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ABSTRACT

A detailed design of a fiber optic propulsion control system, integrating favored sensors and electro-optics architecture is presented. Layouts, schematics, and sensor lists describe an advanced fighter engine system model. Components and attributes of candidate fiber optic sensors are identified, and evaluation criteria are used in a trade study resulting in favored sensors for each measurand. System architectural ground rules were applied to accomplish an electro-optics architecture for the favored sensors. A key result was a considerable reduction in signal conductors. Drawings, schematics, specifications, and printed circuit board layouts describe the detailed system design, including application of a planar optical waveguide interface.

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ABBREVIATIONS

A8	Variable Exhaust Nozzle Throat Area
AB	Afterburner
A/C	Aircraft
A/I	Anti-Ice
CVG	Compressor Variable Geometry
FADEC	Full Authority Digital Electronic Control
F/B	Feedback
FVG	Fan Variable Geometry
LVDT	Linear Variable Differential Transformer
MFC	Main Fuel Control
NH	Compressor/High Pressure Turbine Speed
NL	Fan/Low Pressure Turbine Speed
P5	Turbine Discharge Pressure
PLC	Power Lever Control
PS3	Compressor Discharge Pressure
RVDT	Rotary Variable Differential Transformer
T1	Engine Inlet Temperature
T25	Compressor Inlet Temperature
T5	Low Pressure Turbine Discharge Temperature
T/C	Thermocouple
TM	Torque Motor
VEN	Variable Exhaust Nozzle
VIB	Vibration
WFM	Main Fuel Flow
WFR	Afterburner Fuel Flow

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1.0 SUMMARY

The objective of this program was to conduct a trade study that would result in a preferred electro-optic architecture for servicing sensors and actuators in a fiber optic propulsion control system. This was to be accomplished by evaluating fiber optic sensor modulations, connections between the sensors and the control module, and the electro-optics servicing the sensors. Following the trade study, the GE program team produced a detailed design of the preferred electro-optics architecture.

Electro-optics is defined as a portion of an electronics propulsion system control module which includes:

1. The electronics required to generate optical signals
2. The components required to distribute these signals to propulsion system sensors and actuators
3. The components required to detect and process the modulated optical signals returned from the sensors
4. The electronics required to produce conditioned electrical signals acceptable for use by Full Authority Digital Electronic Control (FADEC) computers.

The program effort comprised the following tasks:

I. Describe the sensor and actuator configuration for a current propulsion system, including a physical layout and specification of interrogation access times.

II. Establish evaluation criteria for optical sensor modulations, connections with the control module, and electro-optics in the control module.

III. Conduct a trade study based on the established evaluation criteria resulting in preferred electro-optics architecture for the propulsion system.

IV. Produce a detailed design of the resulting preferred electro-optics architecture, including Level I drawings, printed circuit board layouts, component definition and specification, and connection schematics.

The resulting design integrated the favored fiber optic sensors with electro-optics architecture, based on propulsion control system ground rules. The number of signal conductors was significantly reduced, compared with the model electrical system. A planar optical waveguide component was identified to interface between the control module chassis connectors and some optical sources/detectors.

2.0 INTRODUCTION

Advanced aircraft propulsion systems must meet increasingly challenging performance requirements and endure more rigorous environmental conditions. Military goals are directed toward high thrust/weight ratios that require high cycle temperatures to improve thermodynamic efficiency, and lighter materials to reduce weight. The use of composite materials for weight reduction makes the control system more susceptible to electromagnetic contamination.

NASA and DoD have recognized that the use of fiber optic technology will provide immunity to electromagnetic interference, and will also provide higher rates of data communication. Weight savings are expected through reduced system conductor count, innovative fiber mounting techniques, and reduced complexity. In addition, fiber optic technology may potentially provide better system performance and the ability to withstand higher environmental temperatures.

In 1975 NASA began work to develop fiber optic sensors for use in aircraft propulsion systems. In 1985 a program called FOCSI (Fiber Optic Control System Integration) was jointly funded by NASA and DoD. This program identified propulsion control system sensor requirements/environments, assessed the status of fiber optic sensor and component technology, and conceived a total fiber optic, integrated propulsion/flight control system.

The current contract evaluates the electro-optic architecture needed to service the sensors and actuators in a propulsion system and presents a detailed design of the preferred configuration.

3.0 CURRENT FADEC PROPULSION SYSTEM

3.1 SENSOR SET IDENTIFICATION

Currently, FADEC technology is being applied to the F404 propulsion system. This application combines a single channel, all electrical, digital control (primary channel) with an analog/hydromechanical backup (secondary channel). The sensor set for the F404 FADEC system is very similar to the standard F404-GE-400 hydro/electro/mechanical system, with the addition of certain electrical sensors and sensor redundancies, but without an afterburner section. The F404 FADEC propulsion system, including an afterburner section and a pyrometer, will be used as a model for the study.

Figure 1 shows approximate positions along the engine axis of the sensor/actuator set. Figure 2 is a list of the sensors, effectors, and discretes, indicating their quantity and specific location.

3.2 SYSTEM SCHEMATICS

The following figures describe the model FADEC system configuration by identifying sensor locations, interfaces, and groupings.

Figure 3 is a sensor and actuator layout for the model FADEC system, approximately to scale. Most components are located on the bottom front portion of the engine. The nine FADEC electrical connectors are associated with the following signals:

C1 - Primary control mode sensors and actuators

C2 - Secondary control mode sensors and actuators

C3 - Afterburner sensors and actuators

C4 and C5 - T5 thermocouple harnesses

C6 - Electrical power from the alternator

C7 and C8 - Aircraft signals, power, indicators, and MIL-STD-1553 bus

C9 - RS232 bus for ground support

Figure 4 is a system diagram indicating the components interfacing with each FADEC connector and the number of conductors required by each component. The condition monitoring sensor signals that go directly to the airframe without passing through the FADEC are also shown.

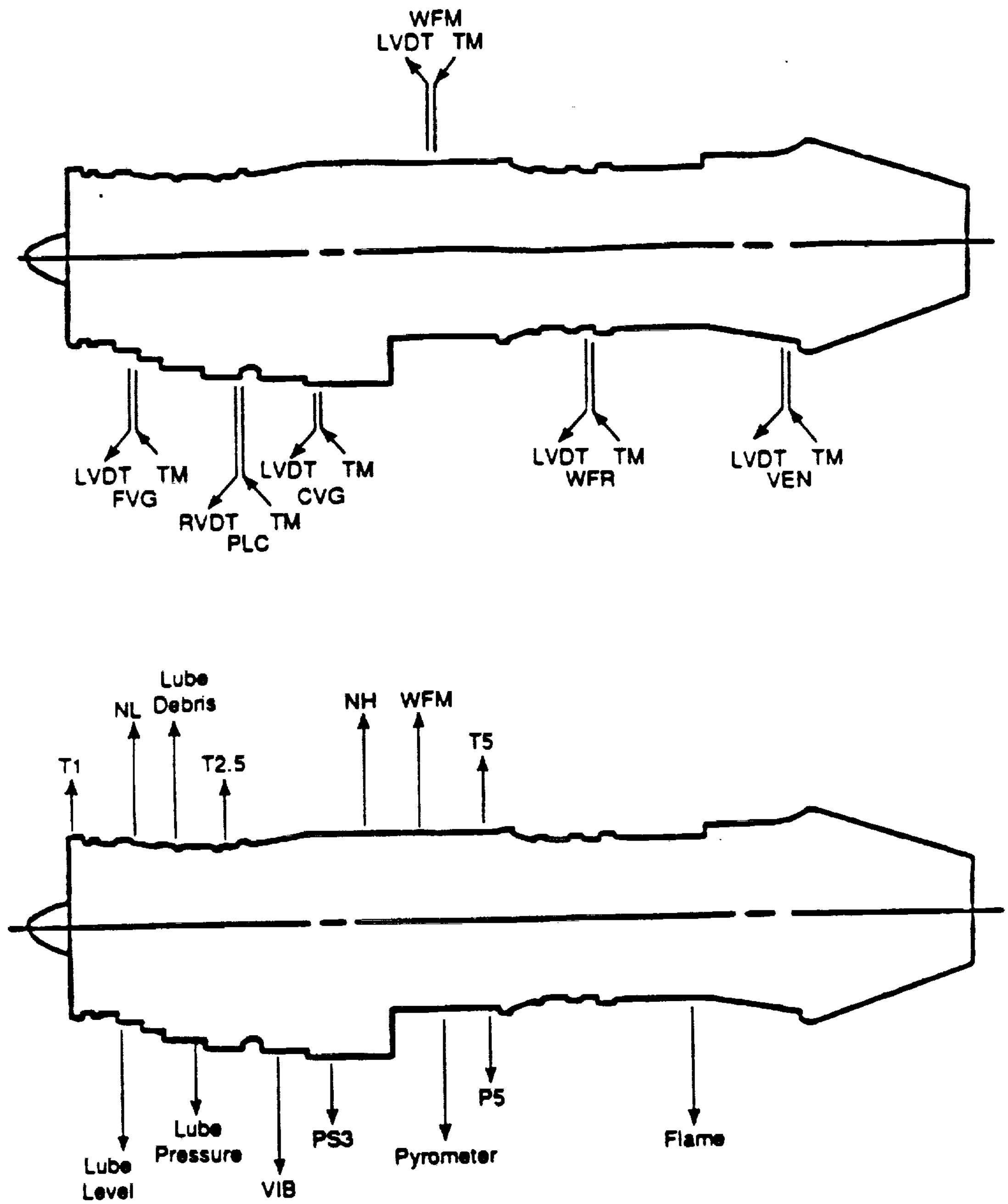


Figure 1. Current Propulsion System Sensor and Effector Set Location Along Engine Axis.

- Linear Position (7): Main Fuel Valve (MFC; Two) CVG (MFC)
  AB Fuel Valve (AB Control) VEN (AB Duct)
  FVG (FVG Actuator; Dual)

- Rotary Position (2): Power Lever Control (PLC; Two)

- Shaft Speed (5): Compressor (Alternator; Two From Dedicated Windings, One Derived From a Power Phase)
  Fan (Fan Duct; Two Sensors With Redundant Conductors)

- Temperature (3 RTD's; 8 Ch/Al Probes):
  Fan Inlet (Fan Duct; Dual)
  Compressor Inlet (Compressor Casing)
  Turbine Discharge (Turbine Casing)

- Pressure (3): Compressor Discharge (FADEC)
  Turbine Discharge (Fan Casing)
  Oil Pressure (Fan Casing)
  } Condition Monitoring Sensors

- Other Sensors: Oil Level (Fan Duct)
  Vibration (Fan Duct)
  Fuel Flow (Compr. Casing)
  } Condition Monitoring Sensors
  Flame Indication (AB Duct)
  Pyrometer (AB Duct)

- Torque Motors (9): Main Fuel Flow (MFC; 2)
  VEN (VEN Power Unit; Dual)
  FVG (FVG Actuator; Dual)
  AB Fuel Flow (AB Control; Dual)
  CVG (MFC)

- Solenoids (8): Mode Transfer (MFC)
  A/C Fuel Shutoff No. 1 (MFC)
  A/C Fuel Shutoff No. 2 (MFC)
  CVG Reset (MFC)
  Anti-Ice (A/I Valve)
  FADEC Fuel Shutoff (MFC)
  AB Solenoid (AB Control)
  NH Lockup (MFC)

- Relays (3): Main Ignition A (MFC)
  Main Ignition B (MFC)
  Augmentor Ignition (MFC)

- Indicators (6): Oil Filter Bypass (Oil Filter)
  Oil Temperature (Oil Level Sensor)
  Fuel Filter Bypass (Fuel Filter)
  Chip Detector (Chip Detector)
  Anti-Ice (A/I Valve)
  Mode Status (FADEC)

Figure 2. Current Propulsion System Sensors, Effectors, and Discretes - Quantities and Specific Locations.

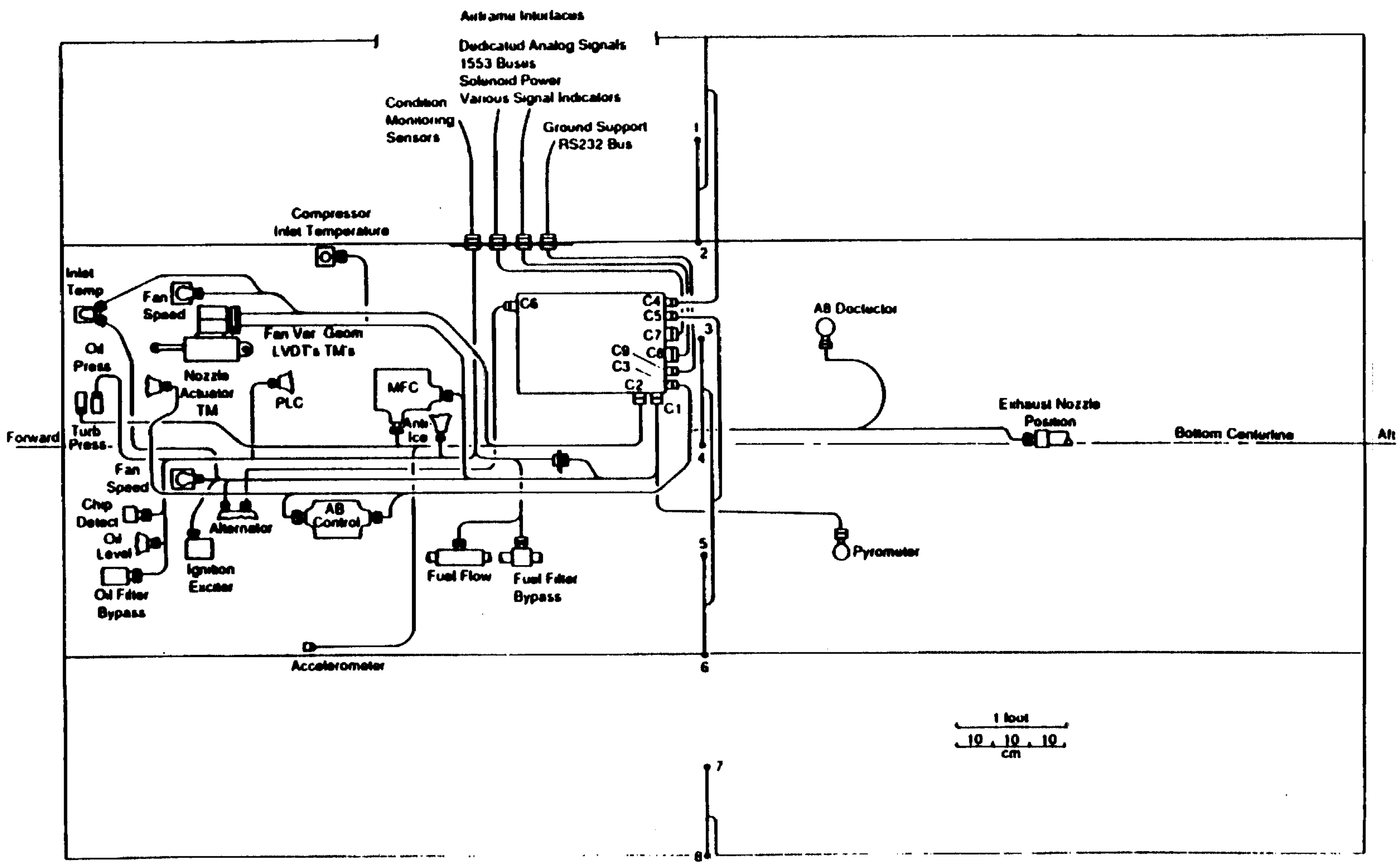


Figure 3. Current Propulsion System Layout.

