- Solenoid valves
- Alternator
- Power conditioning circuitry
- Electrically activated DC power switch
- Photo-switch and circuit with power switch
- Optic source and associated circuitry (within electronic unit)
- Cabling

Information on each building block, including hardware description. cost, weight, and reliability, is presented in the following sections. Requirements for actuation systems were also evaluated. Cost of each building block represents the final cost to the customer and includes typical charges for quality control, additional assembly, installation charges, and normal markups.

D.3.a <u>DC Solenoid</u>

Two solenoids are required for each metering and actuation system: one solenoid for the increase direction and one for the decrease direction. Redundant solenoids were not chosen since the primary mode of failure for a solenoid is leakage out of tolerance, a predictable wear function. Also, this program assumed flight qualified hardware that would have been subjected to substantial testing and development and would have a high confidence level.

Solenoid cycling requirements for a 50,000 hour control system life were established based on the results of the NASA DOI program (Contract NAS3-19898)[2] from the 342-hour endurance test simulating typical flight operations. This number was extrapolated to 50,000 hours and resulted in 1.4 X 10^8 cycles. Since this was in excess of the capability of the solenoids used in the DOI program, a solenoid specification was developed.

To be conservative in terms of cycling requirement, a factor of 3 was applied to the number determined from the DOI program. This resulted in a requirement of 5 X 10^8 Mean Cycles Between Failure (MCBF). The calculation of solenoid reliability is shown in Appendix C.

The cycle requirements for the stator vane actuator (SVA) solenoids were assumed to be the same as for the fuel valve since the stator vanes follow high rotor speed, which responds to fuel flow. The cycle requirements for the bleed actuator solenoid would be substantially less stringent than those for the SVA solenoid because much of the bleed solenoid operation is saturated hard against the open or closed stop.

Other basic requirements were:

- Rise time to 63% flow in less than 5 ms, and preferably less than 3 ms to be compatable with the 65 Hz duty cycle.

- Maximum standoff pressure of 83 Kg/cm^2 (1200 psi)ΔP, which occurs during a servo regulator failure. Normal servo pressure would be 21 Kg/cm^2 (300 psi)ΔP or less.

- Flow requirements at 21 Kg/cm^2 (300 psi)ΔP were 10.8 Kg/hr (24 pph) for the fuel metering valve and 360 Kg/hr (800 pph) for SVA and bleeds to provide a maximum rate of change of 100% in 1 second.

- Leakage flow less than 1%

- Unit to unit flow variation less than 20%

- Nominal coil voltage = 28 volts, and current limited to .5 amps

The solenoid specification including these requirements was sent to several vendors with aerospace and automotive experience. A majority of these vendors felt that the requirements for a solenoid for the fuel metering system were within their design and fabrication experience. The resulting solenoid would be of a modified off-the-shelf variety. Modifications would most likely include hardened seats and metal pintles.

The solenoid would weigh approximately 0.22 Kg (0.5 lb), have a failure rate of approximately 2 failures/million hours, and cost $560.

D.3.b <u>Alternator</u>

The alternator power requirements were derived by plotting the power requirements of each element of the system (CPU and memory, plus all solenoids) versus the high rotor speed spectrum, as shown in Figure 6. It was assumed that 15 watts would be needed to drive each solenoid for each modulated loop and 6 watts for each discrete solenoid. The plot assumes a transient condition where all outputs are active. Alternator sizing is based on this worst case condition and therefore results in excess power which must be dissipated in steady state conditions when most outputs are not active.

Three different types of alternators were evaluated: 1) permanent magnet, single wound; 2) permanent magnet with separate windings for each solenoid; and 3) saturable reactor.

An alternator vendor analyzed control system power requirements and determined size, weight, cost, and reliability of a single winding permanent magnet alternator. Incremental values of size, weight, cost, and reliability were then determined for the other two alternator configurations.

The permanent magnet alternator represents the lightest, most reliable method of power generation and is the conventional approach for a control dedicated alternator. Its primary disadvantage is that it is a constant current device producing considerable excess power that must be dissipated in the control when effector demand is low. This unit would be 4.3 cm (1.7 in.) X 9.4 cm (3.7 in.) diameter, would weigh 0.765 Kg (1.7 lbs), cost approximately $2100 and have a failure rate of 10 failures/million hours.

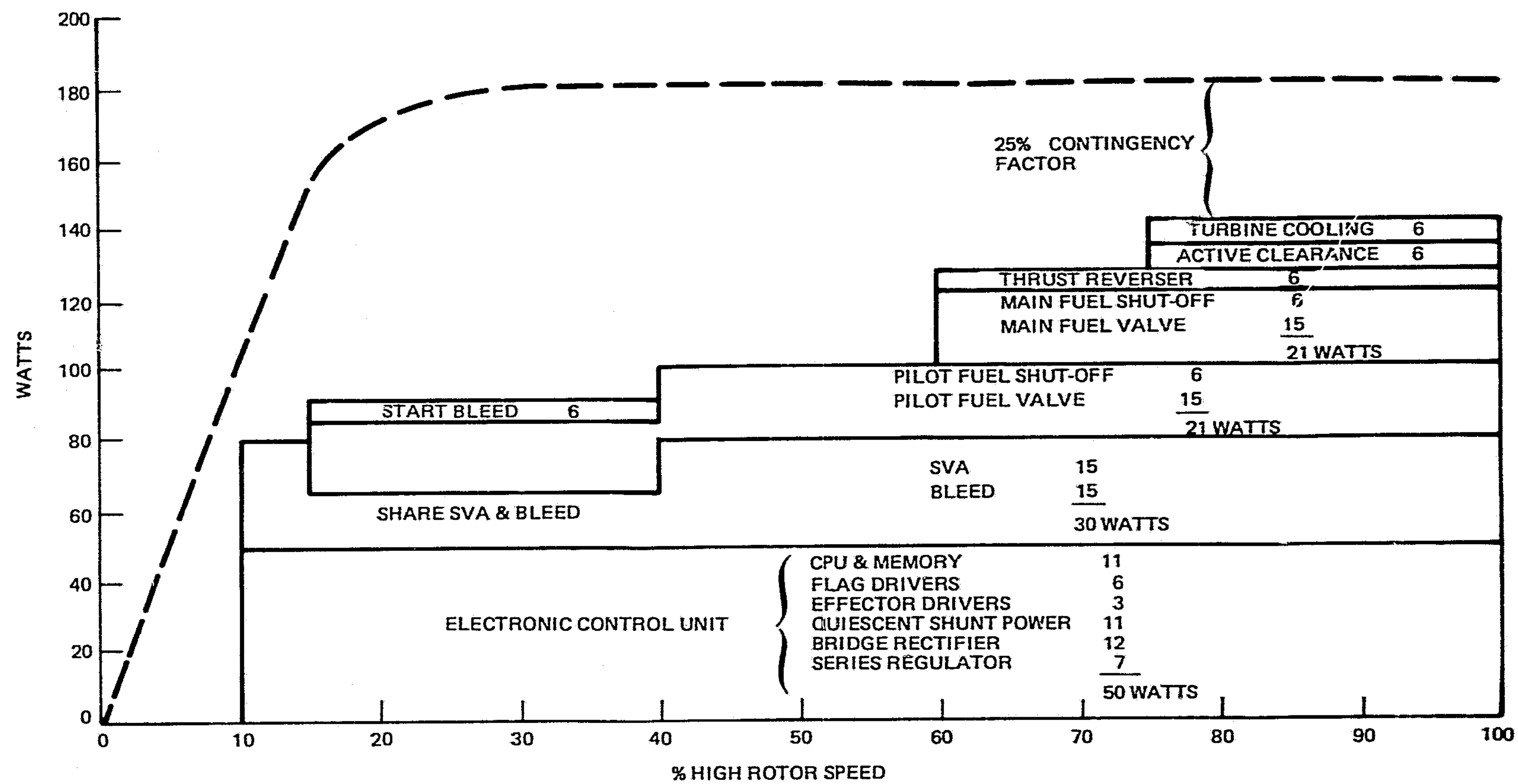

Figure 6 Maximum Control Power Dissipation

The multi-winding alternator would allow close matching of the power generated to the power required at each operating condition, thereby minimizing excess power dissipation. This alternator configuration would require some sort of crude power conditioning for each solenoid winding. The multi-winding configuration would increase alternator length by 1.9 cm (0.75 in.), increase weight by 1.0 Kg (2.2 lbs), increase cost by $600, and increase failure rate by 3 λ (failures/million hours). Increased failure rate is a result of the 14 additional crude power conditioning units and 14 power switches which are located at the alternator.

The saturable reactor alternator configuration utilizes a saturable reactor winding in the alternator as part of the power conditioning circuitry. This circuitry inside the ECU then senses output voltage from the alternator and provides feedback/drive to the saturable reactor winding. The saturable reactor, then, reacts as an AC shunt. As a result, alternator power generation is matched with load requirements and power dissipation in the ECU is minimized. Primary disadvantages of this approach are excessive voltage overshoots which can result during high load switching operations and significant weight increase over the single winding permanent magnet alternator. Compared to the single winding permanent magnet alternator, the saturable reactor alternator is the same diameter but 5 cm (2 in.) longer, weighs 1.35 Kg (3 lbs) more, has a higher failure rate of 13 failures/million hours and costs $1000 more.

D.3.c <u>Power Conditioning Circuitry</u>

Two basic concepts for power conditioning were considered for use with the permanent magnet alternator: dissipative shunt and switching shunt. A third approach using the saturable reactor was also considered and is discussed in the previous section on alternators.

In the dissipative shunt, shown schematically in Figure 7, the three-phase alternator output is full wave rectified to $\pm$ 14 VDC. Solenoid power as well as low voltage series regulation is extracted from the 14 VDC bus. The dissipative shunt is used in the baseline control system. All alternator power in excess of system demand must be dissipated in the control by the shunt transistors. Figure 7 and Table I show a typical worst case power dissipation for the regulator, assuming steady state conditions with two actuators active. For this case, 118 watts may have to be dissipated by the dissipative shunt, or about 60 watts per leg. To prevent excessive junction temperatures in the control, this power would have to be divided between eight dissipation transistors which would require considerable circuit board area. (The number of transistors was determined from a thermal analysis based upon an electronic unit with no supplementary cooling, but relying solely on nacelle cooling when mounted on the engine fan case.)

In the baseline system the dissipative shunt is located internal to the electronic control unit, but as a separate component it would weigh 0.6 Kg (1.3 lbs), cost $700, and have a failure rate of 5.2 failures/million hours.

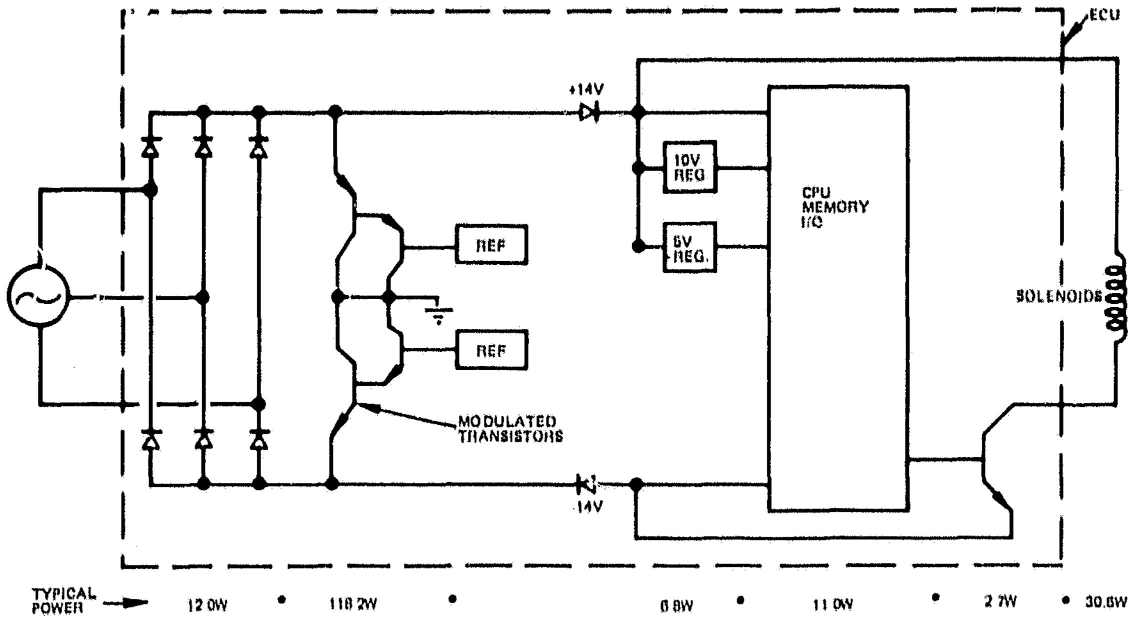

Figure 7 Internal Dissipative Shunt

TABLE I

TYPICAL ECU POWER DISSIPATION (2 ACTUATORS ACTIVE)

Dissipative Shunt	Solenoids
o Input Bridge	12.0 W
o Electronics	11.0 W
o Series Regulators	6.8 W
o Drivers	2.7 W
o Shunt Regulators	118.2 W
* Total EEC	150.7 W
o Effector power	30.6 W
* Total System	181.3 W

The switching shunt power supply, shown schematically in Figure 8, regulates the 14V bus by short circuiting the alternator output when alternator power exceeds bus demand. A control circuit drives a high power (5-7 amp) switch that is open when the 14V bus is low, allowing full alternator power to be rectified and sent to the filter capacitors. If the bus voltage exceeds 14V, the control circuit puts the switch in the conducting mode, whereupon the rectified power is shorted directly to ground. Diodes downstream of the power switches prevent the filtering capacitors from discharging through the switch.

Figure 8 and Table II show a typical worst case power dissipation for the switching shunt.

When the switch is in the non-conducting mode, power dissipation consists mainly of the I^2R losses of the bridge rectifiers (12 watts). When the switch is in the on state the I^2R losses of the switches are added to the power supply dissipation. These losses average 17.5 watts under worst case conditions (minimum solenoid demand) and are due to the 1 Ω resistance of the switch.

As a separate unit, the switching shunt would weigh 0.6 Kg (1.3 lbs), cost $812, and have a failure rate of 6.5 failures/million hours.

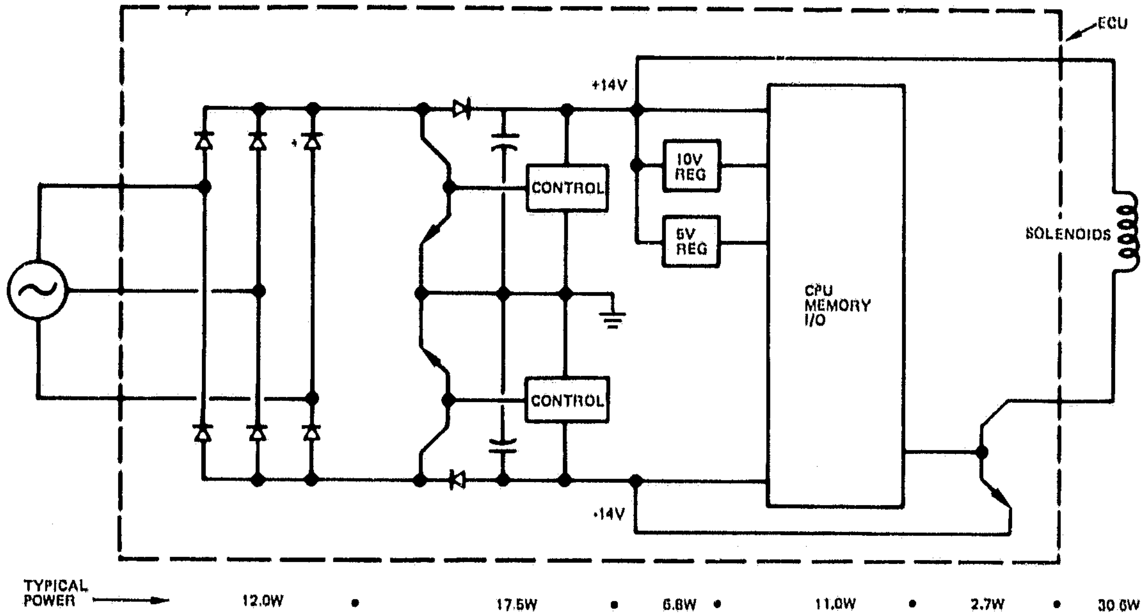

Figure 8 Internal Switching Shunt

TABLE II

TYPICAL ECU POWER DISSIPATION (2 ACTUATORS ACTIVE)

Switching Shunt	Solenoids (S.S.)
o Input Bridge	12.0 W
o Electronics	11.0 W
o Series Regulators	6.8 W
o Drivers	2.7 W
o Shunt Regulators	17.5 W
* Total EEC	50.0 W
o Effector Power	30.6 W
* Total System	80.6 W

D.3.d Electrically Activated Power Switch

The high temperature solid state switch proposed is a gallium arsenide (GaAs) junction field effect transistor (JFET), shown in Figure 9, which is directly compatible with computer outputs. GaAs has a higher operating temperature and lower power loss capability than silicon (Si). A bandgap of 1.4ev for GaAs versus 1.1ev for Si gives GaAs approximately a 100°C operating temperature advantage over Si. GaAs also exhibits five times greater electron mobility (lower resistance) than Si at room temperature (27°C). This mobility advantage increases to eleven at 300°C.

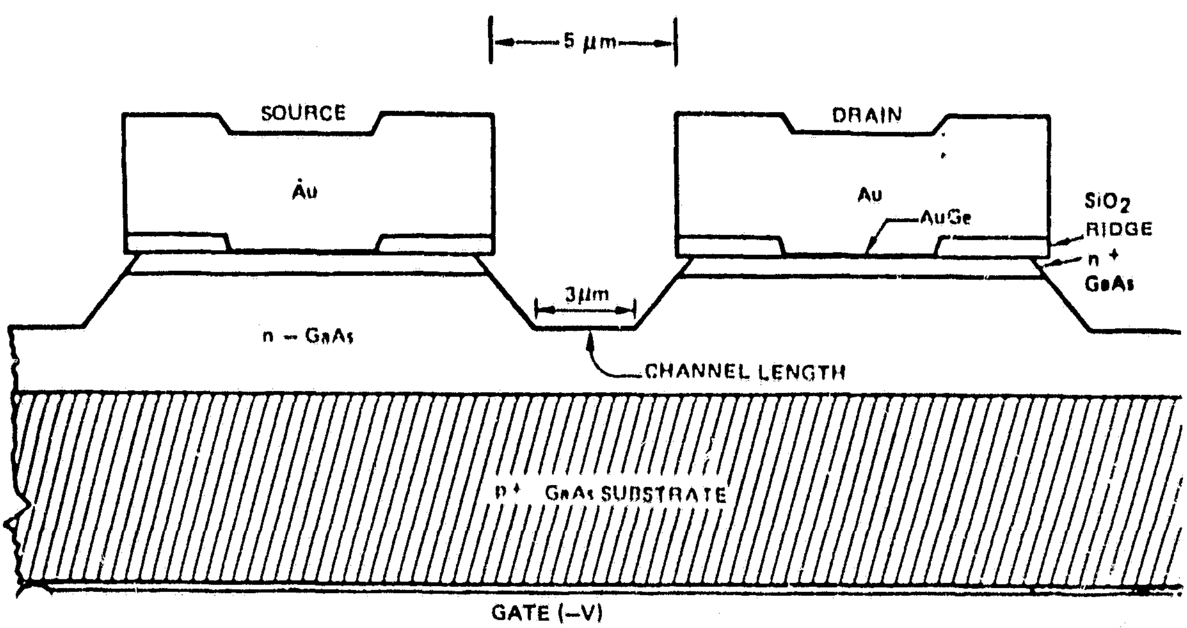

Figure 9 Cross Section of JFET Finger Pair

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Partially offsetting this mobility advantage is the fact that the thermal conductivity of Si is three times better than that of GaAs at room temperature. This advantage falls to about two at 300°C. Consequently, the overall figure of merit advantage (i.e., electron mobility times thermal conductivity) still rests with GaAs. A disadvantage of GaAs technology over Si technology is the present lack of a good technique for obtaining good surface passivation and isolation between a number of devices on a single chip. When Si is exposed to oxygen, a good insulation (i.e., SiO_2) is grown on the surface of the silicon. Such a simple procedure for obtaining good insulators on the surface of GaAs is not presently on hand.

The GaAs JFET switch, shown in Figure 9, is a p^+/n junction device in which negative bias voltage applied to the p^+/GaAs substrate can be used to control the width of the carrier depletion region and thereby control the current flow between source and drain in the n/type layer. Pinch-off of current between source and drain occurs at some value of applied gate voltage characteristic of carrier concentration and channel thickness. In order to increase device current capacity and decrease resistance, many finger-pair elements must be connected in parallel to form an interdigital structure as shown in Figure 10. Electrical characteristics of the power switch are shown in Table III and additional detailed information can be found in Reference 3.

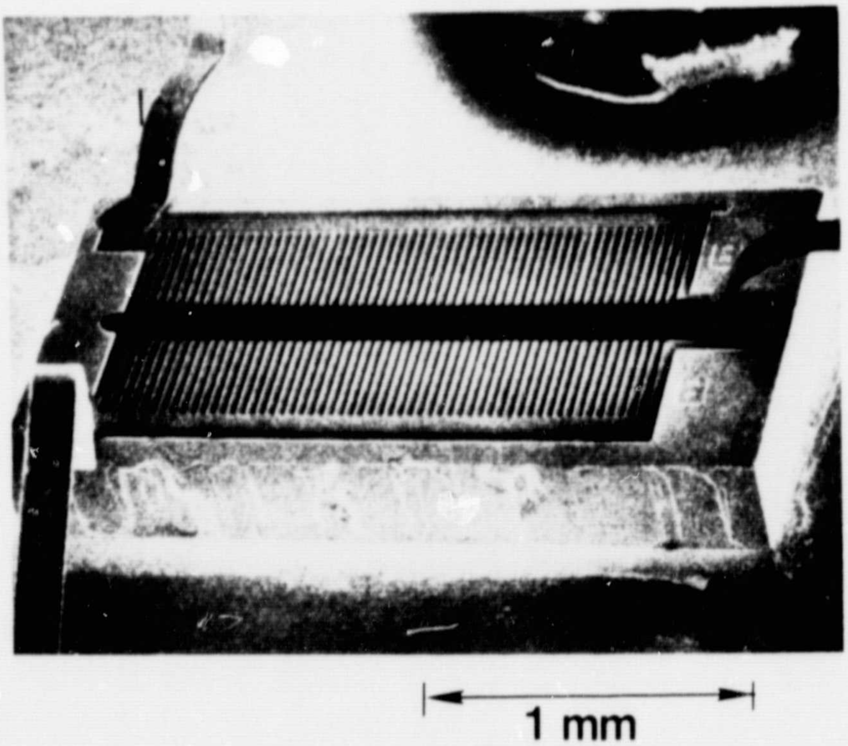


Figure 10 JFET on Wafer

TABLE III

GaAs POWER SWITCH CHARACTERISTICS

Current Switched	1 amp
Maximum "On" Resistance	1 ohm (200°C)
Applied Turn-off Voltage	-10 volts
Power Source Voltage	+28 volts
Ambient Temperature	200°C
Maximum Gate Leakage	.001 amp

Figure 11 shows schematically how the device can be used for control of solenoid DOI's. The JFET approach was chosen since the device has a low on-state resistance and can utilize a low-power digitally compatible input for switching the device into the off-state. The high temperature capability allows the switch to be remotely mounted at the actuator location. Diode protection of the switch is required to prevent switch destruction due to excessive counter EMF that occurs when the coil voltage collapses. The switch is mounted in a standard TO-5 package.

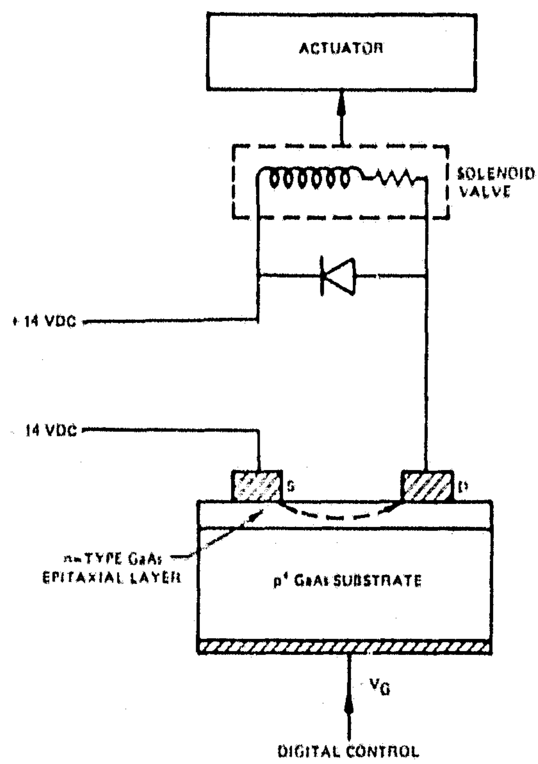


Figure 11 Electronic Control Using GaAs JFET Switch

Weight of the GaAs power switch is approximately 2 grams, cost is approximately $75, and the failure rate is projected at 0.2 failures/million hours.

D.3.e Photo Activated Power Switch, Source and Circuitry

D.3.e.1 Power Switch

The photo activated switch provides the ability to electrically isolate the power switch from the computer command. This reduces the impact of electromagnetic interference, false signal actuation and electrical ground problems.

There is no hope of operating a silicon photo receiver at a temperature of 175°C such as would be required at the actuator location. Present silicon photo receivers are not usable beyond 100°C to 125°C, where their dark current becomes large compared to current generated by photon energy. A GaAs photosensitive device could be developed that would operate as shown in Figure 12 at 175°C if 700 μW of optical power were to be supplied to the photo receiver. Also it may be possible to create a GaAs phototransistor with gain, which would need only 70 μW of optical power.

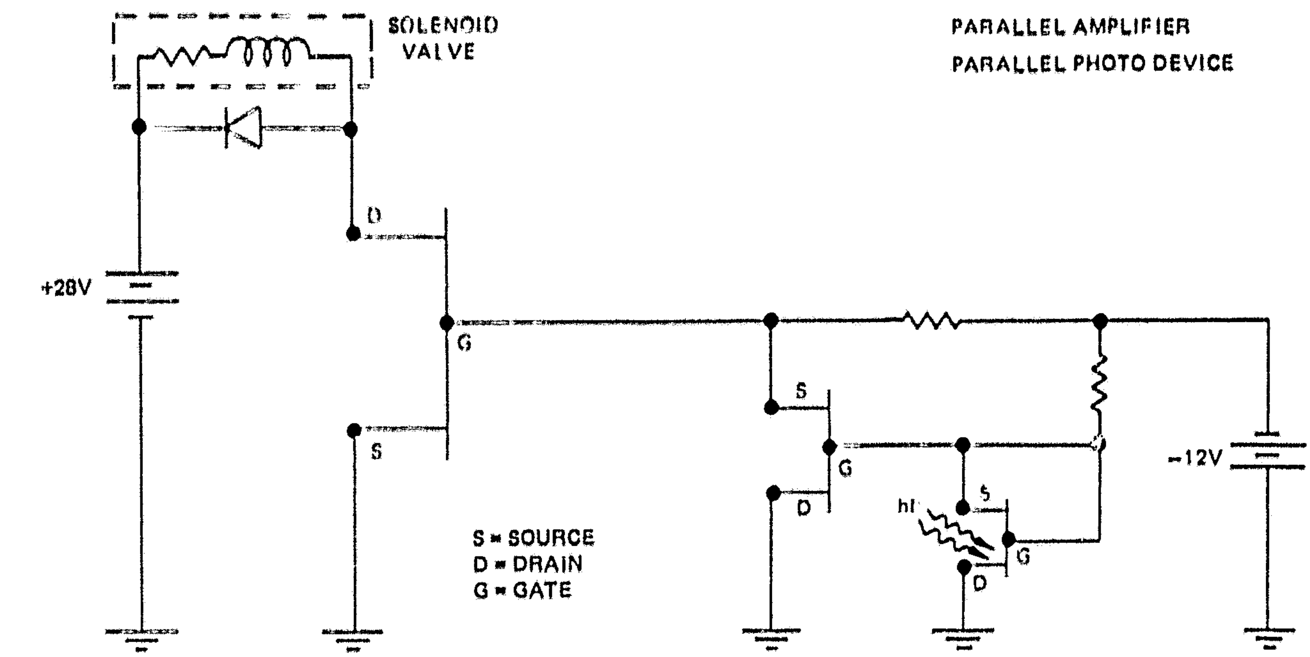
The power switch would be a three-stage device consisting of a GaAs photo cell, GaAs driver, and a GaAs JFET electric switch all mounted on a single monolithic chip. This switch would also require diode protection against excessive counter EMF if used to activate solenoids.

Weight of the photo activated switch is approximately 2 grams, cost is $75, and the failure rate is estimated at 0.3 failures/million hours.