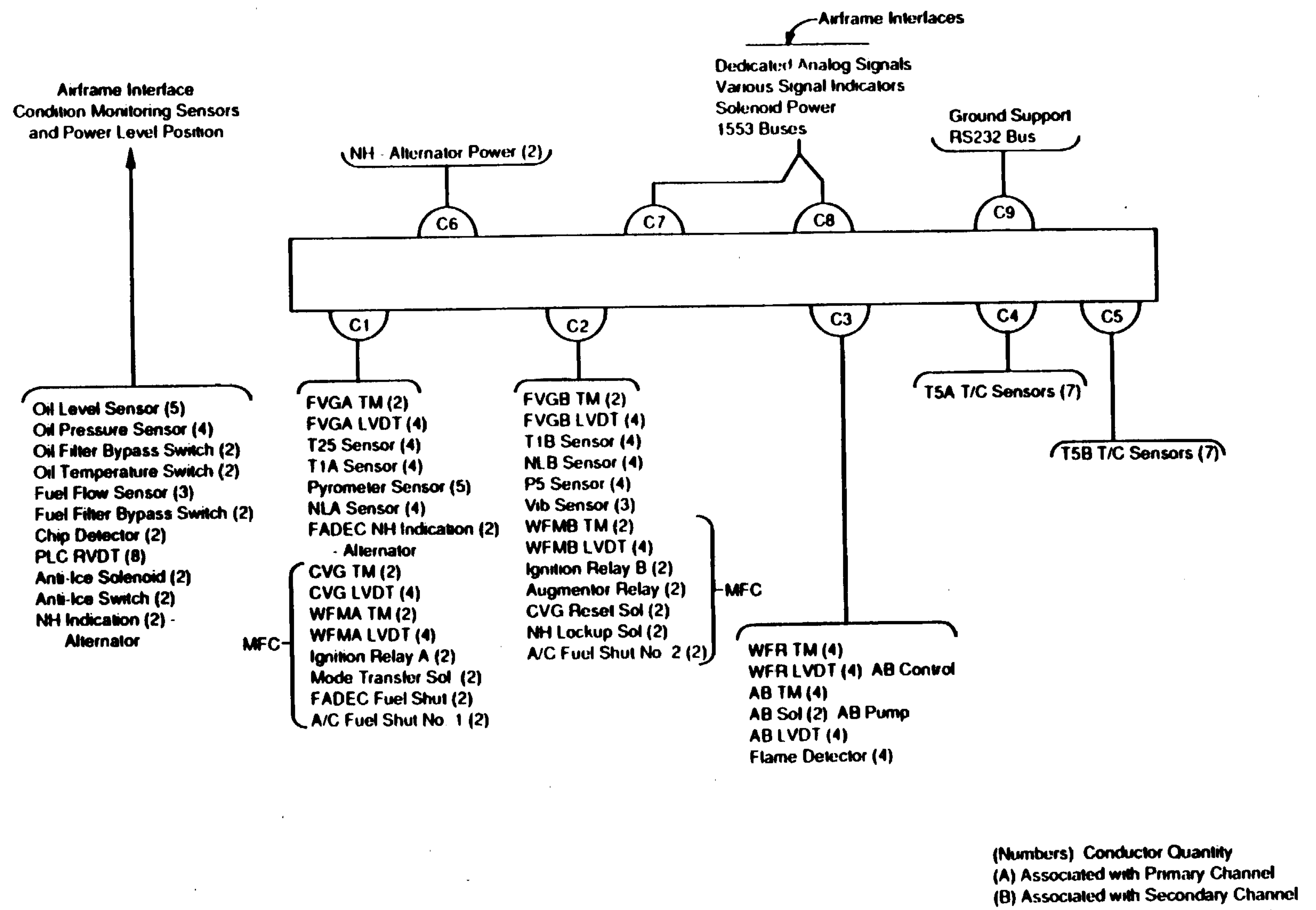


Figure 4. FADEC Connector Interfaces - Electrical System.

Figure 5 is a diagram showing the numbers of each kind of component interfacing with the FADEC from the outside and the internal signal conditioning module arrangement.

Figure 6 is an overall block diagram of the FADEC system.

3.3 INTERROGATION ACCESS TIMES

The FADEC signal sampling periods or sensor interrogation access times were used in the electro-optics detailed design to determine multiplexing capabilities. Every 10 milliseconds, for example, all those marked as such have their digital value updated once. Every 20 milliseconds, those marked as such are updated once, while those marked 10 milliseconds are updated twice. For the model FADEC system, they are as follows:

Inputs:

LVDT's	10 ms	T25	20 ms
Shaft Speeds	10 ms	Pyrometer	20 ms
Flame Detector	10 ms	PS3	20 ms
Oil Pressure	10 ms	P5	40 ms
T5	10 ms	Lube Level	40 ms
T2	40 ms		

Outputs:

TM's	10 ms
Solenoids	10 ms
Relays	10 ms
Indicators	10 ms

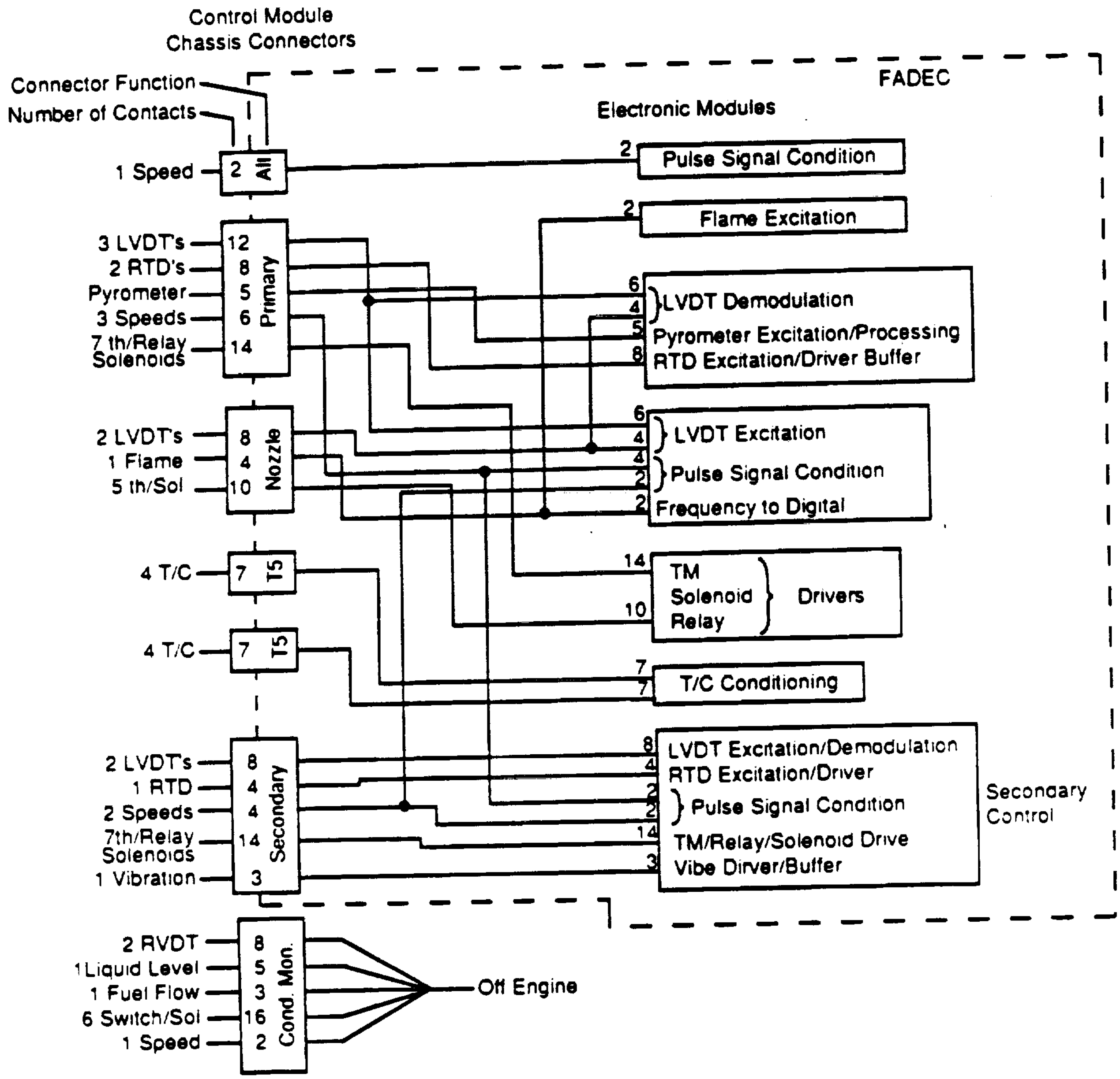


Figure 5. FADEC Electrical Sensor Connections and Internal Electronic Modules.

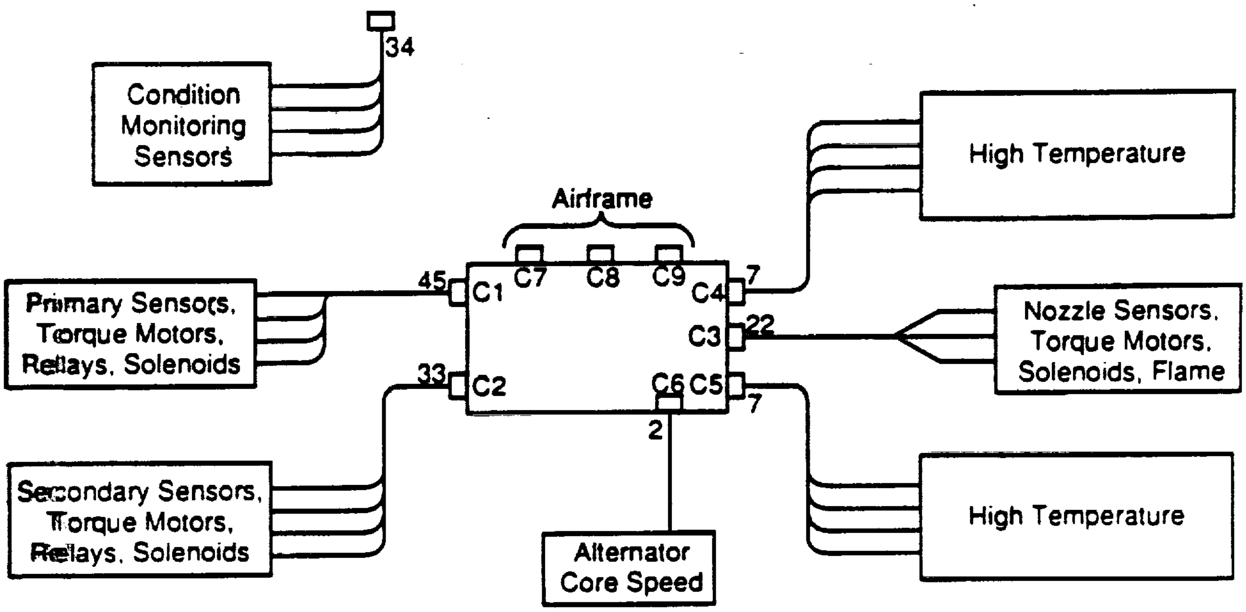


Figure 6. Current FADEC Propulsion System - Overall Block Diagram.

4.0 ELECTRO-OPTICS EVALUATION CRITERIA

4.1 EVALUATION CRITERIA OBJECTIVES

An optical sensor is defined to include the components that transduce the sensed parameter into a modulated optical signal, the interconnection components, and the electro-optic components, as shown in Figure 7. Integration of these components results in a total sensor assembly design intended to meet specified performance requirements. As combined in an overall sensor/actuator system, additional benefits may be realized through component interaction such as multiplexing.

Criteria were therefore established to evaluate the following:

1. The optical modulation produced by the sensors.

2. The connections between the sensors/actuators and the control module.

3. The electro-optic architecture that services the sensors/actuators.

4.2 METHOD OF SYSTEM TRADE STUDY

Figure 8 describes the method used to produce a preferred propulsion system electro-optics architecture. The purpose of the method is to reduce criteria interdependencies by separating the criteria into small, manageable steps. Following is a description of the method.

Given a set of sensors/actuators in the current propulsion system, an initial screening was used to eliminate those sensor candidates that inherently are not suitable for engine application. The criteria for this process were designated Criteria A.

Next, an evaluation ranking method was applied to the remaining candidates of each particular sensor type, such as inlet temperature, shaft speed, displacement, etc. For each candidate inlet temperature sensor scheme, for example, a matrix was used to measure the effects of its known characteristics and attributes (source type, number of fibers, etc.) on the weighted criteria factors of reliability, maintainability, cost, and weight/volume. The criteria for this sensor ranking were designated Criteria B.

Finally, propulsion system layouts/schematics, ground rules, and other system criteria were used together with the Criteria B ranking results and individual sensor block diagrams, to construct preferred electro-optic architecture for the system.

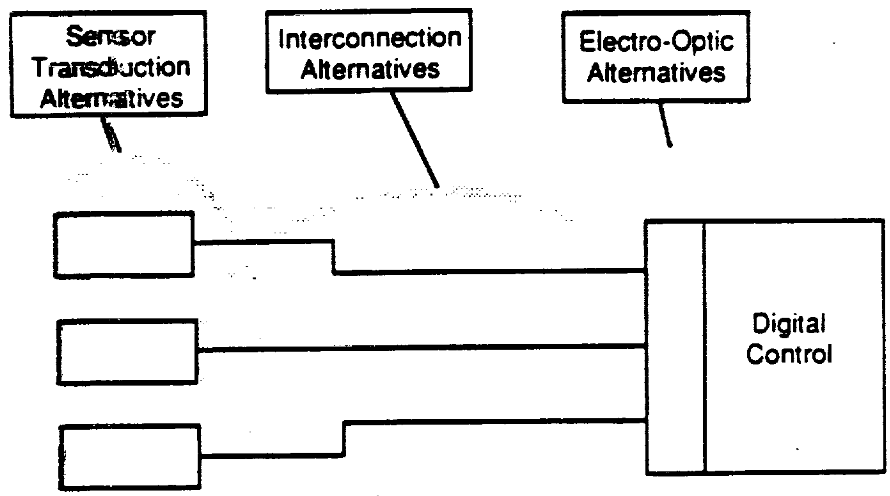


Figure 7. Integration of Components for a Fiber Optic Sensor System.

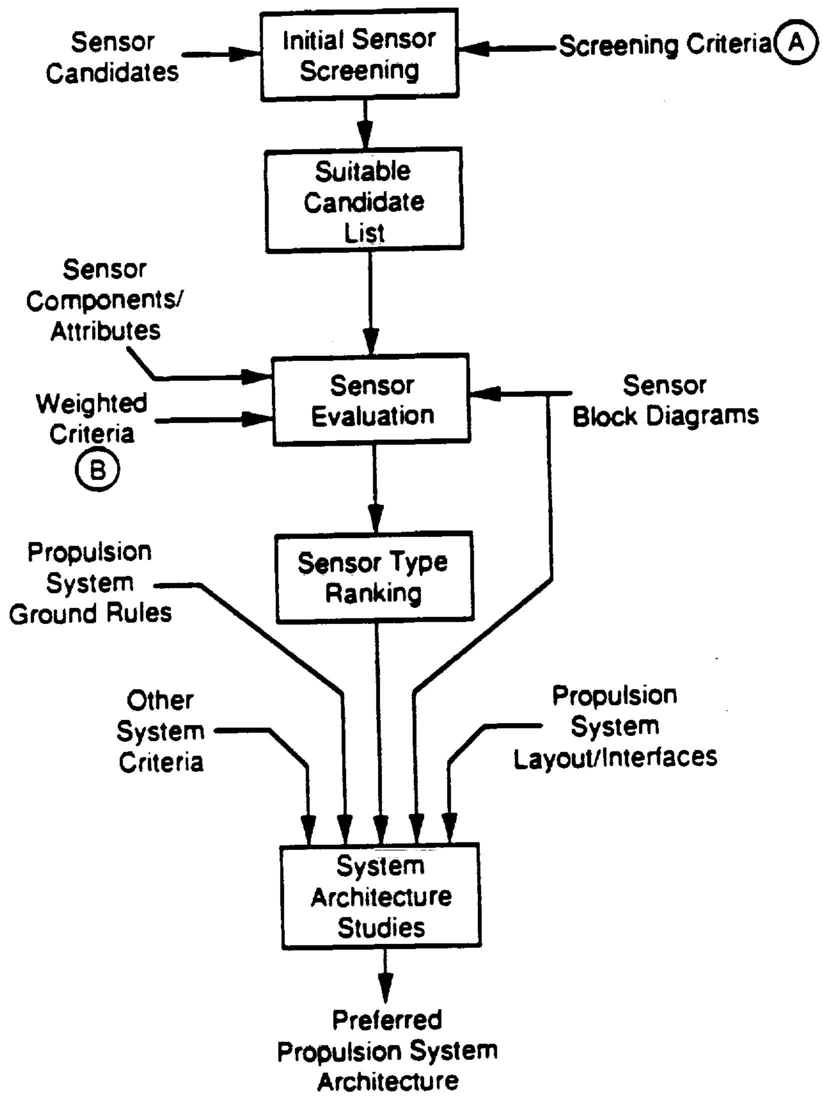


Figure 8. Method of System Trade Study.

4.3 CRITERIA DESCRIPTION

4.3.1 Initial Screening Criteria A

Characteristics of fiber optic sensors that generally are inherently unsuitable for aircraft engine application include:

1. Dependency on Single-Mode Fiber. Connector tolerances required to couple 5 to 10 μm (0.2 to 0.4 mils) diameter, single-mode fiber cores are difficult to achieve. Laser diode sources rated to 125°C are not available. The family of optical interferometers (Mach-Zehnder, Michelson, and Sagnac) are thus eliminated.

2. Materials and Components that are environmentally (temperature, shock, vibration) unsuitable render sensors with certain sources, detectors, transduction techniques, etc., as unsuitable.

3. Performance. The candidate must have no features that prohibit its ability to meet specified performance requirements such as accuracy, repeatability, and time response.

Two other sensor characteristics should be noted, and while not absolute bases for ruling out a candidate, sensors having them were closely scrutinized for application. First, when the light interface in extrinsic sensors is exposed to engine media contamination such as oil, fuel, and bird ingestion, there is a risk of signal obstruction. The use of purge air in an attempt to prevent this condition increases sensor weight and volume. Second, analog sensors with no reference are vulnerable to signal variations due to nonrepeatable connector losses, cable bends and vibration, and large temperature variation, causing loss of calibration.

4.3.2 Sensor Components/Attributes Criteria B

The purpose of the Criteria B trade study was to produce a ranking of the candidates for each sensor type. It consisted of the following steps:

1. A list of sensor components and attributes, broken down in the categories of sources, detectors, fiber protocol, optical elements, transduction technique, and electronics, were identified as shown in Figures 9 through 15. The dashed lines separate subcategories.

2. Within each category or subcategory, the sensor components or attributes were rated from 1 to 10 using the criteria of reliability, maintainability, cost, and weight/volume on a relative basis. General aspects of these criteria are discussed below. Specific discussion is contained in Appendix B.

   - **Reliability** - The sensor is expected to perform as specified over a given lifetime. For advanced fighter engine propulsion control components,

Components/Attributes Pertaining to Sources		Evaluation Criteria (Weight *) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
A1.	IRED-Surface Emitter (Burrus style)	9 + (x10)	5 + (x5.1)	7 + (x6.6)	5 = (x4.8)	185.7
A2.	IRED-Edge Emitter	8	5	5	5	62.5
A3.	IRED-Superluminescent (as for Sagnac sensor)	6	5	4	5	135.9
A4.	Tungsten Lamp	3	5	8	4	127.5
A5.	Xenon Lamp	6	4	6	1	124.8
A6.	No source (as with pyrometer)	10	10	10	10	265.0
A7.	Two sources (for two wavelengths)	7	4	3	5	134.2
A8.	Four sources	5	4	3	4	109.4

(* - See item 3, paragraph 4.3.2, explaining criteria weights)

Figure 9. Sensor Evaluation Criteria Values - Sources.

Components/Attributes Pertaining to Detectors		Evaluation Criteria (Weight) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
B1.	Si PIN Photodiode	9	5	8	5	192.3
B2.	InGaAs PIN Photodiode	9	5	7	5	185.7
B3.	Si Avalanche Photodiode (temp. comp. circuit)	7	5	2	5	132.7
B4.	InGaAs Avalanche Photo-diode (temp. comp. circuit)	7	5	1	5	126.1
B5.	UV Tube (requires high voltage)	5	4	5	3	117.8
B6.	CCD Array	6	3	4	3	116.1
B7.	Two detectors	7	5	7	3	156.1
B8.	Four detectors	6	5	6	2	134.7
B9.	Detector Array	5	5	5	2	118.1

Figure 10. Sensor Evaluation Criteria Values - Detectors.

Components/Attributes Pertaining to Fibers		Evaluation Criteria (Weight) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
C1.	Polyimide Coated Silica (not hermetic)	7	7	8	5	182.5
C2.	Alum. Coated Silica	9	4	5	5	167.4
C3.	Glass (not radiation hard)	5	2	9	5	143.6
C4.	Uncoated Silica	7	3	5	4	137.5
C5.	Gold Coated Silica (not much life testing)	8	3	2	5	132.5
C6.	One fiber	9	7	6	9	208.5
C7.	Two fibers	8	5	4	8	170.3
C8.	Up to eight fibers	6	4	2	7	127 2
C9.	Up to 20 fibers	4	3	1	5	85.9
C10.	Over 20 fibers	3	3	1	4	71.1

Figure 11. Sensor Evaluation Criteria Values - Fibers.

Protocol Attributes		Evaluation Criteria (Weight) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
D1.	Pulse Rate or Frequency	9	7	8	5	202.5
D2.	Digital, Wave. Encode (requires diffr. optics)	9	5	5	5	172.5
D3.	Pulse Delay, Pulse Time, Phase Difference	8	5	6	5	169.1
D4.	Wavelength Shift	8	3	5	5	152.3
D5.	Digital Parallel Lines	8	4	4	3	141.2
D6.	Mod. Intensity or Wave.	7	1	6	5	138.7
D7.	Digital, Time Encode (high speed analog elec.)	7	3	3	5	129.1
D8.	Intensity Ratio	5	3	5	4	117.5
D9.	Intensity Variation	4	2	6	5	113.8

Figure 12. Sensor Evaluation Criteria Values - Protocols.

Components/Attributes Pertaining to Optical Elements	Evaluation Criteria (Weight) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
E1. Tapered Fiber	8	7	6	7	188.9
E2 Selfoc Lens	7	5	8	5	172.3
E3. Coupler, Waveguide	8	7	4	5	166.1
E4 Blackbody	8	6	4	5	161.0
E5. Bulk Optic Lens	8	3	7	2	151.1
E6. Mirror (metal or glass)	8	3	7	2	151.1
E7. Coupler, Fused Taper	7	5	4	4	141.1
E8. Grating (metal or glass)	8	3	3	3	129.5
E9. Filter, Color Separ.	5	3	6	3	119.3
E10. Optical Modulator	5	5	4	3	116.3
E11. Precision Optics	2	2	2	5	67.4
E12. No Connector	10	1	10	9	214.3
E13. Connector, Single Contact	7	3	5	6	147.1
E14. Connector, Multi-Contact	5	2	4	2	96.2
E15. Two Optical Elements	8	5	4	7	165.5
E16. Four Optical Elements	7	4	3	5	134.2
E17. Eight Optical Elements	6	3	1	2	91.5

Figure 13. Sensor Evaluation Criteria Values - Optical Elements.

Transduction Techniques		Reliability (10)	Maintainability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
			Evaluation Criteria (Weight)			
F1.	Total Internal Reflection	8	9	7	8	210.5
F2.	Transmission Mods. Source (sealed)	9	2	9	9	202.8
F3.	Reflection Sealed	8	7	7	7	195.5
F4.	Subcarrier Freq. Interf. (sealed)	6	8	7	7	180.6
F5.	Microbend	6	8	6	6	169.2
F6.	Fluorescence Decay	6	6	6	8	168.6
F7.	Absorption	6	5	6	7	158.7
F8.	Faraday Effect	5	6	4	7	140.6
F9.	Transmission (not sealed)	3	2	8	7	126.6
F10.	Monochromator	5	4	4	6	125.6
F11.	Reflection Exposed	2	2	8	7	116.6
F12.	Moire Interferometry	5	3	3	5	109.1

Figure 14. Sensor Evaluation Criteria Values - Transduction Techniques.

Components/Attributes Pertaining to Electronic Attributes		Evaluation Criteria (Weight) Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)	Total
G1.	Bandwidth Under 10 kHz	9	6	7	5	190.8
G2.	Bandwidth Over 10 kHz	7	5	5	4	147.7
G3.	Bandwidth Over 1 MHz	6	4	4	4	126.0
G4.	Elec. Power Under 1 Watt	8	5	7	7	185.3
G5.	Elec. Power Over 1 Watt	5	3	4	4	110.9
G6.	Elec. Temp. Meas. Circuit	8	4	4	4	146.0
G7.	Elec. Device Heater	7	2	4	4	125.8
G8.	TE Cooler	7	3	3	4	124.3
G9.	Standard Analog Elec.	8	7	8	5	192.5
G10.	Synchronous Detection	8	4	4	4	146.0
G11.	Low Noise and Offset Analog Elec.	5	4	5	5	127.4
G12.	Nonstandard Voltage	4	2	3	3	84.4
G13.	Two Active Elec. Comps.	8	8	7	8	205.4
G14.	Four Active Elec. Comps.	7	7	5	7	172.3
G15.	Eight Active Elec. Comps.	6	6	5	5	147.6
G16.	Over 8 Active Elec. Comps.	5	5	4	4	121.1

Figure 15. Sensor Evaluation Criteria Values - Electronics.

typical specified life ranges from 8000 hours for those mounted on the fan duct, to 4000 hours for those mounted on the turbine casing. It is an ongoing design concern. If reliability is high, maintenance should be low.

- **Maintainability** - Sensors are normally designed to need no calibration or adjustment once in service. Factors include ease of installation and removal. Failure detection is important.

- **Cost** - This includes initial cost and costs to replace, operate, and maintain. As defined to include the transduction element, the interconnections, and the electro-optics, sensors contribute a significant percentage of the control system cost.

- **Weight/Volume** - Again, as defined, sensors are a significant part of the control system weight/volume.

3. Criteria weights were attained by averaging the results of a survey of seven engineers experienced in vendor designed sensor programs. Reliability was given the weight of 10. Weights for the other criteria were judged by each engineer based on the relative attention paid to each factor in a typical sensor design project.

4. The components and attributes of each sensor candidate were identified (see Section 5.1).

5. A total score for each sensor candidate resulted in a ranking (see Section 5.3).

4.3.3 Preferred System Principles

4.3.3.1 System Ground Rules

The following ground rules are applicable to GE propulsion system architectures in the foreseeable future and were applied to this study:

1. The electronic control module (FADEC) consists of one physical unit mounted on the engine, as shown in the current propulsion system layout, Figure 3.

2. Sensor transduction elements are located as shown in the current propulsion system layout, Figure 3.

3. All electro-optic components are located in or attached to the electronic control module.

4. Channels of the electronic control module, primary (A) and secondary (B) for this study, share no electro-optic components and are completely isolated in the sense of failure effects. There is a separate sensor set for each channel.

5. Sharing of electro-optic components within a controls channel, that is, A or B, must be accompanied by sufficient redundancy to maintain a highly reliable system.

6. Connector space on the electronic control module is limited. There must be a significant amount of interface clustering. A connector for each sensor must not predominate.

4.3.3.2 Fiber Number and Multiplexing

An emerging key advantage of fiber optics is seen to be a reduction in the number of engine harness conductors. This will reduce harness weight and could reduce the size and weight of the electronic control module.

The use of multiplexing is a strong factor in the electro-optics architecture design. Multiplexing is necessary to reduce the impact (cost, weight, volume) of adding electro-optics to the control module.

4.3.3.3 System Reliability (References 1 and 2)

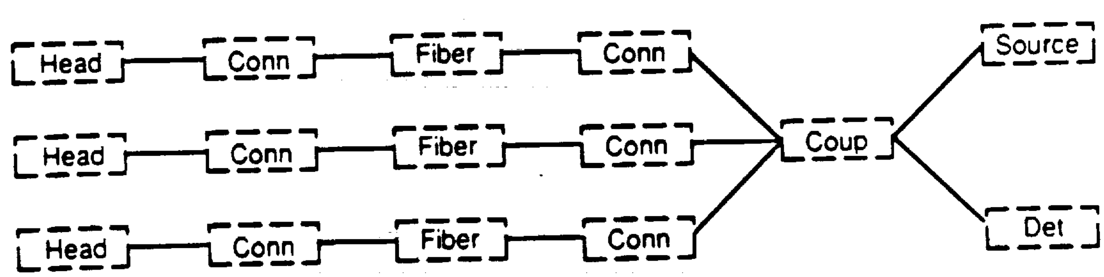
Reliability is the probability that the system will function as intended, within specified limits for a specified period of time in a specific environment. Items in series with no interaction have a combined reliability equal to the product of the individual reliabilities:

$$R_T = \prod_{1}^{n} R_i = R_1 \cdot R_2 \cdot R_3 \cdots R_n$$

For items in parallel, the combined reliability is calculated as follows:

$$R_T = 1 - \prod_{1}^{n} (1 - R_i)$$

For example, compare the reliability of a group of three fiber optic sensors, all having their own source and detector (set A), with a group of three sensors that use a common source and detector through a coupler (set B), as shown below:



$$R_A = \left(1 - [1 - (R_{sec} \cdot R_{coup} \cdot R_{con} \cdot R_{fib} \cdot R_{con} \cdot R_{head} \cdot R_{det})]^3\right)$$

$$R_B = \left(1 - [1 - (R_{con} \cdot R_{fib} \cdot R_{con} \cdot R_{head})]^3\right) \cdot R_{coup} \cdot R_{sce} \cdot R_{det}$$

It is clear from these equations that to achieve the same reliability as an unmultiplexed system, the multiplexed components of a multiplexed system must be relatively superior in reliability. Multiplexing decreases the number of components but may lower the total reliability unless the parts multiplexed are relatively superior in reliability. It would not be wise to multiplex a relatively unreliable component, such as a light source (current assessment).

4.3.3.4 Electro-Optics Locations

Another major issue is the location of the electro-optics inside the electronic control module. A key technical guideline is to minimize the number of fiber optic connections, each of which contribute to optical circuit losses. Following are four alternatives, as also depicted in Figure 16 with the numbers 1 through 4.

1. Placing the electro-optics in the engine harness connector plug backshells would allow the use of standard electrical receptacles on the electronic control module chassis. Because of the hot environment, applications would currently be limited to on/off binary signals such as shaft speed or flame detection, where thermal compensation may not be required. Engine harness complexity and cost would substantially increase, requiring electronic and fiber optic skills.

2. Placing the electro-optics in the electronic control module chassis connector receptacle backshell would require all fiber optic connectors, and somewhat high temperatures because of their attachment to an outside wall.

3. Placing the electro-optics on a dedicated interface board (module) in the electronic control module would require fiber optic links from the chassis connector receptacle to the interface board. The electronic backplane interconnections would still be electronic. The electro-optic interface module could take advantage of internal cooling for increased reliability and stability. The full set of sensor applications could be accommodated. All electro-optics would be physically centralized, providing benefits in serviceability, fault detection, and multiplexing techniques.

4. Placing the electro-optics with its applicable electronic module would require fiber optic links or connections through the electronic backplane interconnection. Electro-optics/electronics skill mixture would be required for manufacturing and servicing.

Alternative 3 provides an environment required for current electro-optics applications, while minimizing fiber optic interconnections. It also facilitates transition from near-term engine demonstrations where the electro-optics is mounted in a separate chassis.