D.3.e.2 Optic Source and Circuitry

There are two candidates for the optic light source, a Light Emitting Diode (LED) and a Laser Diode (LD). LD development is a rapidly growing technology, and the LD is projected to have an efficiency advantage of 10/1 over the LED for the mid-1980's. The present disadvantage of the LD is its inability to operate reliably at the temperatures found in the electronic control unit. However, technology advances are expected to increase the LD capability to the 125°C range necessary for reliable life inside the control unit.

The use of an LD instead of an LED will still result in high power requirements for the output interface. To determine this power requirement, it is first necessary to determine the optic power which must be generated in the electronic unit to provide a minimum of 70 μW of power at the optic power switch.



	GaAs POWER JFET (p^+/n)	GaAs JFET AMPLIFIER (p^+/n)	GaAs PHOTO JFET (p^+/n)
NO ILLUMINATION	OFF	OFF	OFF
WITH ILLUMINATION	ON	ON	ON

Figure 12 Optically Activated Power Switch

Present fiber optic technology as used on the FADEC program shows a 16 db power loss from the light source to the optic receiver. This includes a 7 db loss coupling the optic source to the fiber bundle, a 3 db loss at the first connector, a 3db loss in the cable, and a 3 db loss at the receiver connector. These losses are based upon the use of 5.0 db/M of a high loss cable. Such high loss cable has good light acceptance at its input, and thus represents an optimum choice for a short cable. Thus the total loss is 16 db or a factor of 39.81. While further improvements in connector and cable efficiencies are likely, these effects were not included. Losses for degradation of polished optical surfaces in connectors were also not included. Thus, to deliver just 70μ W of light power, 70μ W times 39.81 or 2.787 mW of light must be generated over the full operating temperature range with the circuit design of Figure 13 and the following assumptions:

1) 0.003 watts of optic power needed from LD

2) electric to optic efficiency of 1.5%

3) 2VDC LD driver

4) 14VDC control bus voltage

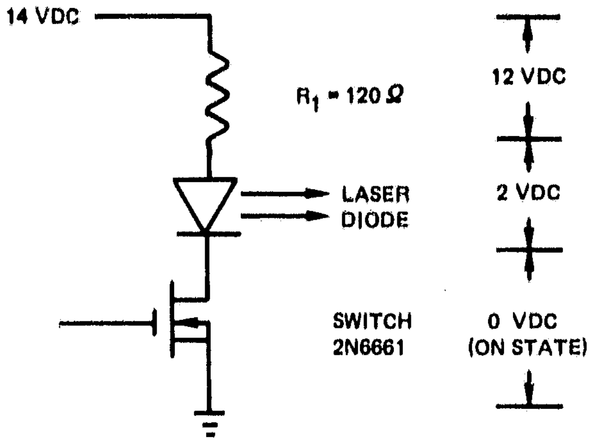


Figure 13 Light Source Circuit

The following calculations determine the power required for each optic driver:

1) 0.003 watts/.015 efficiency = .2 watts LD power

2) $I = \frac{P}{V} = \frac{0.2}{2} = 0.1$ amps LD current

3) $R_1 = \frac{E_1}{1} = \frac{12}{0.1} = 120\ \Omega$ dropping resistor

4) $P_T = E \cdot I = 14\ \text{VDC} * 0.1 = 1.4$ watts total circuit draw

From the above equations, maximum power for the output interface would be 1.4 watts for each modulated loop, and for each discrete in operation. Thus, the worst case would be:

o four modulated loops	5.6 watts
o primary fuel on	1.4
o secondary fuel on	1.4
o active clearance on	1.4
o turbine cooling on	1.4
o start bleed off	---
o thrust reverser off	---
	11.2 watts

As a result of the efficiency differences between the LD and LED, an LED could require as much as 10 times as much power for the same worst case condition. Therefore, the laser diode was selected.

D.3.f Cabling

Cabling requirements were evaluated for the following three basic system configurations:

(1) the baseline system

(2) power switches at actuators - electrical switching

(3) power switches at actuators - optical switching

Based upon the approximate component locations on the engine as indicated in Figure 4, representative cable diagrams were generated for each of the three subject configurations, to define cable type, length, shielding requirements, and number of connectors. Cable costs and weights were then calculated based upon the following assumptions.

- Cabling costs were evaluated for production quantities.
- All electric cables are #20 gage shielded twisted pairs except for the three phase A/C cable and optical pyrometer cable, each of which contain three #20 gage conductors within an outer shield.
- All optic cable is composed of seven fibers and each cable carries one discrete signal.
- Electric cable weight = 0.031 kg/m per shielded twisted pair
- Electric cable cost = $3.96/m per shielded twisted pair
- Optic cable weight = 0.0165 kg/m per seven fiber cable
- Optic cable cost = $3.96/m per seven fiber cable
- Outer shield weight = 0.218 kg/m
- Connector weight and cost are determined from generalized curves versus number of pins.

The resulting cabling costs and weights are summarized in Table IV.

The failure rate for a complete system of cables is assumed to be $\lambda = 5$.

TABLE IV

CABLE COST AND WEIGHT SUMMARY

		1979 Differential cost = dollars	Total Weight Kg (lbs)
Scheme 1	Baseline	0	7 (15.3)
Scheme 2	Switches at Actuator	+1161	7.3 (16.1)
Scheme 3	Optically Commanded Switches	+ 987	6.4 (14.0)

D.3.g Actuation Systems

D.3.g.1 Fuel Metering System

The Fuel Metering System is shown schematically in Figure 14. Operation is similar to the system described in Appendix A. The complete fuel metering system would consist of two of these systems built into one casting.

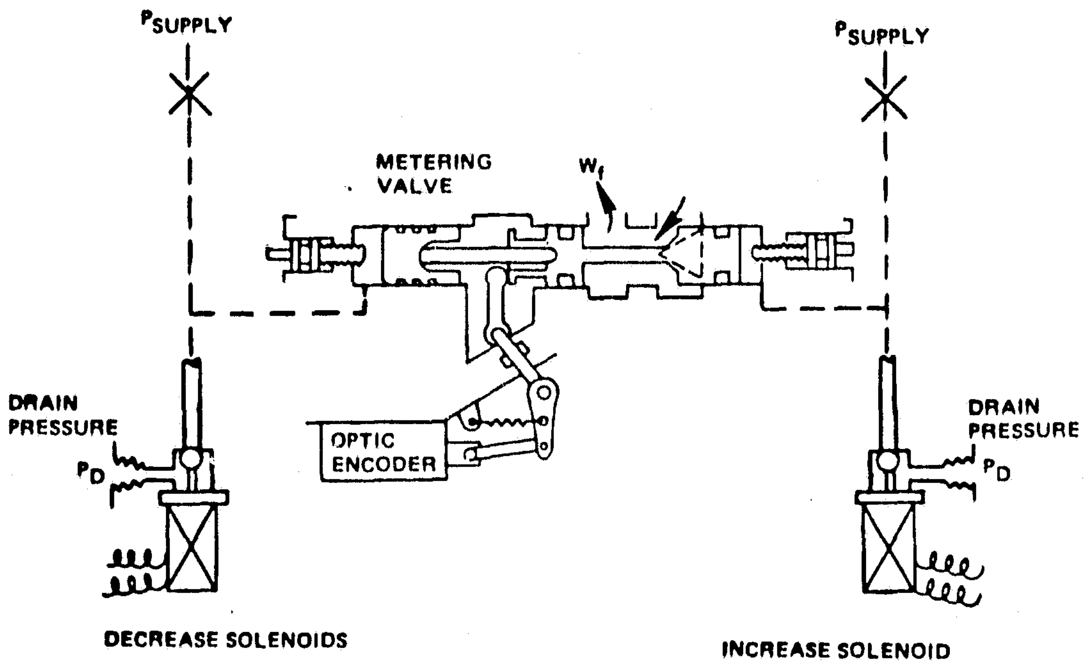


Figure 14 Fuel Metering System

D.3.g.2 <u>Geometry Actuation Systems</u>

The high force levels required for variable geometry actuation result in excessively high flow requirements for typical servo control solenoid valves.

This problem is best illustrated by considering the following example which was derived from typical variable geometry actuator data.

o Actuator output force requirement:	900 Kg (2000 lb)
o Actuator pressure area:	26 cm^2 (4.0 in^2)
o Actuator stroke:	5.0 cm (2.0 in)
o Pressure drop required to support force:	34.6 Kg/cm^2 (500 psi)
o Slew rate required	5 cm (2 in.)/sec

To meet the above slew rate requirement, a servo valve flow requirement of 360 Kg/hr (800 pph) is required.

The 21 Kg/cm^2 (300 psi) pressure differential assumed for typical servo pressure is obviously insufficient to hold the steady state actuator force. A 48 Kg/cm^2 (700 psi) pressure differential, presently used on JT9D's, was therefore assumed for the following geometry calculations.

To generate this flow with the assumed pressure drop available across the servo valve requires a flow area on the order of 0.039 cm^2 (0.006 in^2).

If a simple poppet type of solenoid valve design is considered, flow area can be derived from the following equation:

Flow area = π Dh,

where: D is the valve seat diameter
h is the poppet lift.

Due to practical air gap limitations associated with simple solenoid design, a maximum poppet lift of 0.025 cm (0.01 in.) may be assumed.

This translates into a valve seat diameter of more than 0.45 cm (0.18 in.). The 0.45 cm diameter pintle seat would require a 13.5 Kg a (30-lb) spring preload to prevent solenoid flow in the event the servo regulator fails to 83 Kg/cm^2) (1200 psi). This is determined as follows:

$$\text{Preload} = \left(\frac{D}{2}\right)^2 * \pi * \Delta P \qquad \begin{array}{l} D = \text{pintle diameter} \\ \Delta P = \text{servo pressure} \sim \text{psi} \end{array}$$

$$\text{Preload} = \left(\frac{0.18}{2}\right)^2 * \pi * 1200$$

Preload = 30 lbs.

The present DOI solenoid demonstrator uses a 0.36 Kg (0.8 lb) spring preload, and requires a coil current of 15 watts. A 13.5 Kg (30 lb) spring preload would require a substantially larger coil and more current. Even if this were a feasible approach, the increased servo pressure has an adverse effect on pump heat rejection during idle descent transients. The E^3 engine that this control is based upon has more stringent pump requirements than present production engines. Therefore, increased servo pressure would aggravate the pump heat rejection problem.

The solenoid limitation problem can be solved by adding a second stage or servo amplifier stage between the solenoids and actuator. Figure 15 illustrates the basic principles of both the singlestage and two-stage alternatives. The second stage of the two-stage device is a spring centered spool valve with overlapped control ports to minimize leakage across the load piston when at null. This feature serves to reduce solenoid valve activity thereby improving solenoid valve life and reliability.

A two-stage device was assumed for both the stator vane and bleed actuators in this program. For the servo stage itself, the weight is 0.34 kg (0.75 lb), cost is $910, and the failure rate is 1.0 (failure/million hours).

D.3.g.3 <u>Multi Solenoid Geometry Actuation</u>

The servo valve needed to amplify solenoid flow for the SVA and bleeds could be replaced by multiple solenoids, as shown in Figure 16, to obtain the required servo flow levels. A one-second actuator response rate would require ten (10) solenoids of the type used on the fuel metering valve to provide sufficient flow; however, advantage can be made of engine transient limitations, which require only a two-second SVA opening and a two-second bleed closing to follow normal transients.

Therefore, 15 solenoids are needed for each loop; 5 for bleed closing and 10 for bleed opening (pop open); 5 for SVA opening and 10 for SVA closing (reset).