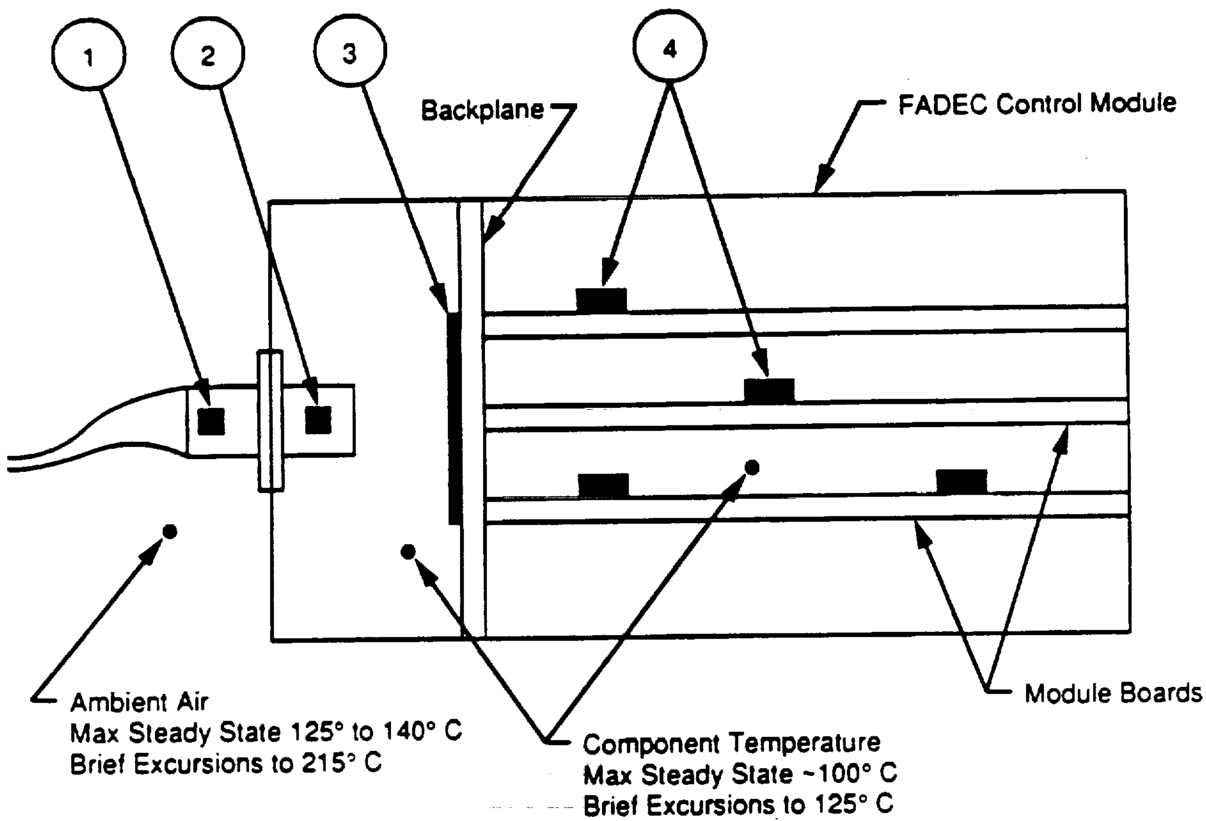


Figure 16. Alternate Electro-Optics Locations.

4.3.3.5 Actuation

In current propulsion systems, torque motors are mounted on actuators and driven from the electronic control module at typically ± 80 milliamps. Solenoids are typically used to open and close a valve using 300ma/16Vdc, and relays are typically used to open and close a circuit using 30ma/14Vdc. For this contract, signals that activate these devices were considered as low level optical signals that operate an optical switch.

To implement an optically controlled, electronically powered torque motor, high temperature optical detection electronic circuitry has been demonstrated (Reference 3). GaAs, silicon carbide, and other semiconductors are possible. Electrical control of fluidic actuation is a demonstrated and acceptable technique. Therefore, for this design, actuation control uses fiber optic signals received at the actuator(s) by high temperature circuitry that drives a torque motor, solenoid, or relay. The optical signals use a constant frequency, varying duty cycle square wave to represent analog level to torque motors and simply on-off signals for solenoids and relays. In order to provide positive and negative signals for compatibility with existing torque motors, two colors are used.

If each torque motor is individually powered, as in the current system, a considerable number of electrical conductors are retained. Use of an electrical power bus configuration would reduce electrical conductors, but would require careful reliability consideration.

Actuation systems directly controlled by fiber optic signals require relatively large amounts of optical energy. Work so far published (References 4 and 5) used about 10 milliwatts of optical energy at the actuator detection to demonstrate optical control of a hydraulic actuator. The optical signal was an input to fluidic amplifier components resulting in an optical/thermal energy exchange. Little work has been done beyond laboratory investigations and essentially nothing has been published about performance over a broad temperature range. With an electronic component temperature requirement from -50° to 125°C, high-output solid-state sources are too large to be practical for this application. These techniques cannot be recommended at this time. Strong technical challenges remain in the areas of sources, systems design, and application across a broad temperature range.

5.0 FIBER OPTIC SENSOR TRADE STUDY

5.1 SENSOR CANDIDATES

Figure 17 lists the fiber optic sensor candidates that passed the initial screening criteria A, indicating their transduction technique and transmission protocol. Each candidate is backed up by a specific vendor design (see * items in Bibliography for those published). Figures in Appendix C break out each candidate, listing its components and attributes used in the trade study.

Some vendors are working toward proprietary advancements in fiber optic sensors, so that consideration of their technology must be postponed.

In the category of low range temperature measurement, both the color ratio (absorption and Fabry Perot) and the Fabry Perot techniques are not included. Ratioing, spectral or otherwise, is a low rated protocol. The published information about color ratioed analog sensors shows that temperature controlled electro-optics is required. Within the FADEC environmental and performance specifications, temperature controlled devices have the following disadvantages, which cause the sensors that need them to be considered environmentally unsuitable for application:

1. There is a significant time (15 minutes) for the device to achieve temperature control.

2. Temperature control may require both heating and cooling functions.

3. To be effective, using only a heating function requires its operation at the upper FADEC limit.

4. Cooling functions are inefficient, creating many more heat calories to dissipate than cool calories at the device.

In a color-ratio sensor, the spectrum resulting from diffraction requires a large detector array. Integrated diffraction techniques are not well developed. In addition, detector arrays need complex sampling electronics and/or complex software. To detect a spectral peak shift from a Fabry Perot temperature sensor, it is necessary to either have detector array resolution smaller than the amount of shift equal to the necessary sensor accuracy, or an algorithm to estimate the peak position between detectors. One vendor uses a Kalman filter algorithm to make estimates. This technique takes significant time to perform the calculation, as it must be performed on the data from the entire array for each reading.

The chosen low-range temperature sensor uses fluorescence from ruby as an indicator. Ruby fluorescence occurs in the red from excitation in the green. The rate of fluorescence decay is a well-behaved function of temperature. Green LED's have been used in one

Sensor Measurand	Transduction Technique	Transmission Protocol	Relia	Maint	Cost	Weight/Vol	Total
Linear and Angular Position	1. Grey scale code plate	Spectrally encoded	74.7	24.3	36.9	22.9	158.8
	2. Collimated transmission	Subcarrier frequency interference	70.0	25.1	38.2	23.0	156.3
	3. Moving monochromator	Wavelength selected	74.0	22.7	36.0	23.5	156.2
	4. Moire pattern movement	Pulse delay	71.9	23.3	37.5	22.2	154.9
	5. Grey scale code plate	Temporally encoded	68.7	24.1	32.1	24.0	148.9
	6. Moving collimated space	Analog with reference	68.3	21.8	35.9	22.4	148.5
	7. Slanted shaft (angular)	Analog level	66.7	21.4	36.1	23.0	147.2
Shaft Rotary Speed	1. Reflective feature	Frequency - one fiber	75.4	28.6	42.1	28.8	175.0
	2. Magneto-optic switch	Frequency - one fiber	75.3	27.9	40.1	25.9	169.2
	3. Reflective feature	Frequency - two fiber	73.3	26.9	38.7	24.3	163.2
	4. Magneto-optic switch	Frequency - two fiber	72.3	23.9	40.1	24.8	161.1
Low Temperature	1. Fluorescence	Temporal phase change	72.8	25.9	39.1	27.1	164.9
	2. Fluorescence	Decay time	68.8	23.9	37.9	23.7	154.3
	3. Total internal reflection	Wavelength encoded	74.1	21.6	34.1	23.4	153.3
	4. Fabry Perot w/multimode	Wavelength select	70.6	22.2	36.1	23.7	152.6
	5. Absorbtion changes	Analog with reference	72.5	23.6	33.4	22.8	152.3
	6. Fabry Perot cavity	Wavelength select	70.0	22.8	36.1	22.0	150.9
High Temperature (4 probes)	1. Blackbody cavity	See Appendix C	77.3	22.4	38.8	28.2	166.7
	2. Blackbody cavity	Figure 48 for description.	77.5	22.3	38.0	27.6	165.4
	3. Blackbody cavity		73.1	21.4	36.7	25.2	156.4
	4. Blackbody cavity		72.9	21.0	36.1	24.6	154.6
	5. Blackbody cavity		72.9	21.0	35.7	24.6	154.2
	6. Fabry Perot cavity		70.6	21.6	33.8	22.0	148.0
	7. Blackbody cavity		67.5	21.0	33.0	22.2	143.7
Vibration	1. Reflection	Analog level with reference	72.2	24.4	38.1	24.8	159.5
	2. Birefringence	Analog level with reference	72.5	22.3	37.6	23.7	156.1
	3. Microbend	Analog level with reference	70.7	25.1	34.9	24.3	155.1
Mass Flow	1. Fiber motion	Frequency w/temperature	80.0	26.8	43.4	28.0	178.2
	2. Reflective	Temporal phase differential	73.1	24.7	42.1	25.1	165.0
	3. Magneto-optic switch	Temporal phase differential	70.7	23.8	37.4	22.4	154.3
Lube Level	1. Reflection	Temporally encoded	70.0	23.6	38.8	24.9	157.3
	2. Absorption	Spectral ratio	72.3	25.9	34.4	23.6	156.4
	3. Reflection	Spectrally encoded	73.8	25.8	34.2	22.5	156.3
	4. Grey code	Separated binary lines	68.1	25.2	37.1	22.5	152.9
Pyrometer	1. Blackbody effect	Spec. ratio (Si/InGaAs)	67.7	21.3	38.8	25.4	153.2
	2. Blackbody effect	Analog level w/InGaAs	66.0	20.7	38.3	27.2	152.2
	3. Blackbody effect	Analog level w/Si	66.0	20.7	37.8	27.2	151.8
	4. Blackbody effect	Spectral content	65.0	20.8	34.9	23.7	144.3
Flame Sensor	1. Flame UV emission	Fluorescent spectral shift	69.2	22.4	41.6	29.2	162.4
	2. Flame UV emission	Analog level	66.7	22.8	40.1	28.4	159.0
	3. Flame UV emission	Spectral content	67.8	20.0	37.7	25.4	151.0

Figure 17. Fiber Optic Sensor Candidates.

published design (Reference 6) to excite the material with a periodic signal which yields a periodic return signal at the longer wavelength. The return signal lags (in time) the excitation signal because of the fluorescence decay phenomenon. The amount of lag or phase difference indicates temperature. The work so far has demonstrated the technique to 170°C with dedicated source and detector circuits. The system has been analyzed to make choices about excitation frequency and processing techniques (Reference 7). The chief reasons this technique was chosen is that it is time based, uses a solid state source, and has a simple algorithm and overall system.

5.2 TRADE STUDY RESULTS

Appendix C contains lists of components/attributes that comprise each sensor candidate, showing how their respective ratings add up to a total average normalized score. Although the scores are close in several cases, the characteristics that drag a score down are often those that are inherent to the candidate such as protocol, transduction technique, and required fibers, optical elements, and electronics, and not characteristics that could easily be substituted.

Another way to present the results is also shown in Figure 17, which displays the contribution of the reliability, maintainability, cost and weight/volume criteria on the total scores. For example, for the spectrally encoded grey scale displacement sensor, the scores were calculated as shown in Figure 18 (refer also to Figures 9 through 15, and Appendix C):

5.3 PREFERRED SENSORS

Listed below are the sensor choices that were applied to the system architecture. In some cases, the highest scored sensor technique was not chosen because of factors difficult to include in the trade study, such as contamination sensitivity.

- **Displacement:** Prefer spectrally encoded Grey scale (No. 1 score).
- **Shaft RPM:** Prefer magneto-optic switch with single fiber (No. 2 score). The reflective technique is vulnerable to contamination.
- **Temperature (low range):** Prefer fluorescence with temporal phase change (No. 1 score).
- **Temperature (high range):** Prefer blackbody cavity using single InGaAs detector, without synchronous detection (No. 1 score).
- **Pyrometer:** Prefer blackbody effect measuring analog level with Si detector (No. 3 score). The two color technique (ratio) is sensitive to contamination. InGaAs wavelengths are sensitive to blade emissivity.
- **Flame Sensor:** Prefer fluorescent spectral shift (No. 1 score).

	Components/Attributes of the Spectrally Encoded Grey Scale Displacement Sensor	Evaluation Criteria (Weight)			
		Reliability (10)	Maintain-ability (5.1)	Cost (6.6)	Weight/ Volume (4.8)
A2.	IRED-Edge Emitter	8	5	5	5
A7.	Two Sources	7	4	3	5
B1.	Si PIN Photodiode	9	5	8	5
B6	CCD Array	6	3	4	3
C1.	Poly./Silica Fibers	7	7	8	5
C7.	Two Fibers Required	8	5	4	8
D2.	Wave. Encoded Protocol	9	5	5	5
E2	Selfoc Lens	7	5	8	5
E6.	Glass or Metal Mirror	8	3	7	2
E8.	Glass or Metal Grating	8	3	3	3
E14.	Multi-Contact Connector	5	2	4	2
E16.	Four Optical Elements	7	4	3	5
F3.	Sealed Reflection Transm.	8	7	7	7
G1.	Bandwidth Under 10kHz	9	6	7	5
G4.	Elec. Power Under 1 Watt	8	5	7	7
G9.	Standard Analog Elec.	8	7	8	5
G16.	Over 8 Active Elec. Comps.	5	5	4	4
		-----	-----	-----	-----
		127	81	95	81

(127 x 10) ÷ 17 = 74.7

(81 x 5.1) ÷ 17 = 24.3

(95 x 6.6) ÷ 17 = 36.9

(81 x 4.8) ÷ 17 = 22.9

Total = 74.7 + 24.3 + 36.9 + 22.9 = 158.8

Figure 18. Example of a Trade Study Score Calculation Using the Encoded Grey Scale Displacement Sensor.

- **Vibration:** Prefer reflection using neodymium fluorescence (No. 1 score).

- **Mass Flow:** Prefer temporal phase difference using reflection No. 2 score. Reflection will take place in filtered fuel. The vortex shedding technique requires temperature measurement to calculate mass flow.

- **Level:** No technique is considered satisfactory. Oil contamination, wetting, foam, and froth will severely affect accuracy.

5.3.1 Sensor Specifications and Block Diagrams

Figures 19 through 26 are block diagrams of the preferred sensors. Appendix A contains a brief specification for those preferred sensors that pertain to the propulsion control system, excluding those used in a condition monitoring function. The specifications present performance, environmental, and physical requirements, including optical power budget estimates.

5.3.2 Analog Sensor Issues

The trade study resulted in choosing unreferenced analog techniques for the pyrometer, flame detector, and high range gas temperature sensor. They have no separable optical connector, being continuous from the collection optics/head to an electrical connector.

The optical cables associated with these aft engine sensors need a very high temperature resistance: 350° to 550°C, depending on exact location. There are currently no adequate separable optical connectors available for this temperature regime. However, several manufacturers have developed fastening methods for terminating optical fiber at such temperatures. Such terminations should be inseparable (such as by welding or wired bolts) unless a clean maintenance shop with appropriate calibration equipment is available, so that signal transmission cannot be affected by maintenance action. The UV transmissive parts of the flame sensor are more susceptible to maintenance action degradation because of oil, fuel, and other common contaminants highly absorb UV.

To preserve analog sensor calibration in the operating and maintenance environment, it is suggested that those sensors be calibrated from entrance optic to electronic amplifier output and that the calibration be maintained by the flightline by not allowing the optical system to be violated. Such a sensor assembly, compared to a connectored system with reference, may have some impact on life cycle cost and maintainability, in the sense that more hardware is associated with each replaceable unit.

Unreferenced optical analog sensors require design effort to prevent environmental sensitivity. If the optical fiber numerical aperture is underfilled, variation due to bending losses is negligible; if the fiber cable is packaged and routed to prevent mechanical interaction with its environment, thermal and vibrational effects are negligible. Pyrometry sensors have a steep relationship between sensor voltage output and target temperature within the normal target temperature range. The sensitivity of the temperature reading (at a blade temperature of 980°C) to transmission variations is about 1.0°C per percent variation.

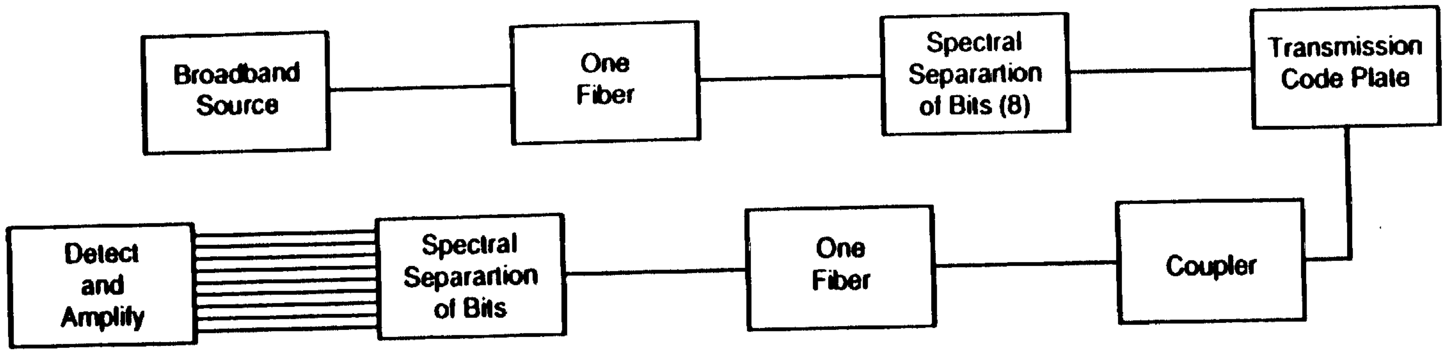


Figure 19. Preferred Fiber Optic Displacement Sensor Block Diagram.

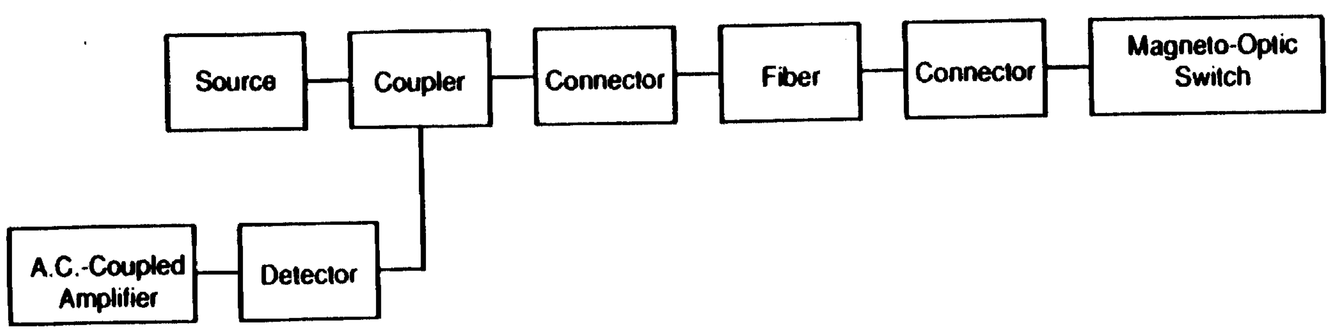


Figure 20. Preferred Fiber Optic Shaft Speed Sensor Block Diagram.

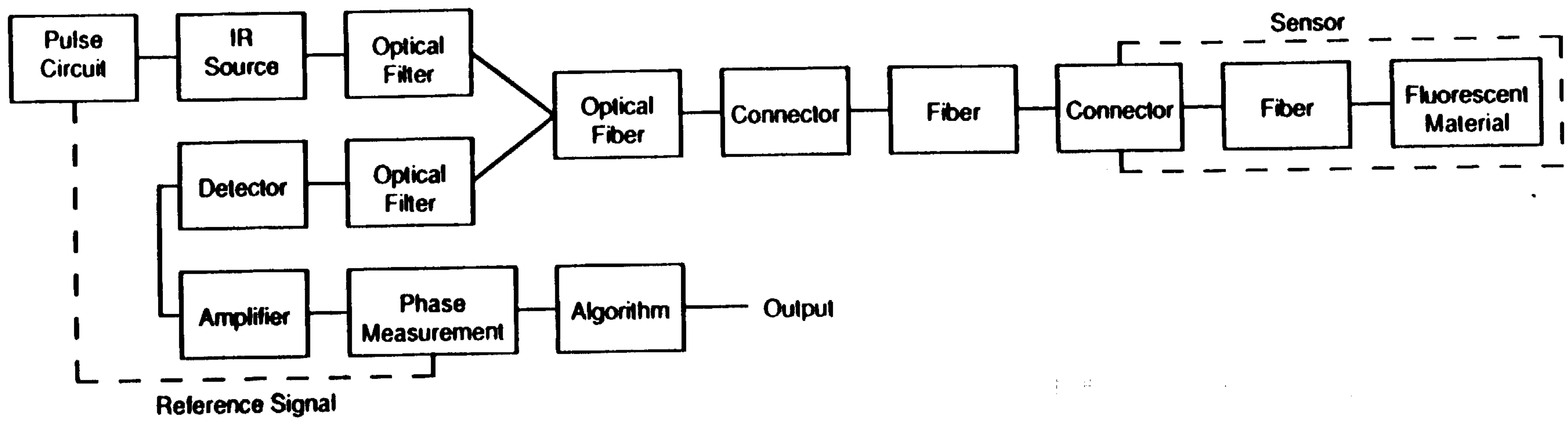


Figure 21. Preferred Fiber Optic Low Range Temperature Sensor Block Diagram.

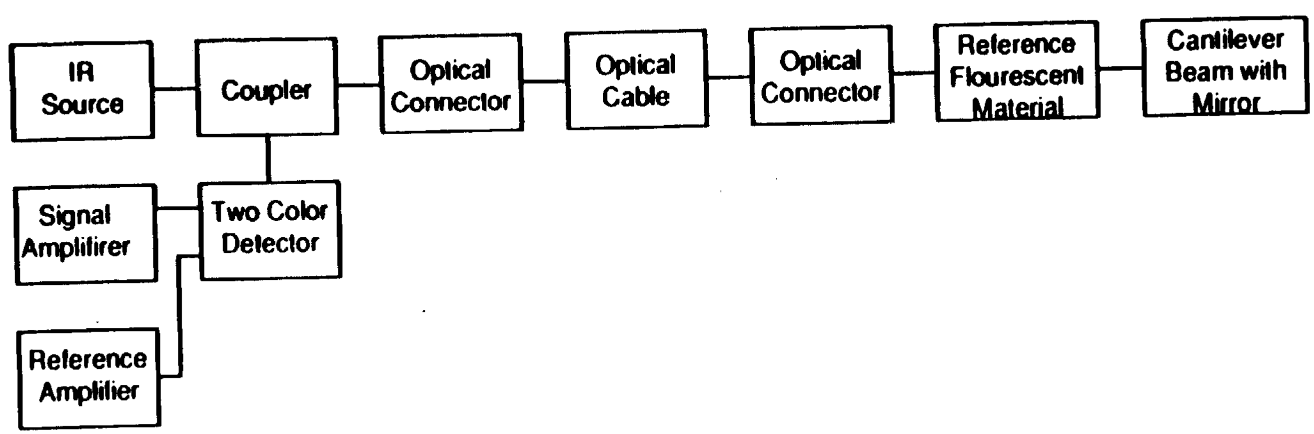


Figure 22. Preferred Fiber Optic Vibration Sensor Block Diagram.

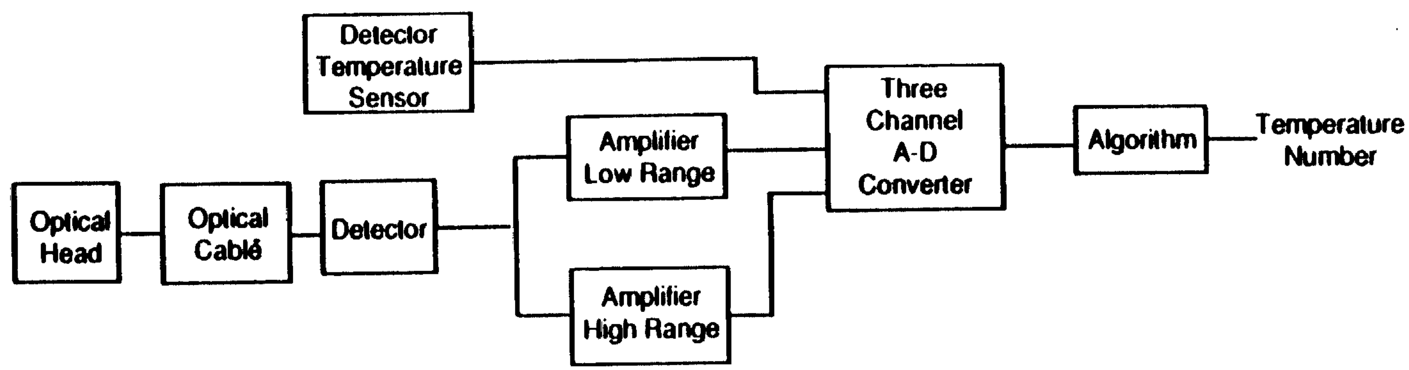


Figure 23. Preferred Fiber Optic Turbine Blade Temperature Sensor Block Diagram (Pyrometer).

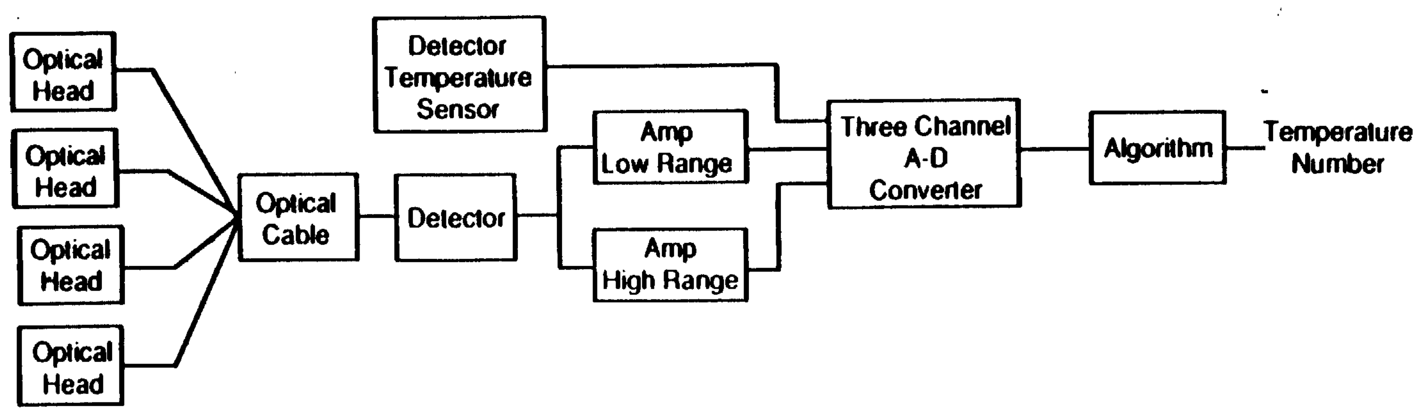


Figure 24. Preferred Fiber Optic High Range Temperature Sensor Block Diagram.

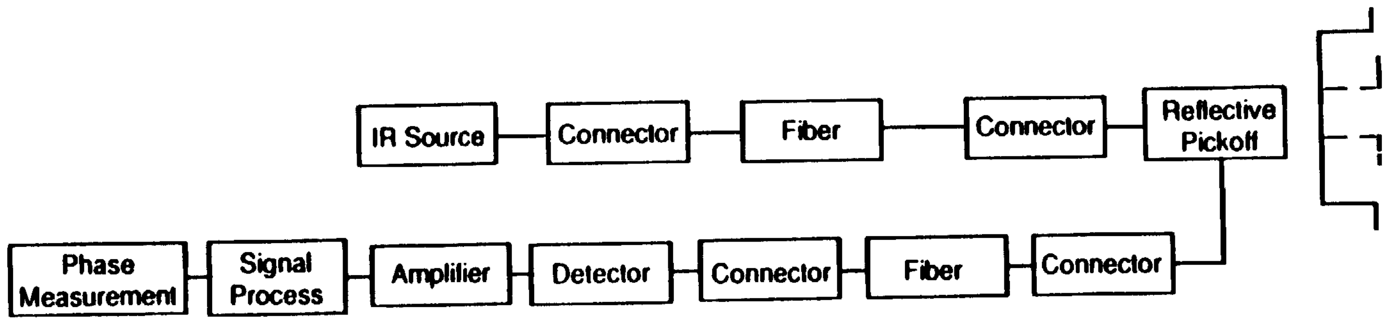


Figure 25. Preferred Fiber Optic Mass Flow Sensor Block Diagram.

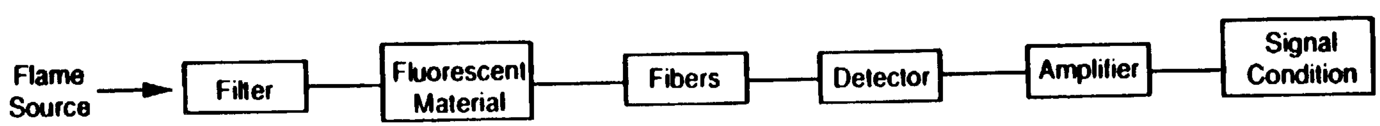


Figure 26. Preferred Fiber Optic Flame Detector Sensor Block Diagram.

6.0 PREFERRED ARCHITECTURE DESCRIPTION

6.1 INTERFACE DESCRIPTION

Figure 27 (compare with Figure 4) shows the sensor and actuator connector interfaces to the electronic control module for a fiber optic propulsion system using the favored sensor choices. It includes the following features:

- Primary and secondary channel connectors have been maintained, with the addition of a dual electrical d.c. bus to service torque motors, solenoids, and relays in each channel. Exhaust nozzle position and afterburner fuel flow functions were also added, having been input on a separate connector in the model system. The exception to this is that only one electro-optic detection circuit module is shown for the eight T5 gas temperature probes; this should be doubled for a completely redundant system.

- Separate modules accommodate each analog sensor input. These items require transmitting light directly from each sensor head to an electro-optics module without the use of fiber-to-fiber optical connectors, as discussed in Section 5.3.2.

- All pressure sensors are located in the electronic control module, requiring pneumatic inputs. The fiber optic vibration sensor, not needing preamplification, is now grouped with the other off-engine signals.

Figure 28 (compare with Figure 5) shows the fiber optic contact interfaces between the sensors/actuators and the electronic control module, including the electro-optic module partitioning that is addressed in the detailed design. Figure 29 (compare with Figure 6) is an overall block diagram of the fiber optic system.

6.2 HARNESS CONSTRUCTION AND LAYOUT

Mixed (wires and fibers) cables were chosen over separate (wires only/fibers only) cables. Separating wires and fibers would require a harness branch and connector for each at every applicable engine component. For example, many actuators and fuel control components contain both torque motors, requiring optically switched electrical power, and fiber optic displacement measurements. The current trend is to try to reduce connector quantities and sizes for purposes of reliability and maintainability, and to reduce weight and cost.

Figures 30 through 33 are layouts of the propulsion system fiber optic harnesses and electrical power bus for the system, directly relating to the fiber optic connector interfaces shown in Figure 27, and the current propulsion system layout in Figure 3.