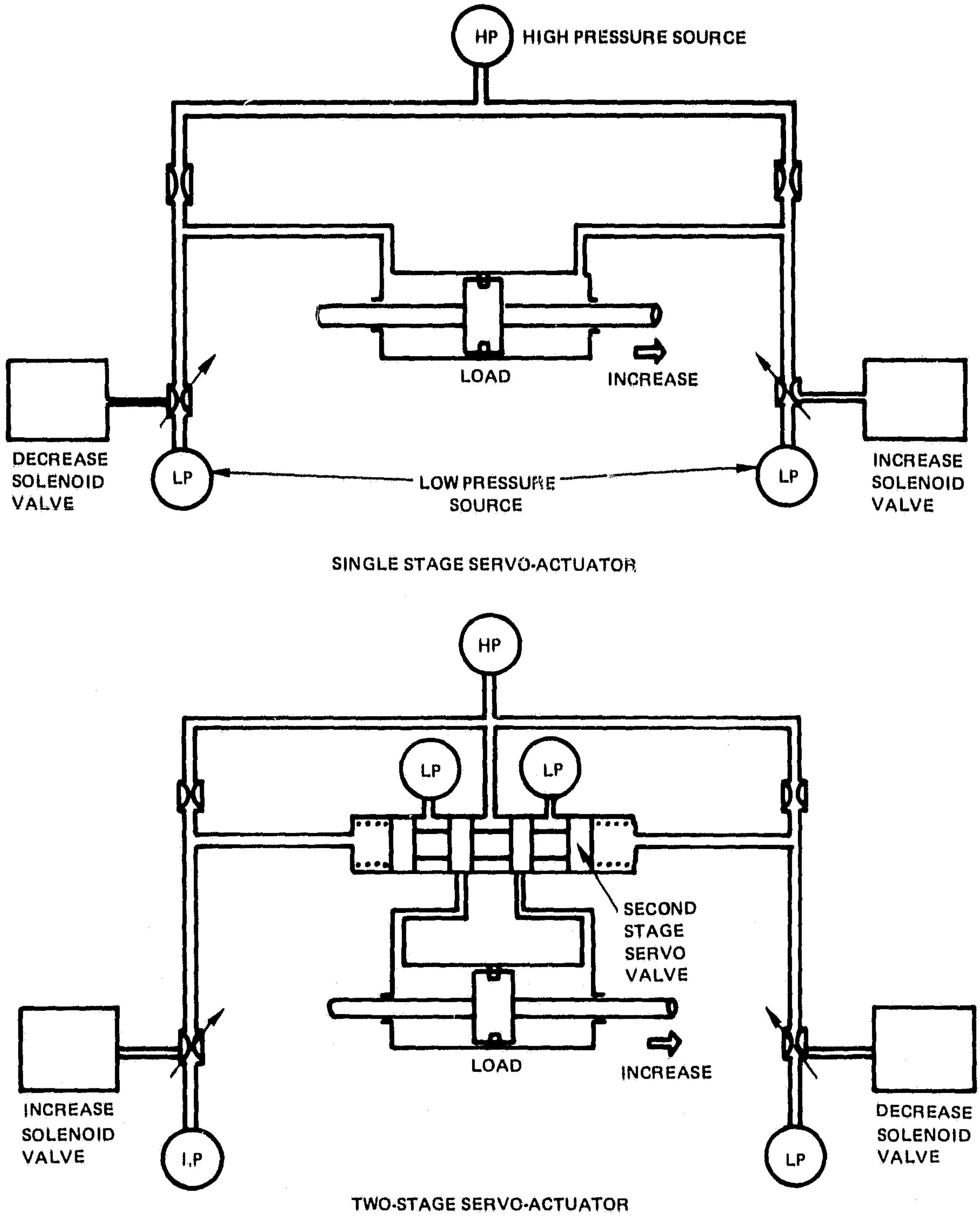


Figure 15 Servo Actuator Alternatives

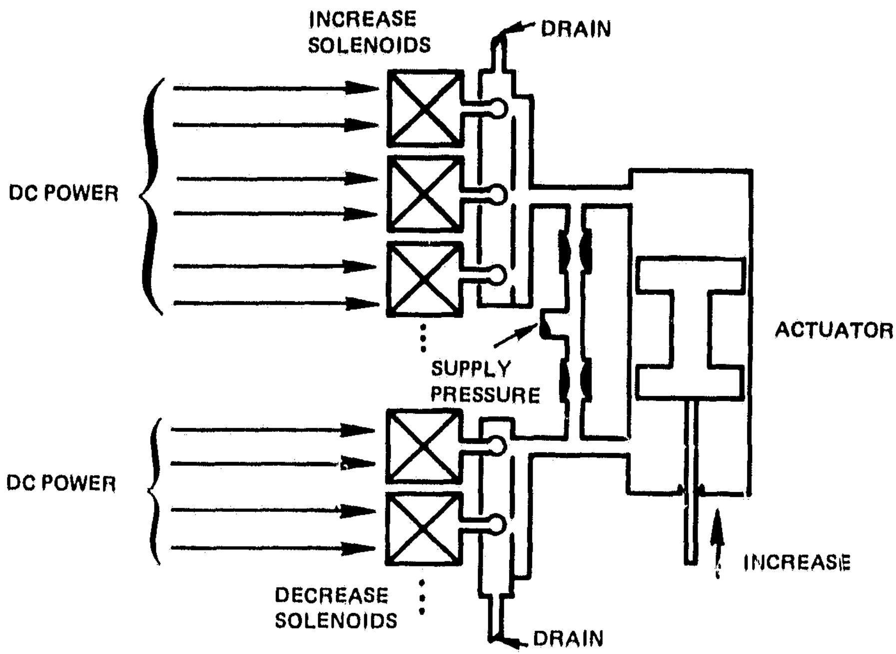


Figure 16 Multiple Solenoid Concept

Solenoid requirements are significantly relaxed using the multi solenoid configuration because most transients do not require maximum slew rate. Therefore, solenoid cycling could be rotated amongst the solenoids. The cycle requirements were assumed to be 25 percent of the two solenoid/servo configuration, or 10^8 cycles. The reduction in cycles allows the use of less expensive off-the-shelf solenoids that cost approximately 1/4 as much as high cycle solenoids, and still retain overall system reliability.

Alternator size and reliability are not affected by this configuration because only one solenoid is required to hold the bleeds open and the stator vanes closed during starting. Above start, the alternator would have sufficient speed (power output) to activate all the solenoids. The alternator used with this mode would have the same cost, weight, and reliability as the other schemes, but would have a different winding.

It is noted that mission reliability levels for such a system would be superior to the two-stage actuation system since it could tolerate several solenoid failures with the only consequence being reduced rate capability.

D.3.h Discretes

The solenoid valves for the six discrete functions were not fully defined, but were assumed to be two-stage devices (i.e., servo assisted), to allow a low power consumption of six watts per solenoid. Based on previous experience at Hamilton Standard, a failure rate (λ) of 4 failures/million hours was assumed. Weight of each unit was estimated to be 0.45 Kg (1 lb) and cost was estimated to be $350.

D.4 ALTERNATIVE SYSTEM CONFIGURATIONS

A number of alternative control system configurations were established with power dissipation circuitry external to the electronic unit and various locations for the power switches external to the electronic unit. The power switches were either electrically or optically activated. Consideration was also given to AC power switches driving AC solenoids. Other alternative configuration concepts were established utilizing multiple solenoid actuation systems and pulse width modulated torque motors in place of solenoids. From these various concepts, a matrix of configurations was established for which LCC and failure rate were calculated for comparison with the baseline system, shown schematically in Figure 17a.

Nine alternative configuration concepts are discussed in the following sections. These are:

- o Electrically activated power switch at actuator
- o Optically activated power switch at actuator
- o Electrically activated power switch at alternator
- o Optically activated power switch at alternator
- o Electrically activated switch on alternator field
- o Optically activated switch on alternator field
- o AC solenoid variations
- o Multi solenoid geometry actuations
- o Torque motors with pulse width modulated drivers

Common to all of the concepts is the routing of solenoid electrical power around the electronic unit, thus eliminating the power dissipation within the unit associated with conditioning power required by the solenoids.

D.4.a Electrically Activated Power Switch At Actuator

A simplified system schematic diagram of the solenoid control paths with this advanced DOI concept is presented in Figure 17b. Compared to the present DOI concept discussed in Appendix A, this advanced concept relocates in the alternator assembly the rectification and that power conditioning circuitry necessary for satisfactory solenoid performance. Power conditioning circuitry in the electronic unit is reduced to that necessary for satisfactory operation of the electronics. The relatively coarse regulated DC output from the alternator circuitry is supplied directly to power switches located within the DOI fuel metering and actuator components. The power switches turn the solenoids on and off through command signals from the electronic unit. Switch activation requires very little power and the electronic unit command signal requires only a line driver as an output interface element to accommodate the cabling impedance.

The major technology item needed to implement this concept is the power switch. The current capacity required for the solenoids used in the DOI demonstration system is nominally 0.45 amps at 28 VDC. No device is presently on the market which combines this level of current capacity, sub-millisecond switching time necessary for satisfactory pulse width modulation, and capability for operation at the 162°C (325°F) maximum sink temperature associated with fuel metering and actuation components. However, the gallium arsenide junction field effect transistor (JFET) desecribed earlier, has been demonstrated to more than satisfy these requirements.

The other technology items needed to implement this concept are power conditioning circuit components with capability to operate at the 177°C (350°F) temperature extreme associated with the alternator package.

D.4.b Optically Activated Power Switch At Actuator

A schematic of this concept is presented in Figure 17c. The system architecture is similar to the concept discussed above. However, the power switch is optically activated via fiber optic signal transmission from a light source in the electronic unit. Light emitting diode (LED) and fiber optic cable technology is available to implement this concept. However, United Technologies Research Center (UTRC) investigations of optically activated GaAs JFET power switch have indicated that the material doping required to enhance photo activation characteristics was not consistent with that required to provide current switching capacity. Therefore, a single, optically activated device could not be projected. Experiments at UTRC have indicated that an optically activated JFET device could be developed with capability to activate the JFET power switch. The resulting output circuit for this approach is shown on Figure 18.

Compared to the electrically activated power switch concept, the optic command approach replaces the line driver in the electronic unit output interface with a current driver and LED circuit. Fiber optic cabling replaces an electrical cable with potential improvements in cost, weight, and reliability. The optic signal transmission aspect of this concept eliminates EMI problems in the output command cable area.

D.4.c Electrically Activated Switch At The Alternator

A schematic diagram of this system concept is presented in Figure 17d. The concept is functionally indentical to that with the switch located at the actuator, except that the power switch has been located within the alternator assembly. This concept eliminates the need for any solid state electronics at the actuators.

D.4.d Optically Activated Switch At The Alternator

Figure 17e shows a schematic of this concept. The concept is functionally similar to the optically activated switch located at the actuator except that the switching control elements are located in the alternator assembly.

D.4.e Electrically Activated Switch On Alternator Field

This concept is pictured schematically in Figure 17f. Instead of opening and closing the circuit between the alternator and the solenoids as in the previous schemes, this concept switches the alternator winding to ground. This concept requires a separate alternator winding and an electrically activated GaAs JFET switch, located at the alternator, as shown in Figure 19, for each of the system's 14 solenoids. A separate alternator winding would be required to supply the electronics, and the associated power conditioning circuitry could be located completely in the electronic unit.

The circuit configuration requires using the GaAs JFET as a shunt device in order to preclude allowing a large alternator open circuit voltage (300 to 400 volts) being generated which would exceed the GaAs standoff capability. The benefit of this approach is a complete divorcing of the solenoid electrical power source from the ECU. The rectifiers, transient suppression diode and the JFET are all assumed to be GaAs and located in the vicinity of the alternator.

D.4.f Optically Activated Switch On Alternator Field

This concept is shown schematically in Figure 17g and differs from the preceding arrangement by the use of an optic command path from the electronic unit.

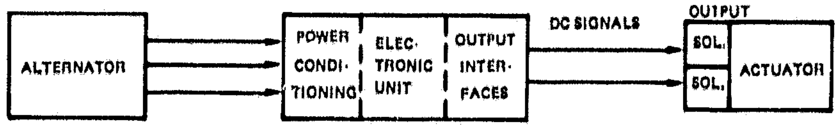


Figure 17a Baseline System Concept

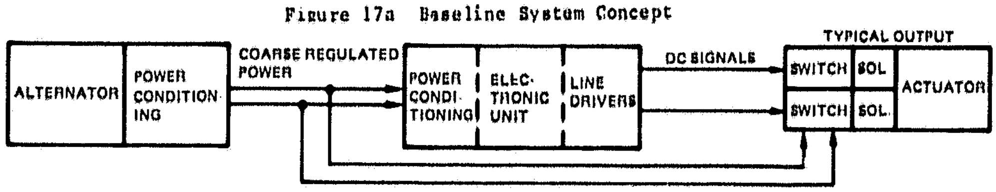


Figure 17b Concept With Electrically Activated Power Switch at Actuator Location

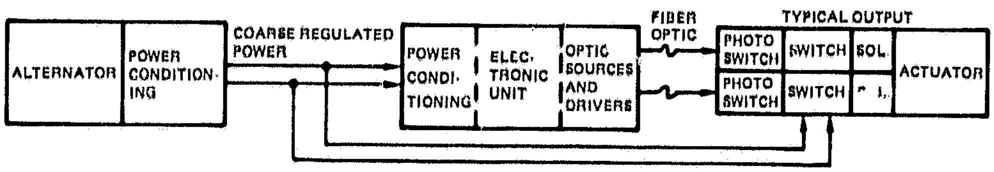


Figure 17c Concept With Optically Activated Power Switch at Actuator Location

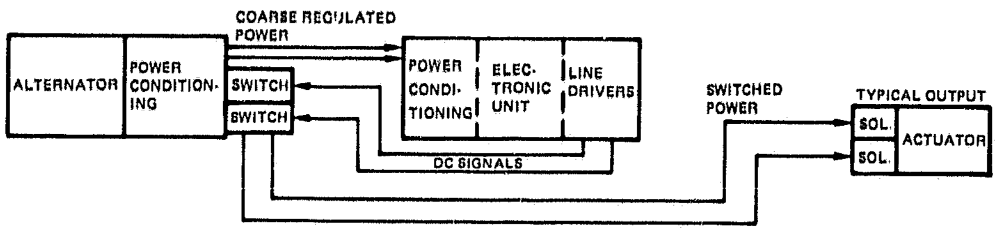


Figure 17d Concept With Electrically Activated Power Switch at Alternator Location

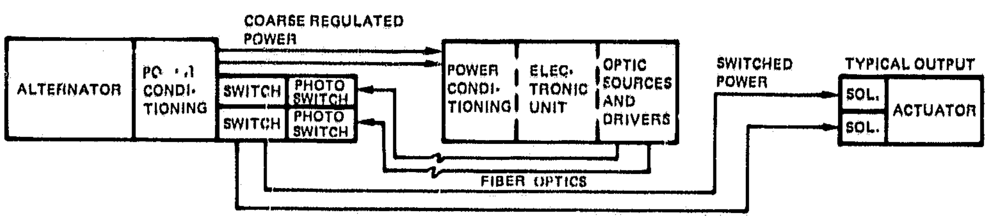


Figure 17e Concept With Optically Activated Power Switch at Alternator Location

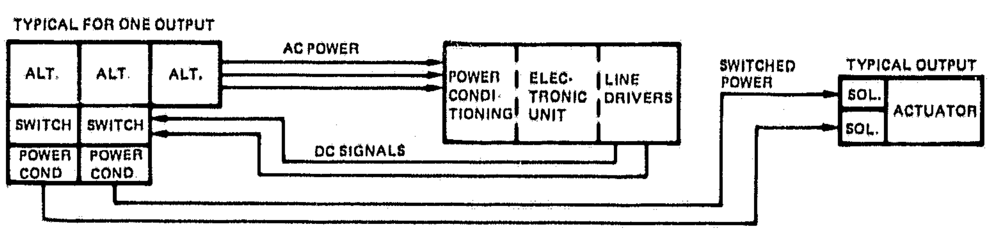


Figure 17f Concept With Electrically Activated Switch on Alternator Field

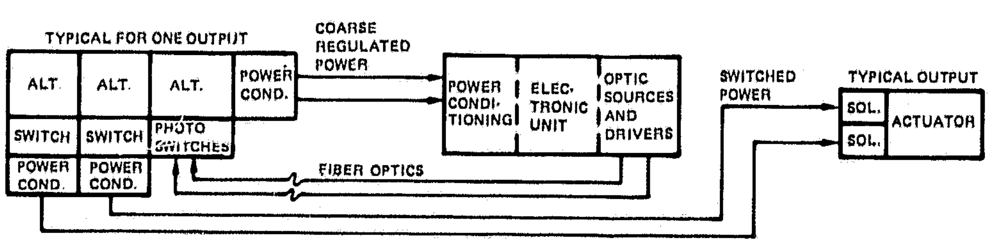


Figure 17g Concept With Optically Activated Switch on Alternator Field

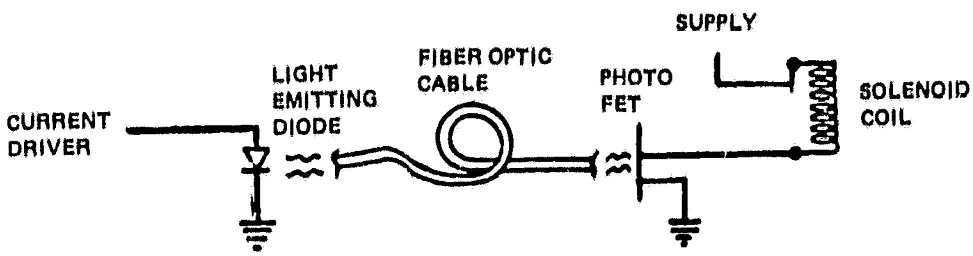


Figure 18 Optically Activated Power Switch Circuit

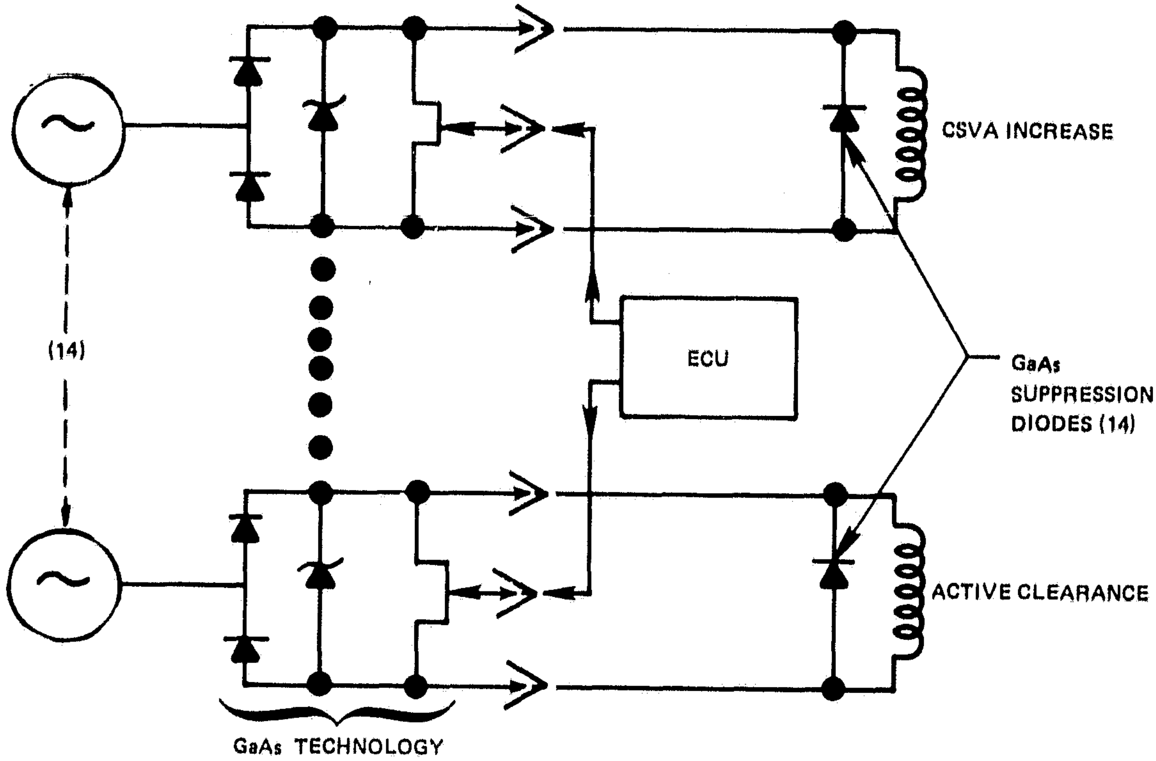


Figure 19 Electrically Activated Power Switch on Multiple Alternator Windings

D.4.g AC Solenoid Variations

Initial comparison of the AC solenoid relative to the DC equivalent was not encouraging. All manufacturers contacted were strongly against the AC device for numerous reasons including these:

- An AC solenoid design would be larger and heavier than its DC counterpart.
- AC solenoids run hot due to eddy current losses.
- Some manufacturers supply DC solenoids with internal rectification as 'AC solenoids'.
- No manufacturer contacted had experience of AC solenoids operating with variation in AC supply frequency (typically 10:1 for the turbine engine application).
- Available experience appeared to be limited to constant frequency applications (60 Hz or 400 Hz).

These limitations of AC solenoids in combination with a requirement for an extensive program to develop a high temperature AC power switch, and the impact of AC solenoids on the alternator design resulted in elimination of AC solenoid configurations from further evaluation.

D.4.h Multi Solenoid Geometry Actuation

The stator vane and bleed actuator flow requirements can be met by using multiple solenoids in lieu of servo stages. This mode would require fifteen solenoids for each loop. Solenoid switches could be located in the electronic control unit, on the solenoid, or on the alternator. The system evaluated had switches located in the electronic control unit. Each solenoid would have its own separate driver to permit digital modulation and thus reduce solenoid cycling.

D.4.i Pulse Width Modulated Torque Motors

Torque motors with pulse width modulated (PWM) drivers could be used in lieu of solenoids and servos for the stator vane and bleed actuators. The two fuel loops could also use pulse width modulated torque motors. A hybrid system with torque motors for SVA and bleeds, and solenoids for fuel flow modulation was evaluated along with a system using torque motors on all these actuation systems.

The PWM interface and torque motor scheme applies saturation current to the coils at all times, and hence does not require a well-regulated power supply. PWM carrier frequency to the coils is 400 Hz or higher, which is well above the coil frequency of 100 Hz. As a result, the coil acts as an averaging filter, and the flapper valve or jet pipe deflector modulates to the average coil current. Torque motor manufacturers feel that the PWM approach will not impact torque motor durability, but such a system has never been tested at P&WA.

E. SYSTEM TRADE STUDIES

The basic approach for determining the best control system configuration was to determine cost, weight, and reliability for each of the system building blocks and from these to calculate LCC and reliability for each of the alternative system configurations and the baseline control system. Components included in the control system were: alternator; power conditioning circuitry; electronic control unit; power switches; fuel flow metering unit and solenoids; solenoids and servo stage for the stator vane and bleed actuation systems; solenoids for discretes; and all cabling. Fuel pumps, fuel lines, actuator rams, sensors, and communication links with the aircraft were not included.

The alternate control system configurations evaluated are summarized in Table V. It is noted that the majority of these system configurations utilize a switching shunt power conditioning circuit located in the electronic control unit, whereas the configurations discussed in the previous section assumed an external power supply. A control system configuration, scheme 2a on Table V, with an external switching shunt power conditioning circuit was also evaluated.

TABLE V

CONFIGURATION MATRIX

	Power Conditioning			Power Switch					
				Type			Location		
Config. No.	Dissipative Shunt In ECU*	Switching Shunt in ECU*	Shunt On Alternator	Silicon	GaAs	Optic GaAs	ECU	Actuator	Alternator
0	X			X			X		
1		X		X			X		
2		X			X			X	
2A			X		X			X	
3		X				X		X	
4		X			X				X
5		X				X			X
6		X	M/W		X				X
7		X	M/W			X			X
8		X		M/S			X		
9		X		T/M			X		
10		X		T/M*			X		

T/M - Torque motors used for modulated effectors
T/M* - Torque motors used for SVA + bleed, solenoids for fuel flows (2)
M/S - Multi solenoids used for SVA + bleed
M/W - Multiple winding alternator. Separate shunt regulator for each of 14 solenoid/winding pairs. Control processor uses switching shunt located in electronic control unit
* - ECU - Electronic control unit.

Selection of the internal switching shunt for the system trade studies was based upon a separate trade study of power conditioning concepts which is discussed in a following section. The system considered for the power conditioning trade study consisted of the alternator, the power conditioning circuitry, and the electronic control unit. This trade study of power conditioning concepts was conducted prior to the complete system trade study, since it was found that selection of the power conditioning concept was not affected by variations in the output driver configurations.

The following sections discuss procedures for calculating the life cycle cost and failure rates for the control system configurations which were evaluated.

E.1 LIFE CYCLE COST AND RELIABILITY CALCULATIONS

The life cycle cost (LCC) for each scheme was based on the sum of the LCC of each of the building blocks over the useful life of the control system. A useful life of 50,000 hours was assumed for this study. LCC is the sum of the following:

1) Procurement Cost - Cost of the component of the control system, including spares, for each engine. The number of spares includes the components of control systems on spare engines plus a number of spare components determined from the component's failure rate, as shown by the curve in Figure 20. This curve was estimated by Hamilton Standard to reflect requirements for support of a domestic fleet which utilizes both field support bases and a central depot repair facility.

2) Fuel Cost - Cost of the fuel required to fly the weight of the component for 50,000 hours on a wide-bodied transport. This is estimated at $850 per kilogram.

3) Maintenance Labor Cost - Each building block was charged a different number of service hours per failure, based on airline data and Pratt & Whitney Aircraft estimates. The labor charge is service charge per failure times the expected number of failures/50,000 hours.

4) Maintenance Material Cost - Each building block was given a material cost per failure based on airline data and Pratt & Whitney Aircraft estimates. Material cost is the cost per failure based on airline data. Material cost is the cost per failure times the number of failures expected in 50,000 hours for that component.

Total control failure rate is the sum of the failure rates (λ) for each component. (λ = the number of expected failures per 10^6 hours.)

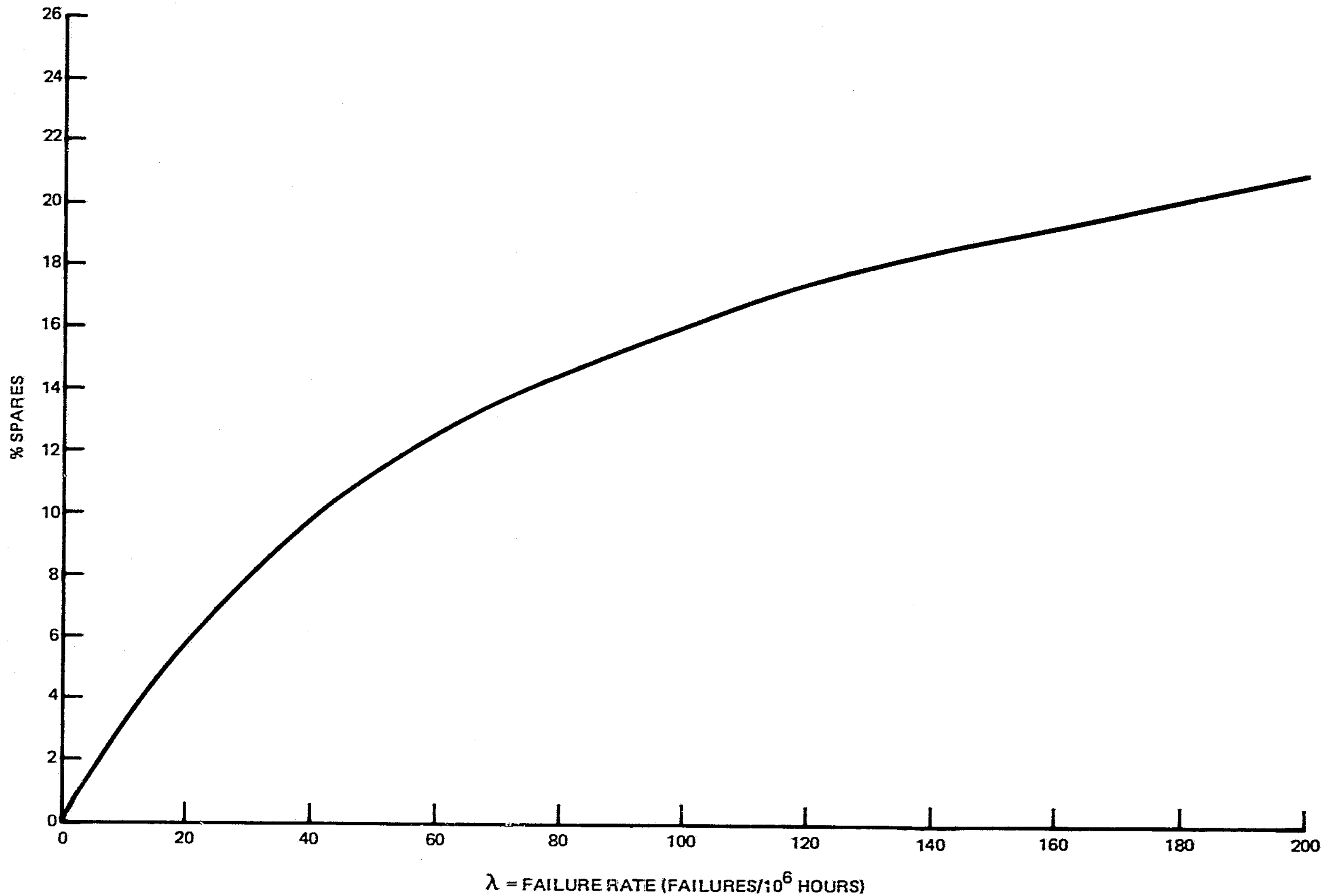


Figure 20 Spare Criteria - Number of Spare Units vs. Failure Rate of the Unit

The control system configuration with the lowest LCC and failure rate should normally be declared the winner; however, LCC and failure rate numbers are usually based on mature components for the time frame projected. Thus, while two configurations may have similar LCC's and failure rates, one may require high technology development programs to develop critical elements. A typical example of this situation is the trade between optic and electrically activated GaAs switches. Both switches were given the same cost, weight, and reliability; however, the non-recurring cost and risk of the optic switch development program are substantially greater than for the electrically-activated switch. Thus, in some instances, a small improvement in LCC and/or failure rate may not be worth the cost of the required development program.

E.2 Electronic Control Unit Thermal and Reliability Analysis

A necessary step in the trade-off evaluations was to ascertain the impact of various power supply and driver concepts on the reliability of the ECU. An accurate reliability assessment required a thermal analysis to define the average junction temperatures of the electronic devices in the ECU.

A preliminary mechanical design of the ECU was established to define best locations of electrical components to minimize junction temperatures. A computerized thermal model of the ECU, which is fan case-mounted and relies on natural convection and radiation for cooling, was then generated. Key components such as the shunt transistors were monitored individually, while other low-power components were characterized by the area they occupied on a particular circuit board assembly. The model was based upon a 4-circuit board design with the junction temperatures of devices on each circuit board analyzed.

Initial thermal analysis results were reviewed to ascertain if established guidelines were met. The present Hamilton Standard guideline for engine-mounted fuel controls is a maximum of +110°C for the device junction temperatures, although +125°C has been accepted by many government agencies as an acceptable guideline. As a result of this review, several design modifications were implemented to conform to the reliability guidelines. As an example, the shunt transistors in the baseline power supply required four devices in parallel to share the load in order to conform to the junction temperature guidelines.

The thermal model was then run for four test cases:

Case 1 Baseline system - internal dissipative shunt power supply and solenoid drivers

Case 2 Internal switching shunt regulator and solenoid drivers

Case 3 External switching shunt regulator and internal solenoid drivers

Case 4 External switching shunt and external solenoid drivers

Since this study was to determine the relative merits of each approach, only one environmental condition was analyzed, and the failure rates were modified to reflect the effects of the mission profile. The thermal analysis was conducted at a worst case anticipated temperature condition 88°C (190°F) ambient air. This case was chosen to assure the integrity of the thermal design in this application.