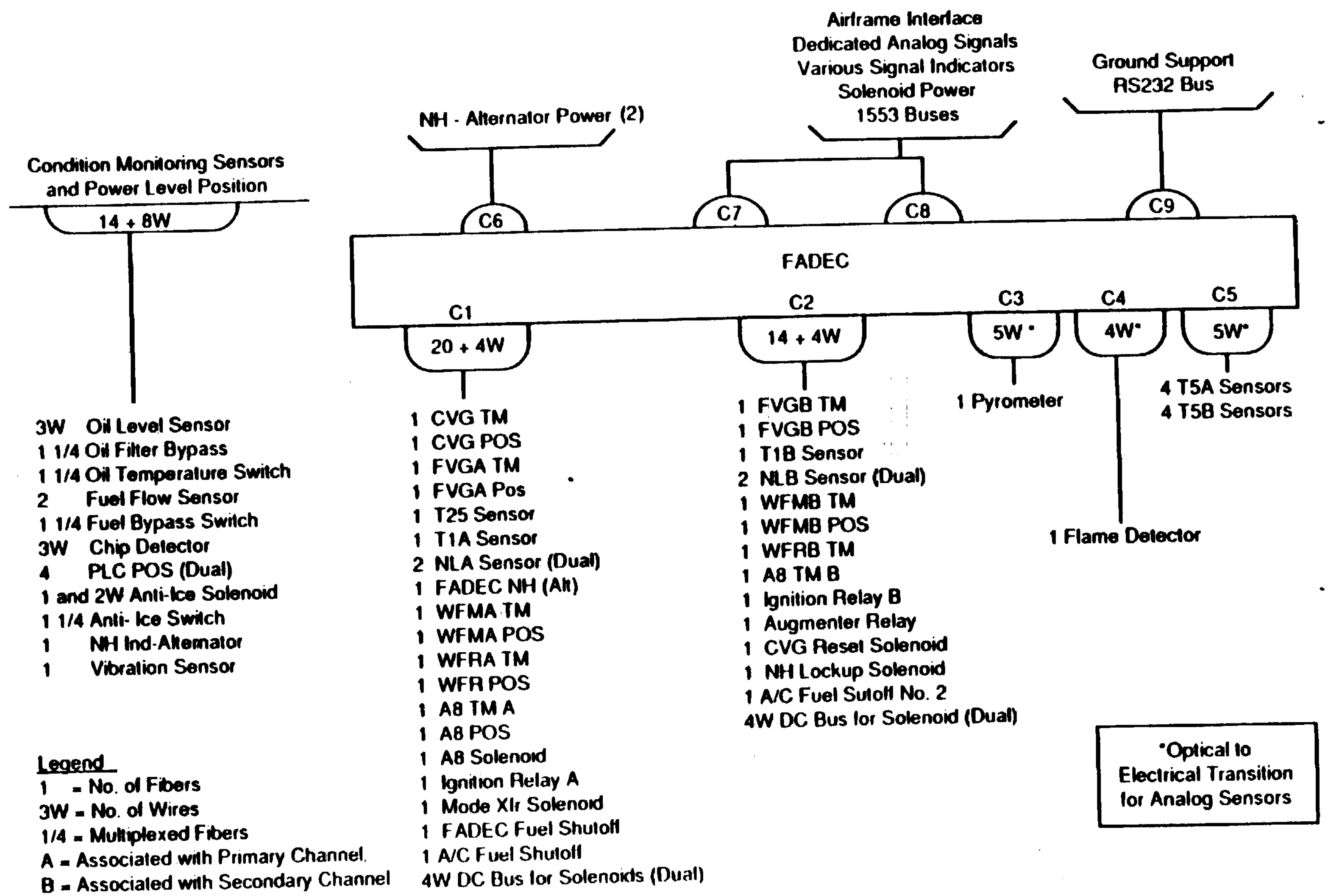


Figure 27. FADEC Connector Interfaces - Preferred Fiber Optic System.

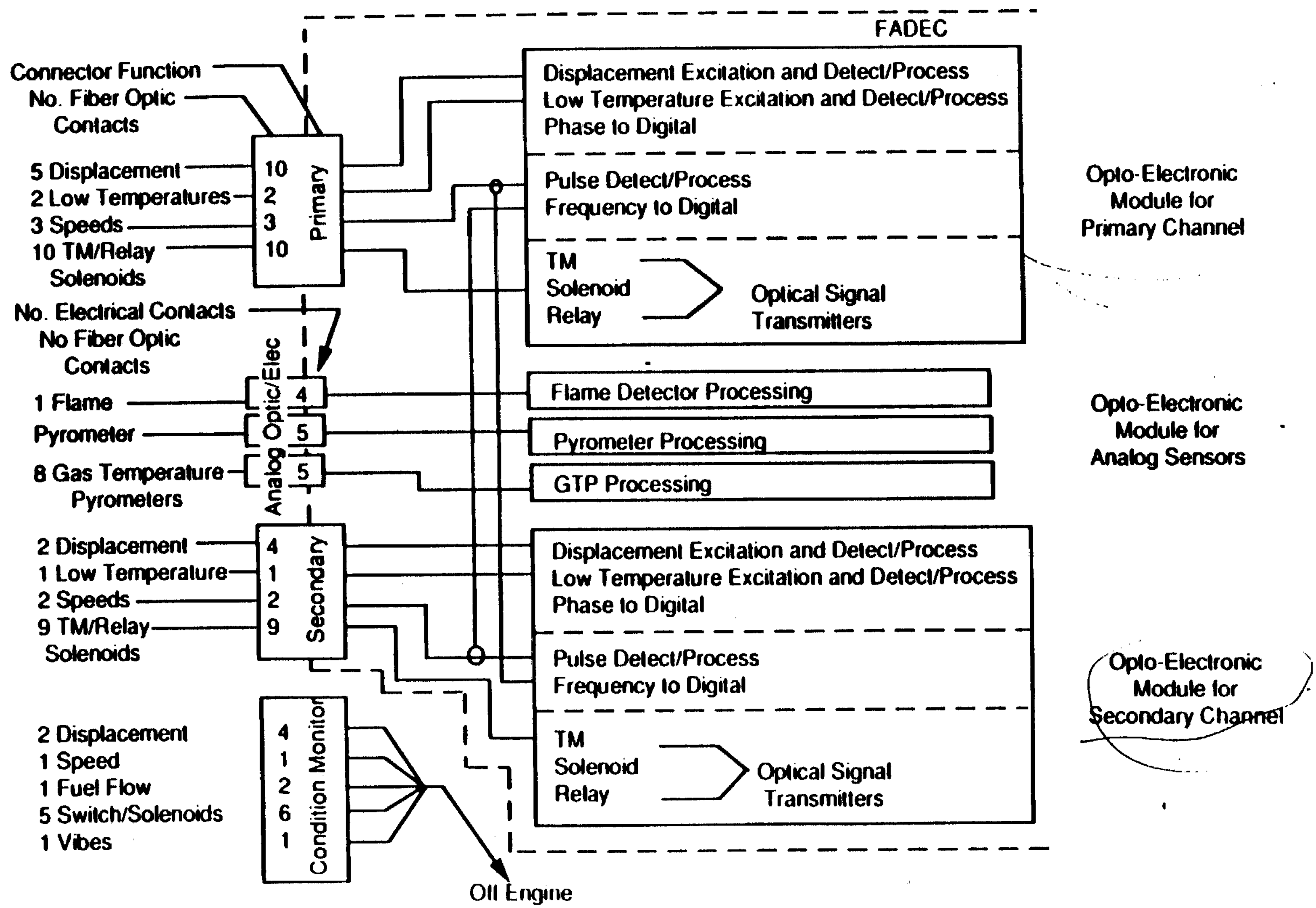


Figure 28. FADEC Fiber Optic Sensor Connections and Internal Electro-Optic Modules.

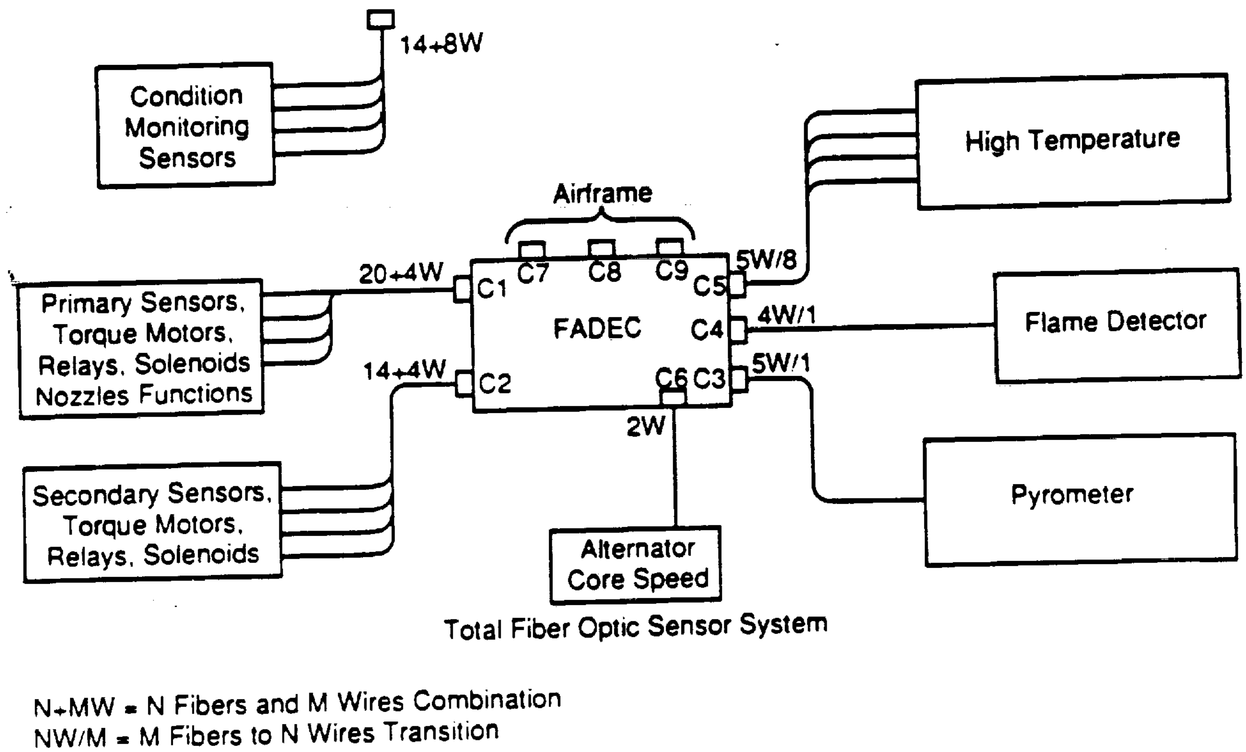


Figure 29. Preferred Fiber Optic System - Overall Block Diagram.

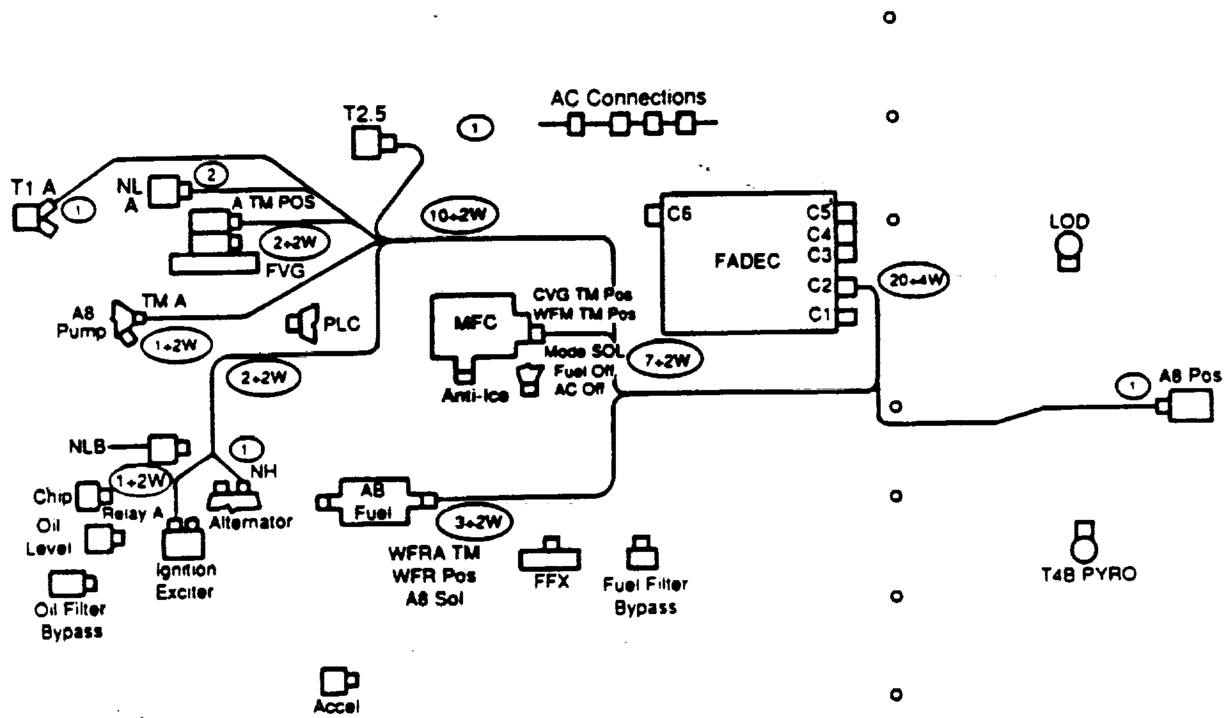


Figure 30. Primary Channel Fiber Optic Harness.

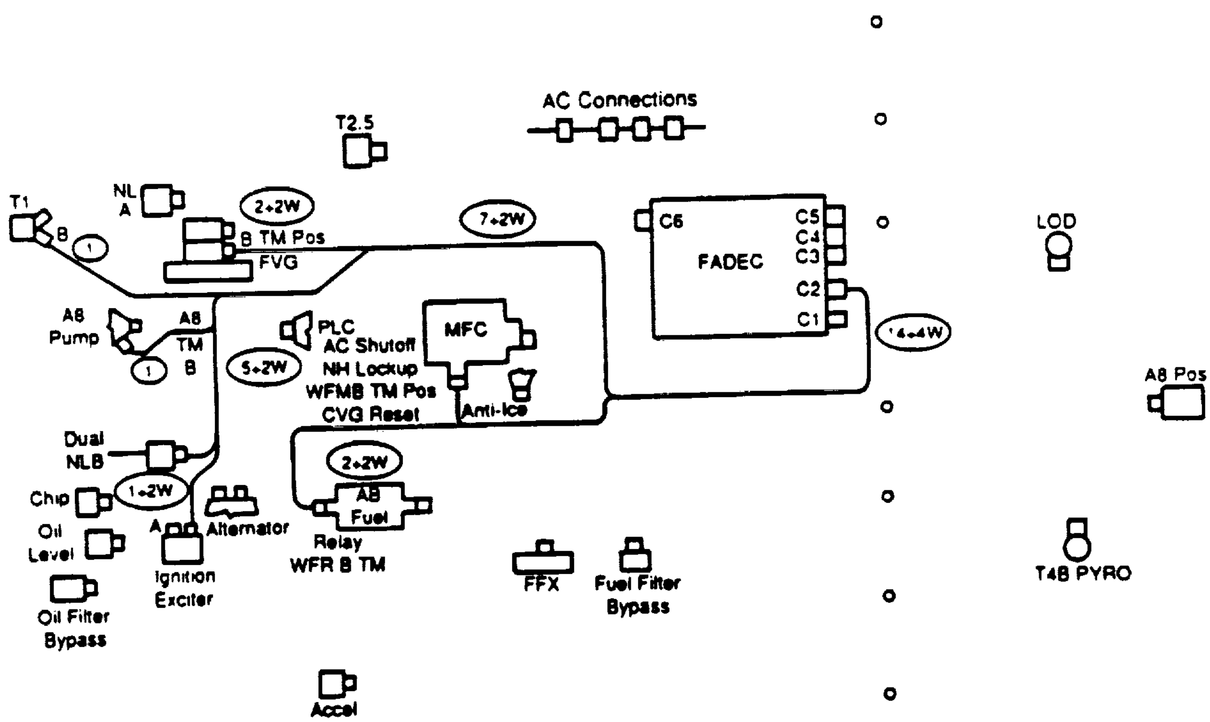


Figure 31. Secondary Channel Fiber Optic Harness.