The results of the thermal design analysis are summarized in Table VI. Using these junction temperatures, Mean Time Between Failures (MTBF = $1/\lambda$) data were generated for the four cases based upon projections of the type of devices available in the mid-1980's, the extrapolation of existing trends, and the assumption of production maturity for each system. The MTBF's are presented in Table VII.

TABLE VI

RESULTS OF THERMAL ANALYSIS OF THE ELECTRONIC CONTROL UNIT

Case	Average Junction Temp.*	Peak Junction Temp.*
1	132°C	137°C
2	105°C	115°C
3	97°C	110°C
4	96°C	110°C

*At 88°C Ambient Temperature

TABLE VII

ELECTRONIC CONTROL UNIT RELIABILITY

Case		MTBF
1	149	6,700 hrs.
2	106	9,400 hrs.
3	100	10,000 hrs.
4	98	10,200 hrs.

F. POWER CONDITIONING TRADE STUDY RESULTS

In Section D.3, "Building Blocks," two power conditioning concepts were described for use with the permanent magnet alternator. These were the dissipative shunt, which was assumed for the baseline control system, and the switching shunt. A third approach, the saturable reactor, was also described, which required a modification of the alternator design. Tables I and II in Section D.3.c showed typical worst case power dissipation in the electronic control unit for the dissipative shunt and switching shunt concepts, respectively.

Power dissipation in the ECU can be further reduced for both the dissipative shunt and switching shunt concepts by moving the shunt and rectifier portions of the power conditioning circuitry out of the ECU and mounting them on the alternator. An example of this approach for the switching shunt concept is shown in Figure 21. Remote mounting of the power conditioning circuitry on the alternator would result in an improvement in reliability of the ECU, as shown in Section E.2. For the baseline system, the ECU with an internal dissipative shunt has a failure rate (λ) of 149 failures per million hours, or an MTBF of 6700 hours. Moving the power conditioning circuitry out of the ECU reduces the ECU failure rate to 100 failures per million hours, or an MTBF of 10,000 hours.

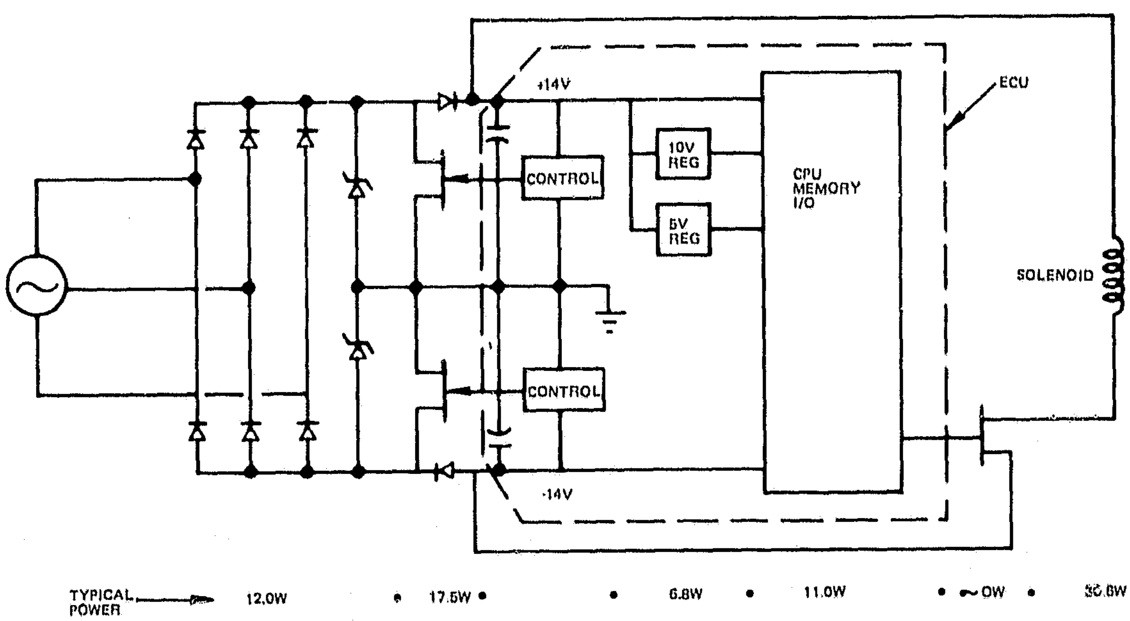


Figure 21 Concept for External Power Dissipation -- Switching Shunt

This improved reliability of the ECU could be obtained by mounting either a dissipative shunt or a switching shunt-type power conditioning circuitry on the alternator. Implementation of either would require, as a minimum, the development of a high temperature switch to tolerate the alternator environment's 177°C (350°F) maximum temperature, and accommodate 5 to 7 amps of current. This would require a substantial research and development program to extend the capabilities of the GaAs switch, which has been demonstrated to accommodate 1 amp at these temperature extremes. Both external power conditioning concepts would also require high temperature rectifiers, which would require only a modest development program.

For the dissipative shunt, each switch noted above would dissipate 5 to 7 watts; so, at least 20 switches (10 in parallel in each leg) would be required to accommodate the excess power from the alternator (up to 120 watts) during steady state conditions. This would impact cost and failure rate for this approach. In order to reduce the number of switches, a GaAs switch would be required which could dissipate higher power. Concepts for such a switch do not presently exist, which implies that a research and development program for such a switch would be very costly and have a high risk of failure. For these reasons, the more conservative GaAs switch requirement was assumed for the external dissipative shunt.

For the remote switching shunt, only two of the switches noted above would be required; so this power conditioning concept would have a reliability advantage over the remote dissipative shunt. However, the ECU reliability calculations presented in Section E.2 show that the switching shunt, incorporated in the ECU, provides a reduction in failure rate from 149 for the dissipative shunt to 106 failures per million hours for the switching shunt. Thus, the benefits of an additional improvement in ECU failure rate of 6 failures per million hours for the remote switching shunt would have to be traded against the cost and risk of the required development programs.

LCC calculations were made for the following power conditioning concepts, and were compared with the baseline system's internal dissipative shunt:

A. Dissipative shunt mounted at the alternator

B. Switching shunt internal to the ECU

C. Switching shunt mounted at the alternator

D. Saturable reactor.

In order to avoid having to evaluate all of these power conditioning concepts for all of the system configurations, the power conditioning concepts were first evaluated by themselves, compared to the baseline system's dissipative shunt, without regard to the configuration selected for the output interfaces. The system evaluated for this power conditioning trade study included the alternator, power conditioning circuitry, and the ECU. Alternative output interface configurations did not affect selection of the best power conditioning concept in terms of LCC and failure rate. The selected power conditioning concept was then used for the detailed trade study of the control system.

Results of the power conditioning trade study, in terms of differentials from the baseline system, are summarized in Table VIII, and more detailed results are shown in Appendix D.

TABLE VIII

TABULATION OF LIFE CYCLE COST* FOR THE VARIOUS POWER CONDITIONING CONCEPTS EVALUATED

System	Initial Cost	Weight Kilograms (Pounds)	Reliability Failures Million Hours*	Maint. Material Cost -$-	Maint. Labor -$-	Procurement Cost -$-	Weight Factor -$-	Maint. Cost -$-	Total -$-
External Dissipating Shunt	+2506	+.1	-42	-345	-191	+2322	-54	-536	+1732
Switching Shunt in ECU	+84	0	-43	-323	-242	-592	0	-565	-1157
External Switching Shunt	+406	-.2	-46	-357	-239	-369	-170	-596	-1135
Saturable Reactor	+686	+.9	-46	-323	-239	+4	765	-562	+207

*All numbers are deltas from the dissipating shunt

The dissipative shunt mounted on the alternator reduces ECU failure rate by 49λ's, some of which is negated by charging the alternator with an additional 7λ's because of the addition of the GaAs electronics. This configuration had the highest LCC, due to the cost of the many GaAs elements mounted on the alternator.

The switching shunt internal to the ECU has the lowest LCC, due entirely to improved reliability, which results in reduced maintenance and reduced inventory of spare line replaceable units. Reduced heat dissipation, and hence lower junction temperature in the ECU, makes a reduction in failure rate of 43 λ possible.

An external switching shunt with GaAs switches and rectifiers mounted on the alternator provides the most reliable system because all the power supply heat dissipation has been removed from the ECU. The LCC of the external switching shunt is higher than the internal switching shunt because the electronic circuits added to the alternator cost more than the circuits removed from the ECU.

The saturable reactor had a higher LCC than the switching shunt configurations because of the high cost and weight of the alternator with a saturable reactor. The saturable reactor is also prone to excessive voltage overshoots during high load switching operations.

The switching shunt located in the ECU was selected for the control system configuration trade studies primarily because it provides significant improvements in LCC and failure rate over the dissipative shunt without requiring a major development program for the power switches.

G. CONTROL SYSTEM TRADE STUDY RESULTS

A summary of the tradeoff study results for the various alternative configurations is shown in Table IX. Detailed charts for each system configuration are presented in Appendix E. The basic conclusions from this study are:

1) The use of a switching shunt regulator in place of a dissipative shunt regulator provides the most significant improvement in control system reliability and LCC.

2) Remote mounted GaAs solenoid drivers provide no reliability or LCC advantages.

3) A hybrid system that uses solenoids for fuel control and substitutes torque motors with pulse width modulated drivers for solenoids in the stator vane and bleed control, results in a system that is slightly more reliable, and no more expensive than the lowest price solenoid system.

TABLE IX

SUMMARY OF TRADE-OFF STUDY RESULTS

System Configuration	Initial Cost -$-	Weight Kilograms (Pounds)	Reliability Failures/ Million Hours	Maint. Failures $/Million Hours	Maint. Material Cost -$-	Failures 50,000 Hours	Maint. Labor -$-	Procurement Cost -$-	Weight Factor -$-	Maint. Cost -$-	Total -$-
0	0	0	0	0	0	0	0	0	0	0	0
1	+84	0	-43		-323		-242	-592	0	-565	-1157
2	+2698	+.2	-42.2		-326		-217	+2725	+170	-543	+2352
2A	+2586	0	-45.2		-360		-215	+2374	0	-575	+1799
3	+2616	-.7	-40.7		-315		-209	+2509	-595	-524	+1390
4	+2728	+.5	-42.5		-326		-223	+2665	+425	-549	+2541
5	+2646	-.4	-41.0		-315		-215	+2449	-340	-530	+1579
6	+5318	+.7	-36.0		-265		-145	+6424	+718	-410	+6732
7	+5236	-.2	-34.5		-254		-137	+6208	-47	-391	+5770
8	+3837	+6.	+16.5		-136		-421	+4902	+7990	+285	+13177
9	+2632	-1.4	-47		+74		-290	+2774	-1190	-216	+1368
10	+392	-.9	-47		-66		-389	-207	-765	-355	-1327

Systems:
- 0 Baseline: Internal Dissipating Shunt, Internal Si Switches
- 1 Internal Switching Shunt, Internal Se Switches
- 2 Internal Switching Shunt, Electrical GaAs Switches On Actuator
- 2A External Switching Shunt, Electrical GaAs Switches On Actuator
- 3 Internal Switching Shunt, Optical GaAs Switches On Actuator
- 4 Internal Switching Shunt, Electrical GaAs Switches On Alternator
- 5 Internal Switching Shunt, Optical GaAs Switches On Alternator
- 6 Separate Alternator Windings, Electrical GaAs Switches On Alternator
- 7 Separate Alternator Winding, Optical GaAs Switches On Alternator
- 8 Internal Switching Shunt, Multi Solenoids On SVA + Bleeds
- 9 Internal Switching Shunt, Torque Motors
- 10 Internal Switching Shunt, Torque Motors On SVA + Bleeds Only

Most of the alternative configurations, listed in Table V, for which LCC and failure rate were calculated as shown in Table IX, assume the internal switching shunt power regulator that was recommended in the previous section. Schemes 0 and 2A are exceptions. Scheme 0 is the baseline system with a dissipative shunt, while scheme 2A is an external switching shunt presented to illustrate a system where the power conditioning and drivers are external and no effector power goes through the electronic control unit.

The switching shunt (Scheme 1) has an improvement of 43 λ in failure rate and \$1157 in LCC over the baseline dissipative shunt (Scheme 0) as shown in Table IX. Both modes use solenoid drivers mounted in the electronic control unit.

Control LCC increases when the solenoid drivers are relocated from the electronic control unit to the solenoids (Schemes 2 and 3, Table V). Increased LCC results from the fact that the cost of adding the GaAs power switch electronics to the solenoids is greater than the cost of removing electronics circuits from the electronic control unit. Also the extra cable between the alternator and solenoids necessary to implement the schemes results in additional procurement cost and weight. ECU failure rate is reduced by 2 λ's because the drivers are moved to the solenoids. Driver heat dissipation has little effect on the ECU failure rate because the switches dissipate relatively small amounts of power. Solenoid reliability is reduced because of the addition of GaAs electronics, so overall system reliability remains about the same.

The optically-activated power switch configuration, Scheme 3, has a lower LCC than the equivalent electrical system, Scheme 2, because of lower acquisition cost and weight of the optic cables. Reliability of the optic system is lower than the electrical system because the failure rate of the optic driver is 2-1/2 λ's higher than that of the electrical driver.

Alternator-mounted drivers (schemes 4 and 5) increase LCC slightly compared to Schemes 2 and 3, due to incrased cabling cost and weight resulting from longer cable runs. Alternator costs increase due to the addition of GaAs power switches on the alternator, instead of the solenoid. A disadvantage of this configuration is that placing the driver on the alternator instead of the solenoid or ECU results in more difficult fault diagnosis, because failure of an actuation system can no longer be isolated to a single line replaceable unit.

The use of separate dedicated alternator windings for each solenoid (schemes 6 and 7) results in a significant increase in LCC, because a GaAs circuit for coarse power regulation along with the usual switch and diode protection would be needed for each of the 14 solenoids. The extra circuits and windings on the alternator result in a 6 λ increase in failure rate and a 0.225 Kg (0.5 lb) weight penalty. An open solenoid coil will result in a failure of a shunt GaAs JFET, thus propagating a fault to another line replaceable unit. Finally, this configuration results in distributing the effector system to three locations, creating a more difficult line replaceable unit fault isolation problem.

The use of multiple solenoids (Scheme 8) to replace the servo stage for the stator vane and bleed actuation systems resulted in the heaviest and highest LCC system. The extra cost of solenoid cabling and driver interfaces resulted in more than a $13,000 LCC increase over the baseline system. Approximately half of the extra $13,000 LCC was fuel penalty to carry the extra weight of the solenoids and cables. This system would have a very high mission reliability because of the fault tolerant ability of the control to compensate for a failed solenoid. Failure rate and maintenance charges would be higher, however, due to the high part count.