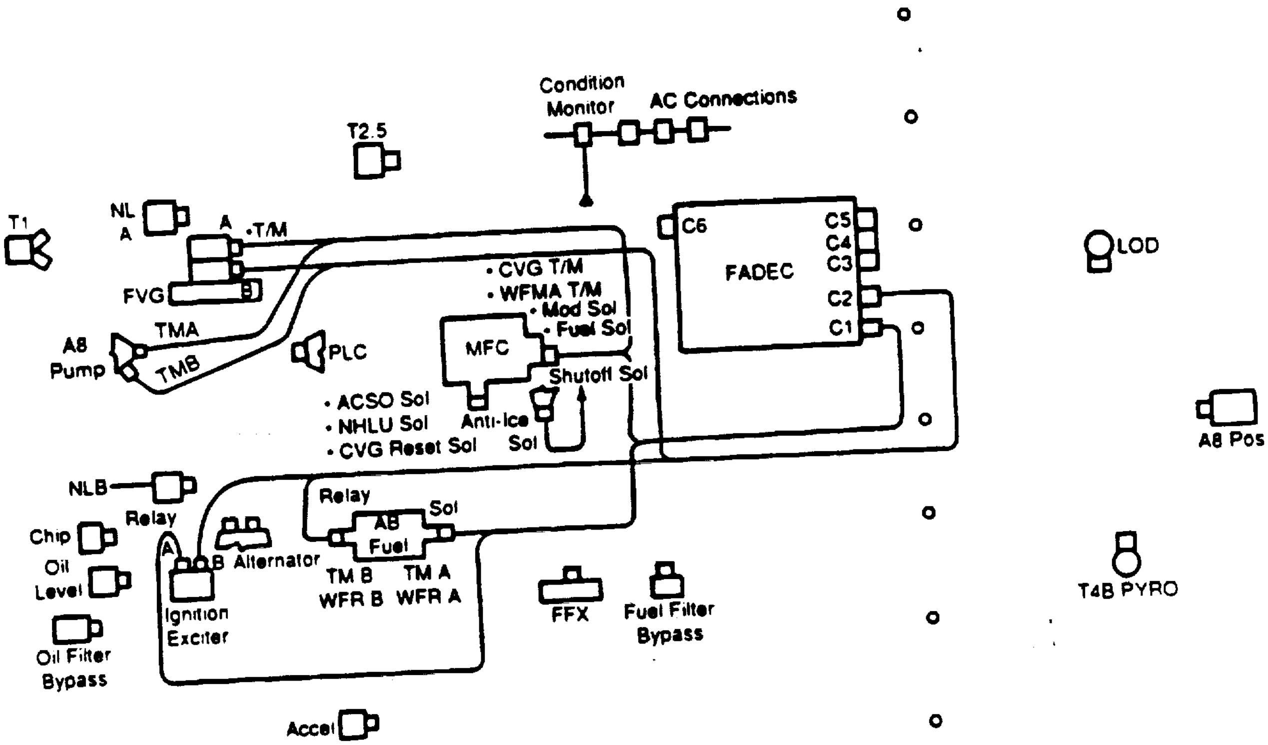


Figure 32. Electrical Power Bus For T/M's, Relays, and Solenoids.

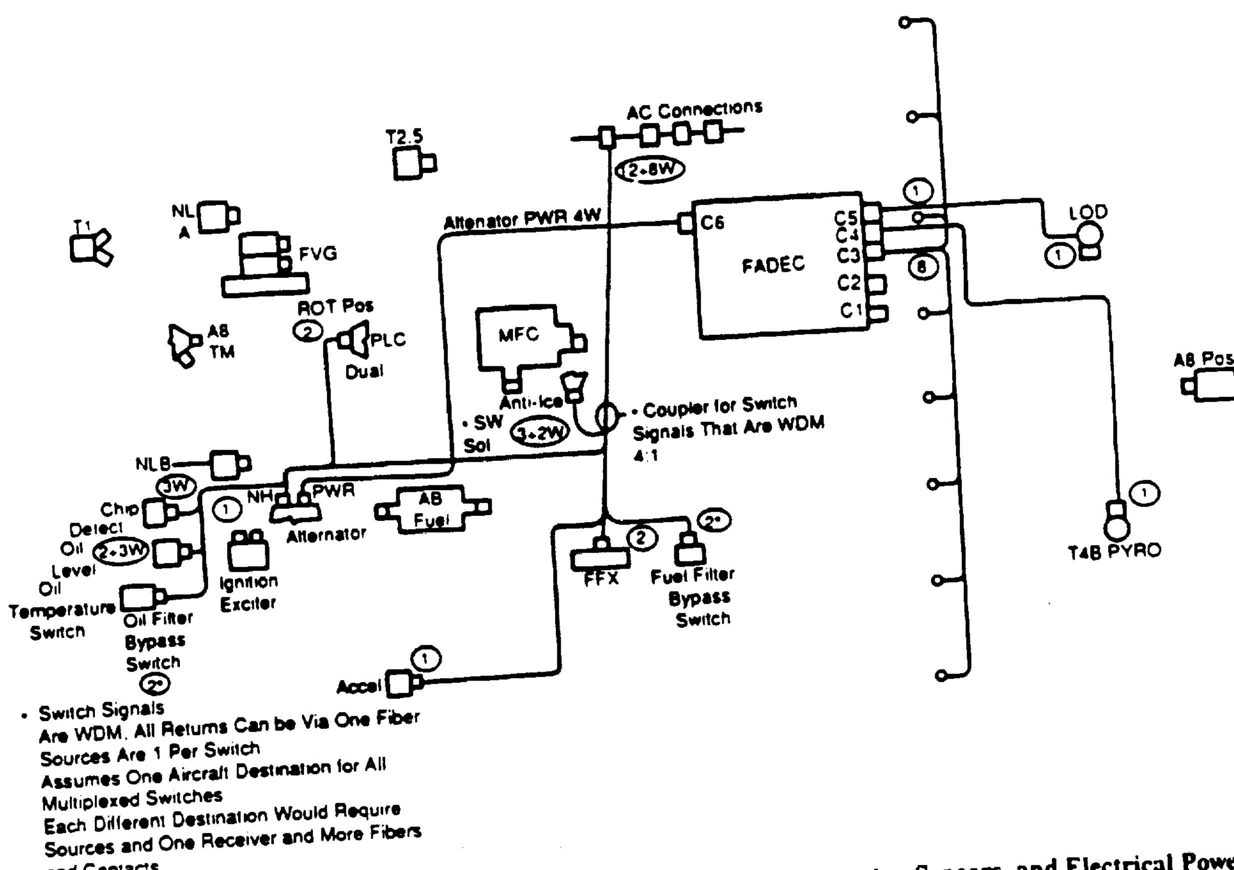


Figure 33. Harnesses for Fiber Optic Analog Sensors, Mixed Cable Monitoring Sensors, and Electrical Power.

6.3 ELECTRO-OPTICS DETAILS

6.3.1 Decisions on Sharing Electro-Optics

Using the control system architectural ground rules discussed in Section 4.3.3.1 as guidelines, decisions were made pertaining to sharing electro-optic control module components.

Since optical sources are at present a relatively unreliable control system component, the tendency in this electro-optics design will be to minimize the sharing of optical sources between sensors. IRED's currently have a relatively short life (10,000 hours at 125°C) compared to other electronic components. Sources should be mounted together directly on a cooled surface. Those sources that interrogate sensors attached to the same receiving electro-optics should be sequentially energized so that outputs can be attributed to a particular sensor. This approach further increases source life by decreasing their duty cycle.

Receiver electro-optics will be shared as much as possible within the respective primary and secondary electronic control module channels. Detectors and their processing electronics are much more reliable than sources.

6.3.2 Electro-Optics Schematics

Figure 34 shows a schematic of the electro-optics for the five displacement sensors, two low range temperature sensors, and three shaft speed sensors associated with the control module primary channel. For the displacement sensors, each of eight narrowband bit sources is sequentially pulsed and coupled to all five sensors. A dedicated detector for each sensor receives a "yes" or "no" bit-train response. The temperature sensors each have a separate source coupled back to a common detector. A similar scheme is used for the speed sensors.

Figure 35 shows the electro-optics for the high range temperature sensor, the turbine blade temperature sensor (pyrometer), and the flame detector, that is, the analog type signal fiber optic sensors. Light from the sensor head is received along a sealed, nonseparable fiber optic cable assembly. The detectors must be temperature compensated.

Figure 36 shows the electro-optics for the torque motors, relays, and solenoids, that is, components requiring electrical power. Each torque motor requires two sources corresponding to the bidirectional movement of the valve.

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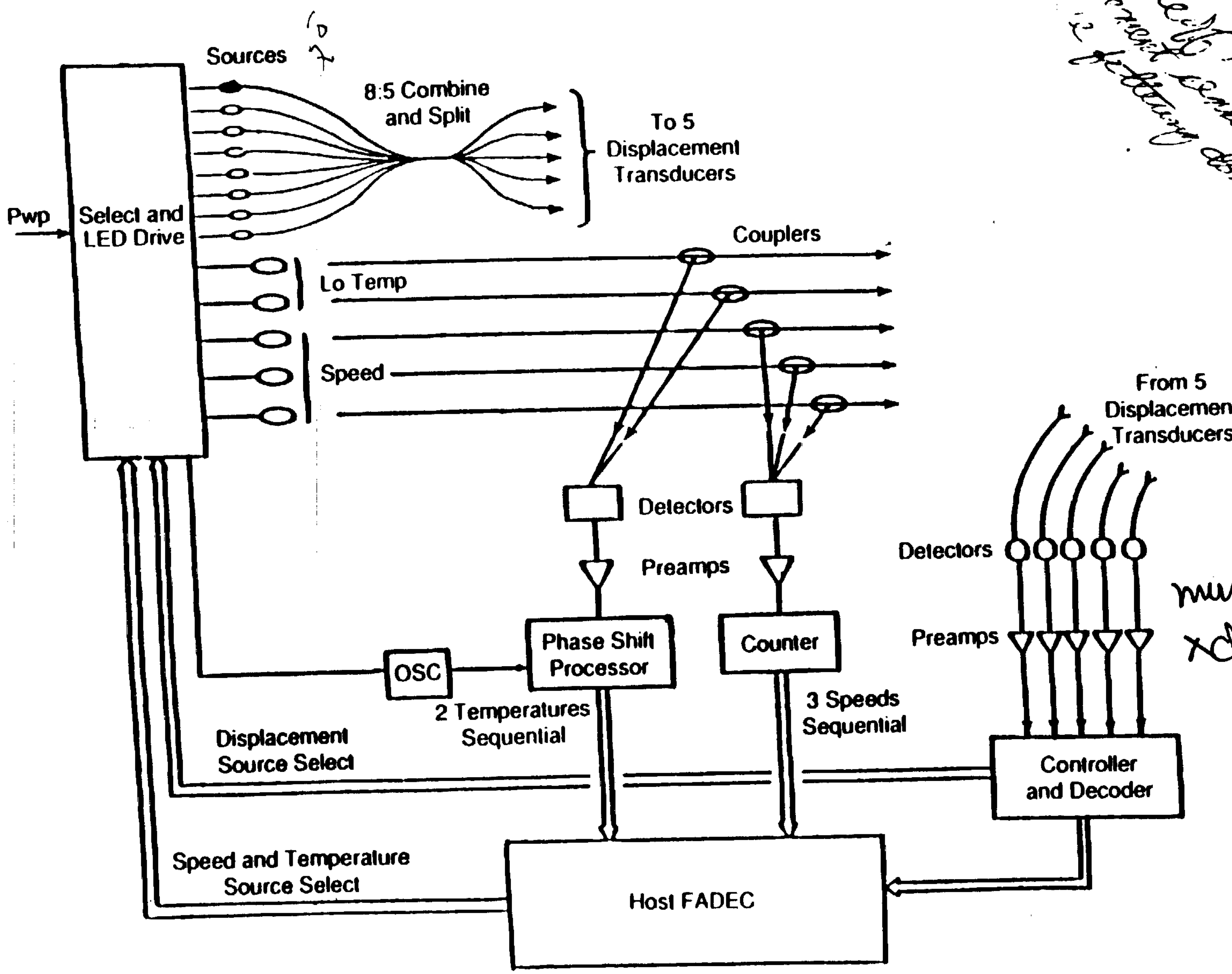


MS50 preferred tradeoff this approach for displacement sensors with broadband ... filtering done at sensor.

mux-displacement xducers on one line

Figure 34.Combined Low Temperature, Shaft Speed, and Displacement Sensors Electro-Optics For Primary Channel of Control Module.

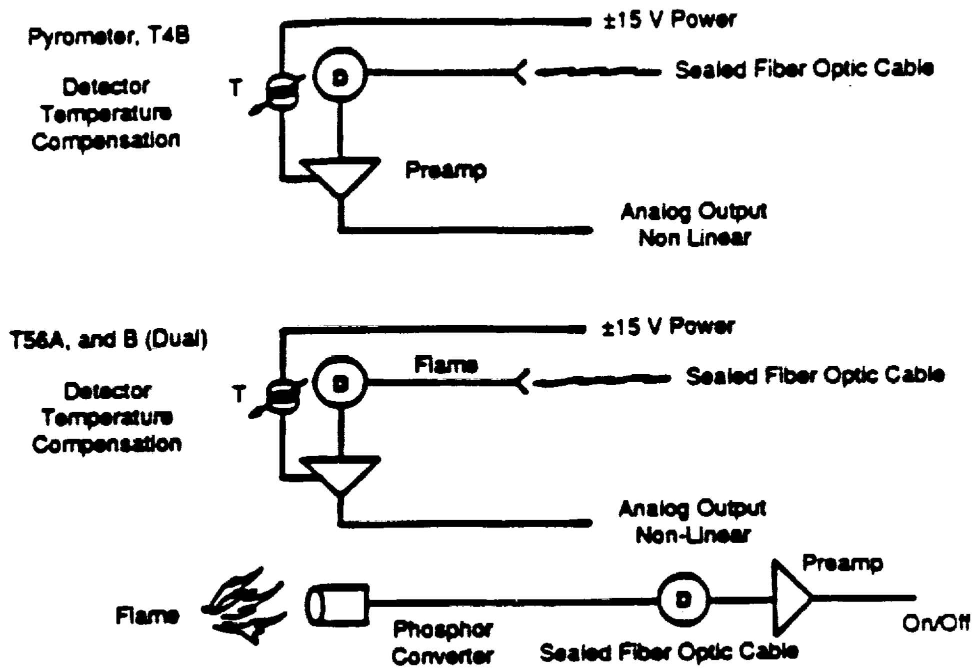


Figure 35. Analog Sensors Electro-Optics.

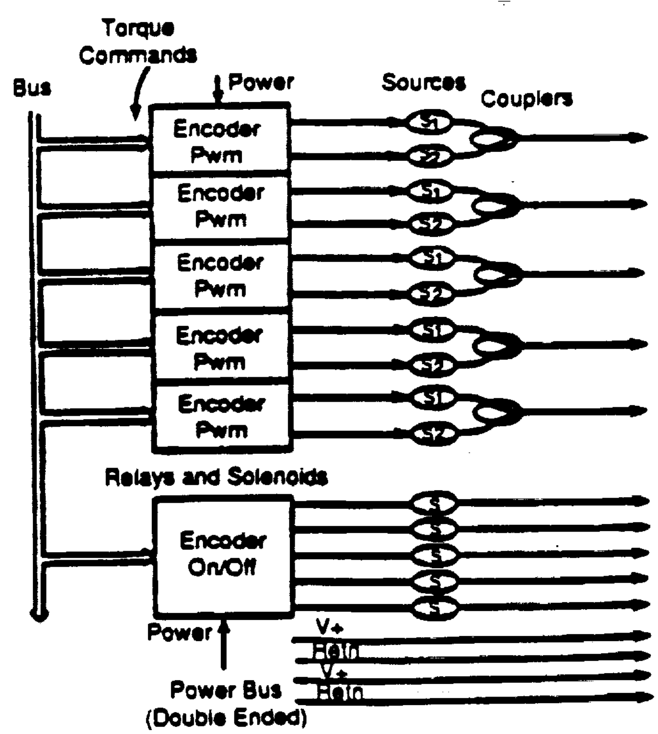


Figure 36. T/M, Relay, and Solenoid Electro-Optics.