Pulse width modulated torque motors can reduce procurement costs for the stator vane and bleed actuation systems because the torque motor includes the servo. The fuel valves (2) could also be controlled by pulse width modulated torque motors (Scheme 9). A hybrid system (Scheme 10) consisting of torque motors for the stator vane and bleed and solenoids for the fuel valves has the lowest LCC because the fuel valve can be controlled with low cost solenoids without a servo amplifier stage, while the SVA and bleed use a torque motor that includes the servo valve. The use of torque motors or solenoids results in the same reliability; however, high cycle solenoids would require a development program.

The LCC equation does not include EMI susceptibility or radiation, fire survivability, or development risk, however these could be determining factors in systems with a similar LCC. All actuation schemes studied would produce approximately the same amount of radiated EMI, because a current step on the line between the alternator and solenoid occurs whenever a solenoid is activated. Switch location on the alternator, electronic control unit, or solenoid is not significant if the current an length of wire are approximately the same.

Optic activation would be immune to absorbed EMI, while the electrically-activated GaAs would be most susceptible because of the low signal levels used to activate the driver; however, the effects of absorbed EMI would be diminished to some extent because the response time of the solenoid would act as a natural filter. The ECU-mounted silicon drivers would be relatively free of EMI false activation because the low impedance of the solenoid coil would tend to ground the signal.

The results of the study show that significant heat dissipation can be removed from the electronic control unit by a power ciruit design change without the use of high temperature GaAs electronics.

Coarsely regulated power routed through the electronic control unit and switched with silicon (Si) switches is not detrimental because dissipation in the silicon switch is on the order of 0.5 watts per switch when the solenoid is being activated. Thus, moving the switches out of the electronic unit only decreases dissipated power by approximately 0.5 watts times the number of active solenoids, or about 2.7 watts for the typical power dissipation example shown in Table II. The remaining circuitry in the electronic unit to activate the power switches would be 0.002 watts per active solenoid.

Even though the remote power conditioning circuitry and remote power switch concepts have a small impact on reliability and life cycle cost, these configurations may be necessary in order to minimize EMI effects on the electronic unit. EMI may result from switching of the relatively high power signals required to activate the solenoids. With the high power lines routed through the electronic unit, EMI may have a detrimental impact on electronic unit operation. Potential EMI problems were not evaluated in this program since hardware was not built and tested for the power conditioning circuitry or output drivers.

Finally, torque motors with pulse width modulator drivers provide lower initial cost and, hence, lower LCC than solenoids when used in applications where servo flow requirements exceed single stage solenoid capabilities.

H. CONCLUSIONS

The following conclusions result from life cycle cost and reliability trade study:

1) The use of solenoids as effectors aggravates power dissipation in the power conditioning circuit, thereby reducing reliability in the electronic control unit.

2) The most effective way to reduce power supply dissipation is by changing the power conditioning mode from dissipative shunt to switching shunt. However, the non-sinusoidal output resulting from switching the alternator may result in unacceptable electromagnetic radiation.

3) Relocating the power conditioning circuit from the electronic control to the alternator gives a small improvement in overall system reliability, but would require a significant program to develop the GaAs technology necessary.

4) The use of GaAs switches mounted on the effector solenoids provides no overall improvement in system reliability, life cycle cost, or radiated electromagnetic interference.

5) The use of torque motors with pulse width modulated drivers may be an attractive alternative to the use of solenoids as effectors.

I. RECOMMENDATIONS

1) A switching shunt power supply should be built and tested for power regulation under large power transients, such as found with solenoid operation. The test should be made with the switches and diodes located on the alternator, as well as inside the electronic control unit, to check for EMI radiation. The test would have to be run with hardware that closely resembles production packaging, cabling and alternator for the EMI results to be valid.

2) A solenoid effector test should be conducted to investigate radiated EMI. The test rig would have to consist of hardware packaging, cabling and solenoid mounting that closely resembles production hardware to ensure valid EMI data.

3) A detailed trade study should be conducted to determine the merits of pulse width modulation of torque motors vs. solenoid effectors. This study would include in-depth design of production-type hardware to better evaluate cost, weight, reliability, and performance of both systems.

4) A pulse width modulated torque motor configuration should be build and tested against the solenoid effector configuration. An endurance test would be run on both systems to determine the effects on the coils and moving elements.

APPENDIX A

DIGITAL OUTPUT INTERFACE CONCEPT

NASA has recognized the burden carried by present systems employing analog servo drive and feedback measurements, and sponsored the Pratt & Whitney Aircraft Digital Output Interface (DOI) program (NASA Contract NAS3-19898) to identify and initiate development of a concept aimed at improving this vital functional area of digital electronic controls. During the DOI program, a novel concept defined by Pratt & Whitney Aircraft and Hamilton Standard was mutually selected with NASA, through a comprehensive trade study, as the most promising digital output interface approach for a fuel metering valve actuation loop. The DOI concept, shown schematically in Figure A-1, employs on-off solenoids as the servo device and an optic encoder for position feedback. The solenoids are pulse width modulated under software command from the control computer to provide digital modulation of metering valve velocity. The optic encoder provides a parallel digital word output requiring only simple light emitting diode (LED) and photo diode circuitry within the electronic control. Optic signals are transmitted between the encoder and the electronic control via a lightweight fiber optic cable. This concept virtually eliminates EMI susceptibility due to the on-off, amplitude-independent nature of the solenoid commands and the electrically passive optic sensor. However, the electrical cable required to couple the solenoids to the control must still be double shielded to reduce the radiated EMI to acceptable non-interference levels. The on-off nature of the solenoid power conductors is known to create significant EMI unless carefully shielded. Power regulation requirements for the output interface are also reduced with this concept relative to the analog approaches currently used.

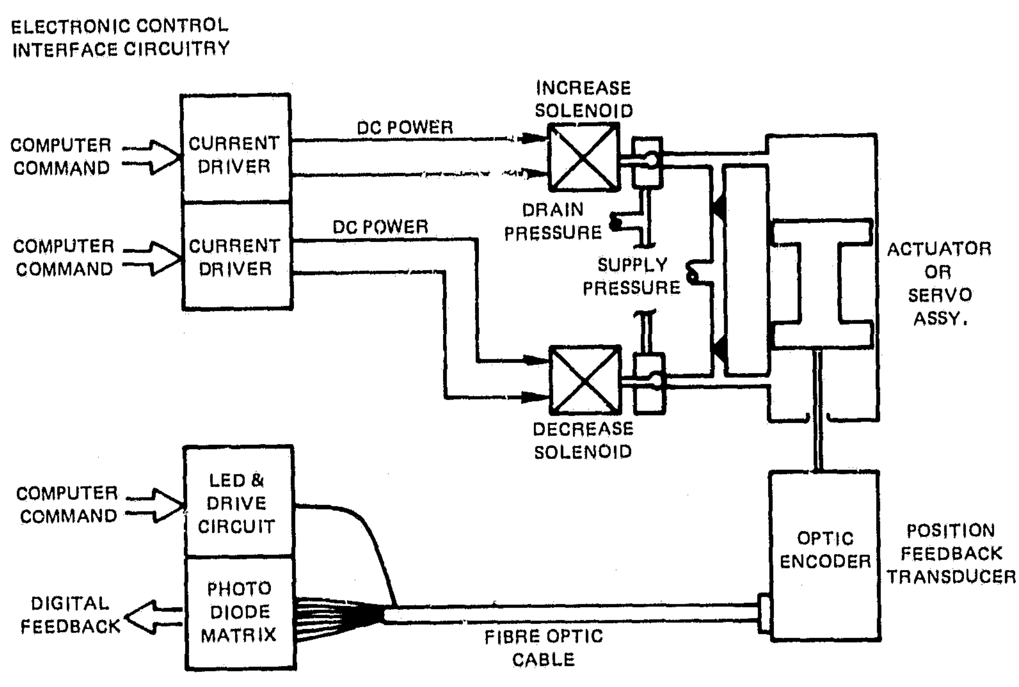


Figure A-1 Digital Output Interface System

APPENDIX B

COMPONENT ENVIRONMENT CONSIDERATIONS

Environment considerations play a significant role in the design of electronic control systems. Factors which have the greatest influence on electronic control design include temperature, vibration, and electromagnetic interference. However, these factors also play a major role in component selection for other elements in the control system, i.e., the alternator, fuel metering, geometry actuators, and electrical cabling. The following discussion is presented to illustrate the environmental exposure associated with the various engine control component areas which are relevant to incorporating advanced DOI concepts in the system design.

B.1 Temperature

Temperature environment is of particular importance to electronic control unit design, since the available silicon circuitry is generally limited to operation up to a maximum junction temperature of +125°C (+275°F), however, the overall average operating temperature exposure must be considered for operational reliability impact. Conductive, convective and radiant heat loads are considered carefully, along with internal heat generation, in the design process. Table B-I lists fuel and ambient temperature exposure profiles typifying subsonic transport applications.

Temperature environment is also of significant importance in the design of other control components. Fuel metering and fuel activated engine geometry actuators are inherently subjected to pumped fuel temperatures. System design measures are employed to ensure that extreme fuel temperatures do not exceed the coking point. Since the coking temperature with present fuels is approximately +162°C (+325°F), and may decrease with alternate fuels being considered for use in the future, this level closely represents the maximum requirement for servo and feedback elements located within the fuel metering and actuator components.

TABLE B-I

ELECTRONIC CONTROL FUEL AND AMBIENT AIR TEMPERATURE PROFILE DISTRIBUTION FOR A TYPICAL SUBSONIC TRANSPORT APPLICATION

Percentage of Life	Cooling Fuel Temperature	Nacelle Air Temperature
0.5%	68°C (155°F)	110°C (230°F)
10.5%	49°C (120°F)	88°C (190°F)
21.5%	32°C (90°F)	66°C (150°F)
57.0%	29°C (85°F)	48°C (119°F)
10.5%	18°C (65°F)	51°C (124°F)

The control alternator is engine gearbox mounted, where design measures are applied to limit maximum oil temperature to approximately 176°C (+350°F). The mass of the alternator results in relatively small impact from the ambient air, such that the oil temperature can be considered the sink level for electrical elements located in the assembly. It should be mentioned that the cold extreme temperature (typically, -55°C or -65°F) is significant to alternator design, since the magnetics are weakest at this condition.

Electrical and optic cabling are basically subject to the nacelle ambient environment. The extremes for even subsonic transport applications require materials selections in electrical connectors which result in cabling cost being a measurable contribution to system cost. This factor is one feason fiber optic signal handling shows potential benefits relative to electrical approaches. These cables are also subject to the potential of nacelle fires. Current design objectives require that the cable be able to withstand a 1100°C (2000°F) flame for five minutes and remain functional. Fiber optics also offer potential benefits compared to electrical cabling for this consideration.

B.2 Vibration

Vibration environment is a major consideration in the structural design of all control components. Although electronic controls have been successfully designed for hard mounting on engines, contemporary designs generally apply vibration isolation in the mounting brackets and occassionally on internal components, to maximize reliability. MIL STD 810C is generally used as an initial specification starting point, although engine vibration test data is acquired to determine the actual spectrum as soon as possible during the control installation design process.

B.3 Electromagnetic Interference

Electromagnetic interference is an essential consideration for design of an electronic control system. It is obvious that EMI within the system, i.e., signal noise, etc., is within the direct realm of influence of the system designers, and has to be eliminated or accommodated in the course of achieving satisfactory control performance during system development. EMI from outside the system is generally not within the control system designers' sphwere of influence. Although general specifications (i.e., MIL STD 461 and 462) are generally employed as design requirements and complied with in the design, actual exposure can vary significantly from application to application. Military applications pose the greatest design impact, as evidenced by the general use of double shielded electrical cabling with its attendant cost and weight. The advent of high power radar and other EMI sources has led to specifications for EMI fields of hundres of volts/meter at frequencies well past the Gigaherta range in some recent aircraft applications. Design treatment of the electronic control to meet these severe requirements involves careful treatment of all electrical lines penetrating the unit, usually adding structure and feed-through filer components to the basic design.

Lightning poses another EMI threat to the control system. Presently, electronic systems designers rely on double shielding and wire pair twisting to minimize induced voltages from lightning strikes on the aircraft.

APPENDIX C

SOLENOID RELIABILITY CALCULATION

Specifications to the solenoid vendors were for a mean cycle between failure of 5 X 10^8 cycles.

If we assume the solenoid failure distribution fits a standard Weibull curve, the formula for reliability would be:

(1) $R_W(T) = e^{-(T/\eta)^{\beta}}$

and

(2) $\lambda_W(T) = \frac{\beta}{\eta}\left[\frac{T}{\eta}\right]^{\beta-1}$

where R (T) is the reliability (percent survivors) at T cycles

T is the number of cycles of interest

η is average life from Weibull curve in cycles

β Weibull slope (assume 3.3313 for normal wear out distribution

λ_W (T) failures/cycle at T

If we assume 50 percent failures (R (T) = 0.5) at T = 5 X 10^8 cycles and working backward we have:

(1) $0.5 = e^{-(5 \times 10^8/\eta)^{3.313}} = e^{-X}$

$\therefore X = 0.693$

or

$$0.693 = \left(\frac{5 \times 10^8}{\eta}\right) 3.313$$

$$\therefore \eta = 5 \times 10^8/(0.693)^{1/3.313}$$

at η = 5.58 X 10^8 cycles at 1.4 X 10^8 cycles [50,000] hours)

(2) $\eta_W(T) = \dfrac{3.313}{5.58 \times 10^8} \left[\dfrac{1.4 \times 10^8}{5.58 \times 10^8}\right]^{2.313}$

$\lambda_W(T) = 2.42 \times 10^{-10}$ failure/cycle

$\therefore$ Number of failures in 50,000 hours =

$1/2\ (1.4 \times 10^8) \cdot (2.42 \times 10^{-10}) = \dfrac{0.033}{2}$ = failure/50K hours

(the 1/2 approximates the area under the curve since $\lambda_\omega(0) = 0.0$)

at 10^6 hours

$\lambda_W = 0.33$

The above is assumed valid because the primary mode of failure is wear related leakage. However, an overall failure rate (failures/10^6 hours) λ of 2 was assumed, to be conservative, and account for unknowns in the development of a new solenoid.

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APPENDIX D

DETAILED LCC CHARTS
POWER CONDITIONING TRADE STUDY

BASELINE WEIGHT & RELIABILITY

DEVICE	WEIGHT KILOGRAMS/POUNDS	RELIABILITY FAILURES MILLION HOURS	MAINT. MATERIAL COST - $	MAINT. LABOR $	WEIGHT FACTOR $	MAINT. COST $
ALTERNATOR	.8/1.7	10	150	119	680	269
ECU	8.1/17.8	149	1118	838	6885	1956
CABLES	7/15.3	5	150	50	5950	200
SERVO STAGE (A)	.8/1.75 (x 2)	1/4 (x2)	15/50 (x2)	10/48 (x2)	680 (x2)	123 (x2)
FLOW BODY (B)	8.2/18	35/8	1050/100	1111/96	6970	2357
DISCRETES (C)	2.7/6	24	378	120	2295	498
OVERALL	28.4/62.3	241	3076	2450	24140	5526

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE
(C) HARDWARE/SOLENOID

LIFE CYCLE COST STUDY

SCHEME A EXTERNAL DISSIPATING SHUNT REGULATOR ON ALTERNATOR

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	2100	.1/.3	0/7	23	84	3498	286	107	3891
EEC	-224	-.4/-.9	-49	-368	-275	-1176	-340	-643	-2159
CABLES									
SERVO STAGE (A)									
FLOW BODY (B)									
DISCRETES									
OVERALL	1876	-.3/-.6	-42	-345	-191	2322	-54	-536	1732

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

Column 1 — Initial cost, sum of the component costs for each scheme.
Column 2 — Weight, sum of the component weights.
Column 3 — Reliability, sum of the component rates.
Column 4 — Maintenance material cost for the assumed life of 50,000 hours.*
Column 5 — Labor cost **
Column 6 — Procurement cost = Initial cost (Column 1) x (1.0 + % spares)
Column 7 — Weight factor, cost to fly X kilograms for 50,000 hours. Requires 0.4 kg JP4 to fly 1 kg dry weight for a 4484 km (3000 mi.) mission assuming average speed of 257 meters per second (575 miles per hour) and JP4 at $0.15 per liter, cost to fly 1 kg of dry weight for 50,000 hours = $850.00
Column 8 — Maintenance Cost = Material (Column 4) + Labor (Column 5)
Column 9 — Total Life Cycle Cost = Columns 6 + 7 + 8

	* MAINTENANCE MATERIAL COSTS ASSUME:	** MAINTENANCE LABOR COSTS ASSUME:
FLOWBODY	$ 600/FAILURE	$ 675/FAILURE
ALTERNATOR	$ 600/FAILURE	$ 238/FAILURE
CABLE	$ 600/FAILURE	$ 200/FAILURE
EEC	$ 150/FAILURE	$ 150/FAILURE
DISCRETE	$ 315/FAILURE	$ 100/FAILURE
SERVO	$ 300/FAILURE	$ 200/FAILURE
SOLENOID IN FLOW BODY	——	$ 238/FAILURE

LIFE CYCLE COST STUDY

SCHEME B INTERNAL SWITCHING SHUNT

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST - $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	84	0	-43	-323	-242	-592	0	-565	-1157
CABLES									
SERVO STAGE (A)									
FLOW BODY (B)									
DISCRETES									
OVERALL	84	0	-43	-323	-242	-592	0	-565	-1157

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme A

LIFE CYCLE COST STUDY

SCHEME C EXTERNAL SWITCHING SHUNT REGULATOR ON ALTERNATOR

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	630	.2/.5	0/3	10	36	807	170	47	1024
EEC	-224	-.4/-.9	-49	-368	-275	-1176	-340	-643	-2159
CABLES									
SERVO STAGE (A)									
FLOW BODY (B)									
DISCRETES									
OVERALL	-406	-.2/-.4	-46	-358	-239	-369	-170	-596	-1135

(A) TWO INDEPENDENT UNITS (SYA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme A

LIFE CYCLE COST STUDY

SCHEME D SATURABLE REACTOR

DEVICE	INITIAL COSTS (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	910	1.3/3	3	45	36	1180	1105	81	2366
EEC	−224	−.4/.9	−49	−368	−275	−1176	−340	−643	−2159
CABLES									
SERVO STAGE (A)									
FLOW BODY (B)									
DISCRETES									
OVERALL	686	.9/2.1	−46	−323	−239	4	765	−562	207

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme A

APPENDIX E

DETAILED LCC CHARTS
SYSTEM TRADE STUDY RESULTS

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LIFE CYCLE COST STUDY

SCHEME 1

DEVICE	INITIAL COSTS (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	84	6	-43	-323	-242	-592	0	-565	-1157
CABLES	0	0	0	0	0	0	0	0	0
SERVO STAGE (A)	0	0	0	0	0	0	0	0	0
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES (6)	0	0	0	0	0	0	0	0	0
OVERALL	84	0	-43	-323	-242	-592	0	-565	-1157

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

Column 1 — Initial cost, sum of the component costs for each scheme.
Column 2 — Weight, sum of the component weights.
Column 3 — Reliability, sum of the component rates.
Column 4 — Maintenance material cost for the assumed life of 50,000 hours.*
Column 5 — Labor cost **
Column 6 — Procurement cost = Initial cost (Column 1) x (1.0 + % spares)
Column 7 — Weight factor, cost to fly X kilograms for 50,000 hours. Requires 0.4 kg JP4 to fly 1 kg dry weight for a 4484 km (3000 mi.) mission assuming average speed of 257 meters per second (575 miles per hour) and JP4 at \$0.15 per liter, cost to fly 1 kg of dry weight for 50,000 hours = \$850.00
Column 8 — Maintenance Cost = Material (Column 4) + Labor (Column 5)
Column 9 — Total Life Cycle Cost = Columns 6 + 7 + 8

	* MAINTENANCE MATERIAL COSTS ASSUME:	** MAINTENANCE LABOR COSTS ASSUME:
FLOWBODY	\$600/FAILURE	\$675/FAILURE
ALTERNATOR	\$600/FAILURE	\$238/FAILURE
CABLE	\$600/FAILURE	\$200/FAILURE
EEC	\$150/FAILURE	\$150/FAILURE
DISCRETE	\$315/FAILURE	\$100/FAILURE
SERVO	\$300/FAILURE	\$200/FAILURE
SOLENOID IN FLOW BODY	—	\$238/FAILURE

LIFE CYCLE COST STUDY

SCHEME 2

DEVICE	INITIAL COST $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST - $ (4)	MAINT. LABOR $ (5)	PROCUREMENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	63	-.1/-.2	-45	-338	-253	-652	-85	-591	-1328
CABLES	1165	.3/.8	0	0	0	1475	255	6	1730
SERVO STAGE (A)	210 (x2)	0	0/0/.4 (x2)	2 (x2)	5 (x2)	258 (x2)	0	7 (x2)	265 (x2)
FLOW BODY (B)	420	0	0/.8	3	12	559	0	15	574
DISCRETES	630	0	0/1.2	5	14	827	0	19	846
OVERALL	2698	.2/.6	-42.2	-326	-217	2725	170	-543	2352

(A) TWO INDEPENDENT UNITS (SYA & BLEED) EACH CONTAINS 2 SOLENOIDS

(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 2A

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	630	.2/.5	0/3	11	36	807	170	47	1024
EEC	679	-5/1.15	-51	-383	-287	-1810	-425	-670	-2905
CABLES	1165	.3/.8	0	0	0	1475	255	0	1730
SERVO STAGE(A)	210	0	0/0/.4 (x2)	2 (x2)	5 (x2)	258(x2)	0	7 (x2)	265(2)
FLOW BODY (B)	420	0	0/0/.8	3	12	559	0	15	574
DISCRETES	630	0	0/1.2	5	14	827	0	19	846
OVERALL	2586	0	-45.2	-360	-215	2374	0	-575	1799

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

SCHEME 3 LIFE CYCLE COST STUDY

DEVICE	INITIAL COSTS (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST - $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	154	-.1/-.2	-43.5	-327	-245	-649	-85	-572	-1306
CABLES	992	-.6/-1.3	0	0	0	1256	-510	0	746
SERVO STAGE (A)	210 (x2)	0	0/0/.4 (x2)	2 (x2)	5 (x2)	258 (x2)	0	7 (x2)	265 (x2)
FLOW BODY (B)	420	0	0/0/.8	3	12	559	0	15	574
DISCRETES	630	0	1.2	5	14	827	0	19	846
OVERALL	2616	-.7/-1.5	-40.7	-315	-209	2509	-595	-524	1390

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 4

DEVICE	INITIAL COSTS (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST $ (4)	MAINT. LABOR $ (5)	PROCUREMENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	1470	.2/.5	0/2.5	12	30	1804	170	42	2016
EEC	63	-.1/-.2	- 45	- 338	-253	-652	- 85	-591	-1328
CABLES	1195	.4/1.	0	0	0	1513	340	0	1853
SERVO STAGE (A)	0	0	0	0	0	0	0	0	0
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES (6)	0	0	0	0	0	0	0	0	0
OVERALL	2728	.5/1.3	-42.5	-326	-223	2665	425	-549	2541

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 5

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST - $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	1470	.2/.5	0/2.5	12	30	1804	170	42	2016
EEC	154	-.1/-.2	-43.5	-327	-245	-649	- 85	-572	-1306
CABLES	1022	-.5/-1.1	0	0	0	1294	-425	0	869
SERVO STAGE (A)	0	0	0	0	0	0	0	0	0
FLOW BODY (B)	0	0	0	0	2	0	0	0	0
DISCRETES (6)	0	0	0	0	0	0	0	0	0
OVERALL	2646	-.4/-.8	-41	-315	-215	2449	-340	-530	1579

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 6

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST- $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	4060	.4/1.	3/6	73	108	5563	463	181	6207
EEC	63	-.1/-.2	-45	-338	-253	-652	-85	-591	-1328
CABLES	1195	.4/1.	0	0	0	1513	340	0	1853
SERVO STAGE (A)	0	0	0	0	0	0	0	0	0
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES (6)	0	0	0	0	0	0	0	0	0
OVERALL	5318	.7/1.8	-36	-265	-145	6424	718	-410	6732

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 7

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	4060	.4/1.	3/6	73	108	5563	463	181	6207
EEC	154	−.1/−.2	−43.5	−327	−245	−649	− 85	−572	−1306
CABLES	1022	−.5/−1.1	0	0	0	1294	− 425	0	869
SERVO STAGE (A)	0	0	0	0	0	0	0	0	0
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES (C)	0	0	0	0	0	0	0	0	0
OVERALL	5236	−.2/−.3	−34.5	−254	−137	6208	−47	−391	5770

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 8

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST - $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	1960	.8/1.7	−36	−271	−202	2195	680	−473	2402
CABLES	1737	3.4/7.7	2.5	75	25	2255	2890	100	5245
SERVO STAGE (A)	70(x2)	2.6/5.75(x2)	29/−4(x2)	30(x2)	299 (x2)	226(x2)	2210(x2)	329(x2)	2765(x2)
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES(6)	0	0	0	0	0	0	0	0	0
OVERALL	3837	9.4/20.9	16.5	−136	421	4902	7990	285	13177

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

SCHEME 9 LIFE CYCLE COST STUDY

DEVICE	INITIAL COSTS (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST- $ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	28	-.1/-.2	-45	-338	-253	-779	-85	-591	-1455
CABLES	0	0	0	0	0	0	0	0	0
SERVO STAGE (A)	210(x2)	-.4/-.88(x2)	3/4(X2)	136(x2)	-18(x2)	286(x2)	-340(x2)	118(x2)	641(x2)
FLOW BODY (B)	2240	-.5/-1	8/-8	140	-1	2981	-425	139	2695
DISCRETES	0	0	0	0	0	0	0	0	0
OVERALL	2632	-1.4/-296	-47	74	-290	2774	-1190	-216	1368

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

LIFE CYCLE COST STUDY

SCHEME 10

DEVICE	INITIAL COSTS $ (1)	WEIGHT KILOGRAMS/POUNDS (2)	RELIABILITY FAILURES MILLION HOURS (3)	MAINT. MATERIAL COST-$ (4)	MAINT. LABOR $ (5)	PROCURE-MENT COST $ (6)	WEIGHT FACTOR $ (7)	MAINT. COST $ (8)	TOTAL $ (9)
ALTERNATOR	0	0	0	0	0	0	0	0	0
EEC	28	.1/.2	45	338	253	779	85	591	1455
CABLES	0	0	0	0	0	0	0	0	0
SERVO STAGE(A)	-210(x2)	.4/.88(x2)	-3/4(x2)	-136(x2)	18(x2)	-286(x2)	340(x2)	-118(x2)	-64(x2)
FLOW BODY (B)	0	0	0	0	0	0	0	0	0
DISCRETES	0	0	0	0	0	0	0	0	0
OVERALL	-392	.9/1.96	47	66	289	207	765	355	1327

(A) TWO INDEPENDENT UNITS (SVA & BLEED) EACH CONTAINS 2 SOLENOIDS
(B) TWO VALVES IN ONE BODY (PILOT AND MAIN) 2 SOLENOIDS PER VALVE

See notes for Scheme 1

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LIST OF SYMBOLS

AC	-	alternating current
ACC	-	active clearance control
cm	-	centimeter(s)
CMOS/SOS	-	complementary metal oxide semiconductor/silicon on sapphire
CPU	-	central processing unit
db	-	decibel(s)
DC	-	direct current
DOI	-	Digital Output Interface
E^3	-	Energy Efficient Engine
ECU	-	electronic control unit
EEC	-	electronic engine control
EMF	-	electromotive force
EMI	-	electromagnetic interference
ev	-	electron volt(s)
FADEC	-	Full Authority Digital Electronic Control
GaAs	-	gallium arsenide
gm	-	gram(s)
Hz	-	Hertz
ICB	-	intercompressor bleed
I^2R	-	power dissipation through a resistor in watts
JFET	-	junction field effect transistor
Kg	-	kilogram(s)
LCC	-	life cycle cost(s)
LD	-	laser diode
LED	-	light emitting diode
LPC	-	low pressure compressor
m	-	meter(s)
MCBF	-	mean cycles between failures
Mn	-	Mach number
ms	-	millisecond(s)
MTBF	-	mean time between failures
mw	-	milliwatts
p^+	-	positive doped substrate
pph	-	pounds per hour
P&WA	-	Pratt & Whitney Aircraft
PLA	-	power lever angle
PROM	-	programmable read only memory
PWM	-	pulse width modulation
Si	-	silicon
S_iO_2	-	silicon dioxide
SOV	-	shutoff valve
SVA	-	stator vane actuator
TCC	-	turbine cooling control
UTRC	-	United Technologies Research Center
VDC	-	volts direct current
W_f	-	fuel flow
λ	-	failure rate (failures per 10^6 hours)
μ w	-	microwatts
Ω	-	ohms resistance

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