7.0 PREFERRED ARCHITECTURE DETAILED DESIGN

7.1 TOP LEVEL ASSEMBLIES AND DOCUMENTATION

The interface between the fiber optic sensors and the electronic control module consists of five subassemblies as shown in Figure 37. These were shown in schematic form in Figure 28. This electro-optic system interrogates and reads engine fiber optic sensors and provides the information to the propulsion control system computer.

Primary and secondary opto-electronic modules service the fiber optic sensors associated with the primary and secondary channels, respectively. Each of the three analog fiber optic sensors is serviced by a separate analog module. For completely separate primary/secondary control channels, the T5 gas temperature probes should have incorporated two separate identical analog modules for each four probe set.

The design package for the above assemblies consists of the following documents:

1. Fiber Optics/Electronic Control Module Interface Assembly Drawing (similar to Figure 37) and Parts List
2. Primary Opto-Electronic Module Layout (similar to Figure 39), Block Diagram (Figure 38), and Interconnect Diagram (Figure 40)
3. Electro-Optic Integrated Component Outline Drawing (Figure 43)
4. Primary Opto-Electronic Module Analog Board, Resistor Board, and Digital Board; Schematic Diagram, Printed Circuit Board Layout (Figure 41), and Parts List for each
5. Pyrometer Module Assembly Drawing (Figure 45), Printed Circuit Board Layout (Figure 44), Schematic, and Parts List
6. Gas Temperature Module Printed Circuit Board Layout, Schematic, and Parts List
7. Flame Sensor Module Printed Circuit Board Layout, Schematic, and Parts List

7.2 PRIMARY CHANNEL OPTO-ELECTRONIC MODULE

The opto-electronic module for the primary channel consists of a mechanical frame, an electro-optic integrated (EOI) component, an analog printed circuit (PC) board, a digital PC board, a resistor PC board, an interface optical connector, and other internal electrical connectors, ribbon cables, and mechanical parts. A functional block diagram is shown in Figure 38.

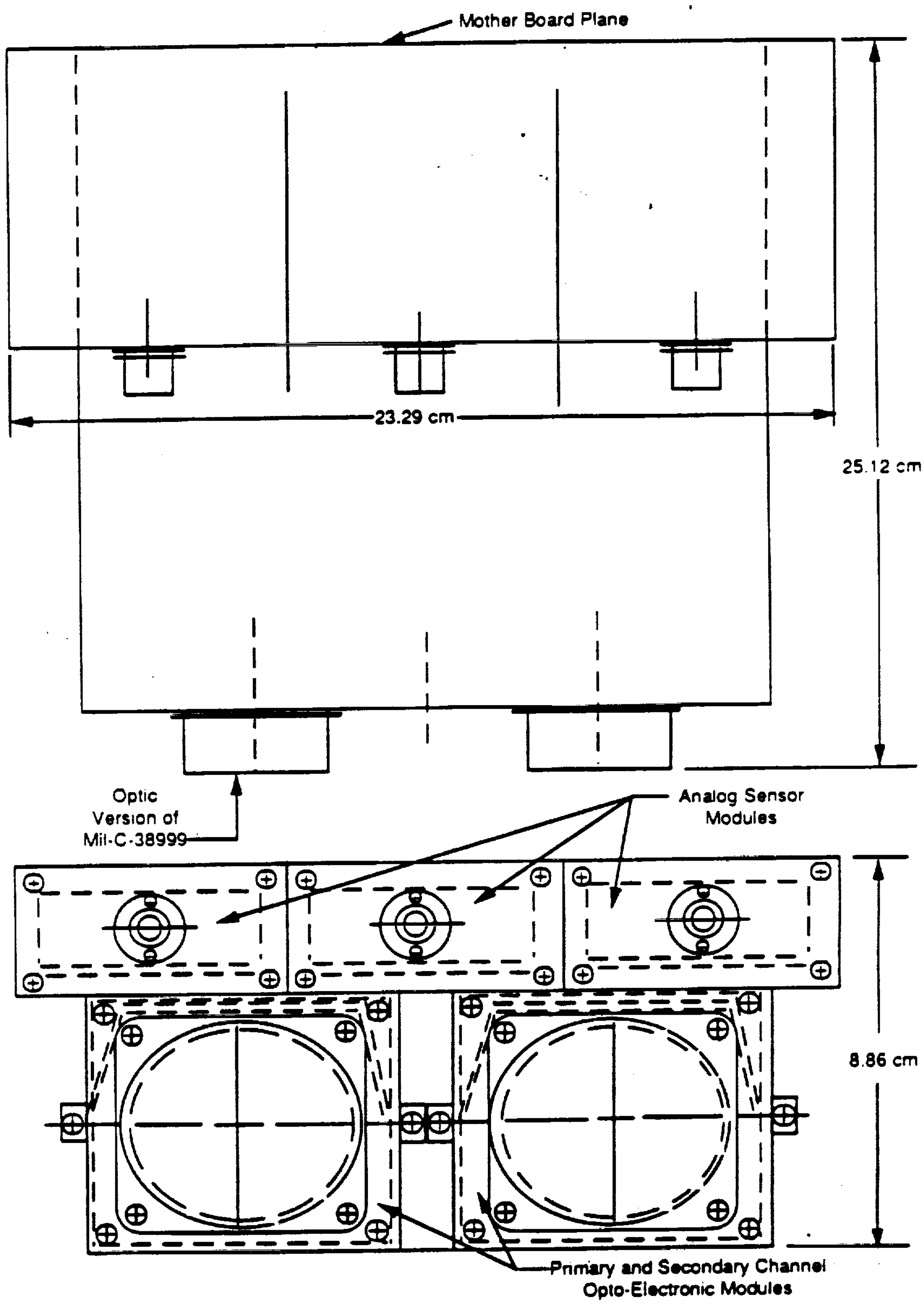


Figure 37. Fiber Optic Sensor/Electronic Control Module Interface.

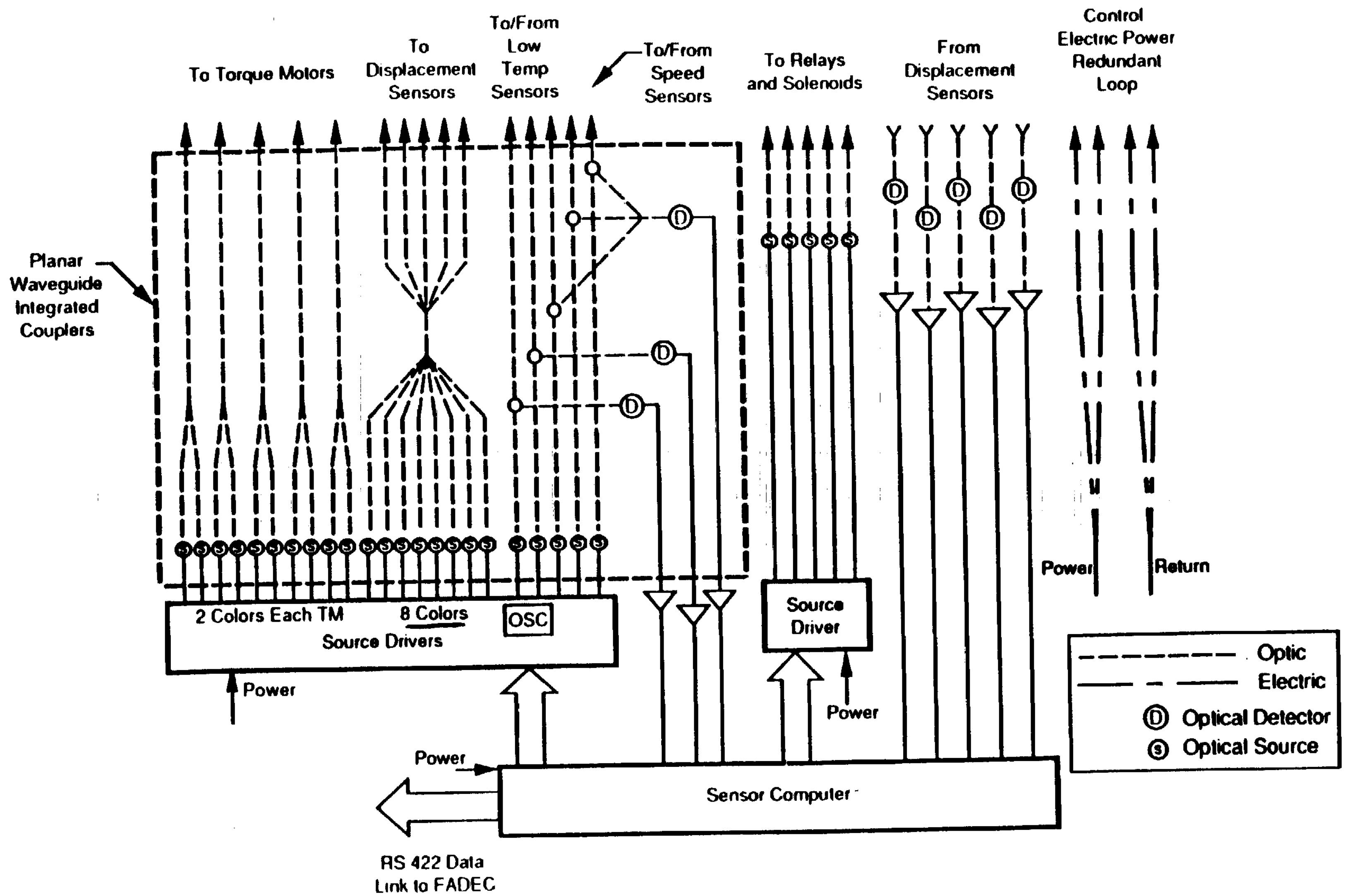


Figure 38. Primary Channel Opto-Electronic Module Functional Block Diagram.

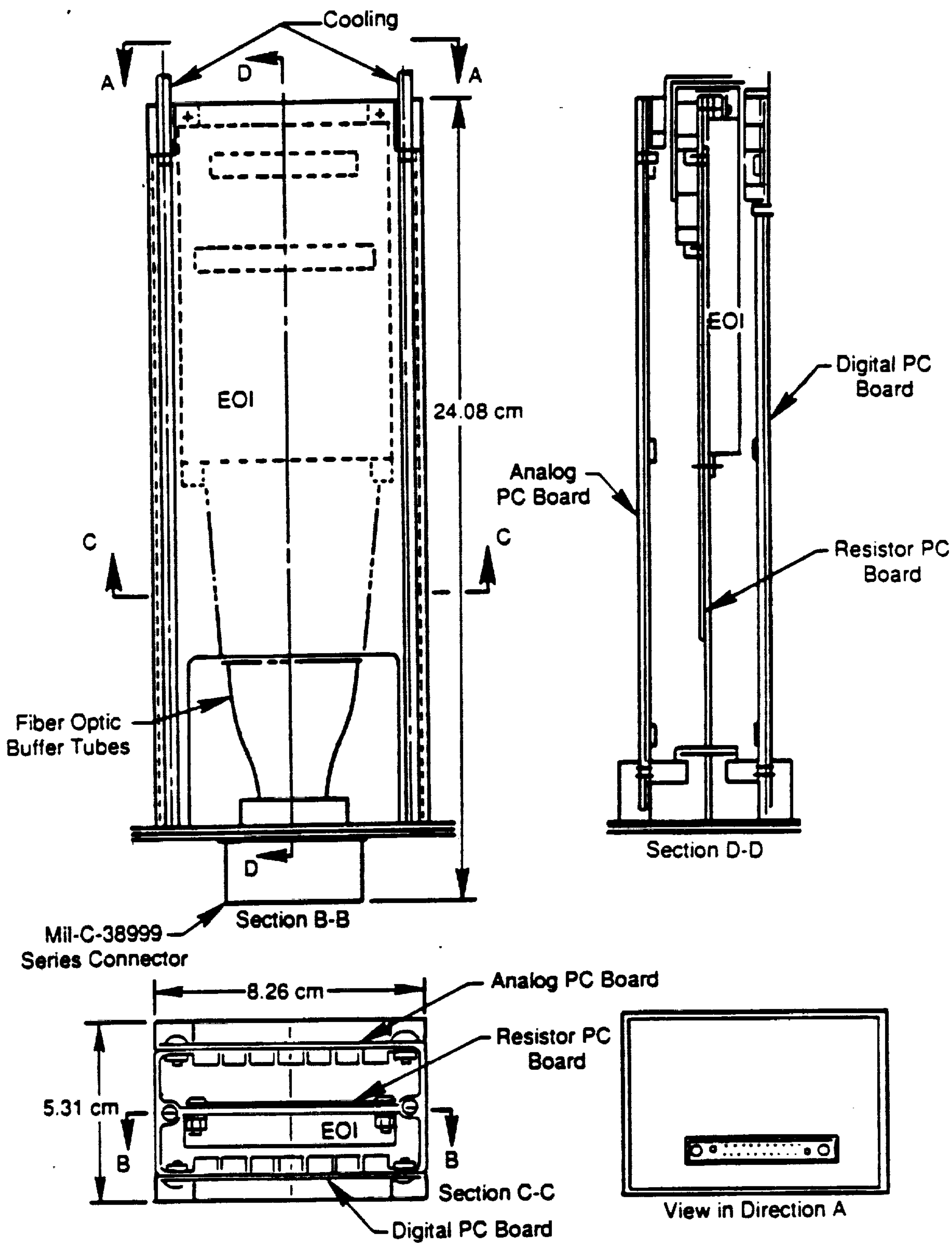


Figure 39. Primary Opto-Electronic Module Layout.

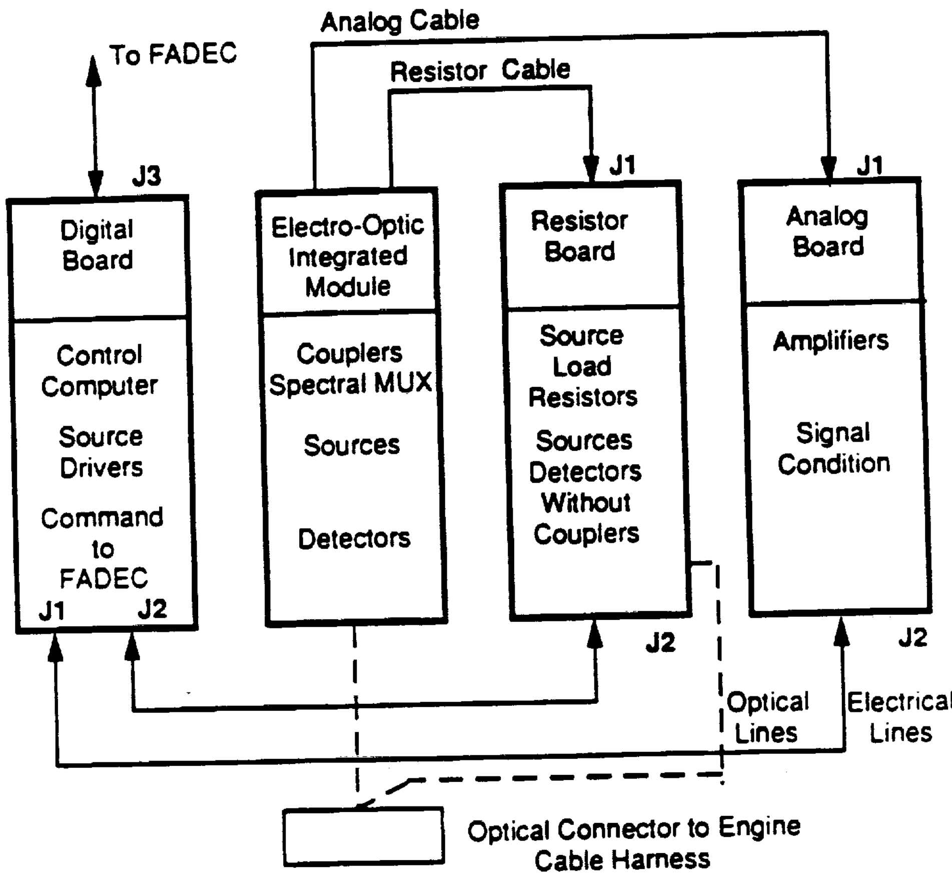


Figure 40. Electro-Optic Architecture Interconnection Diagram - Primary Channel.

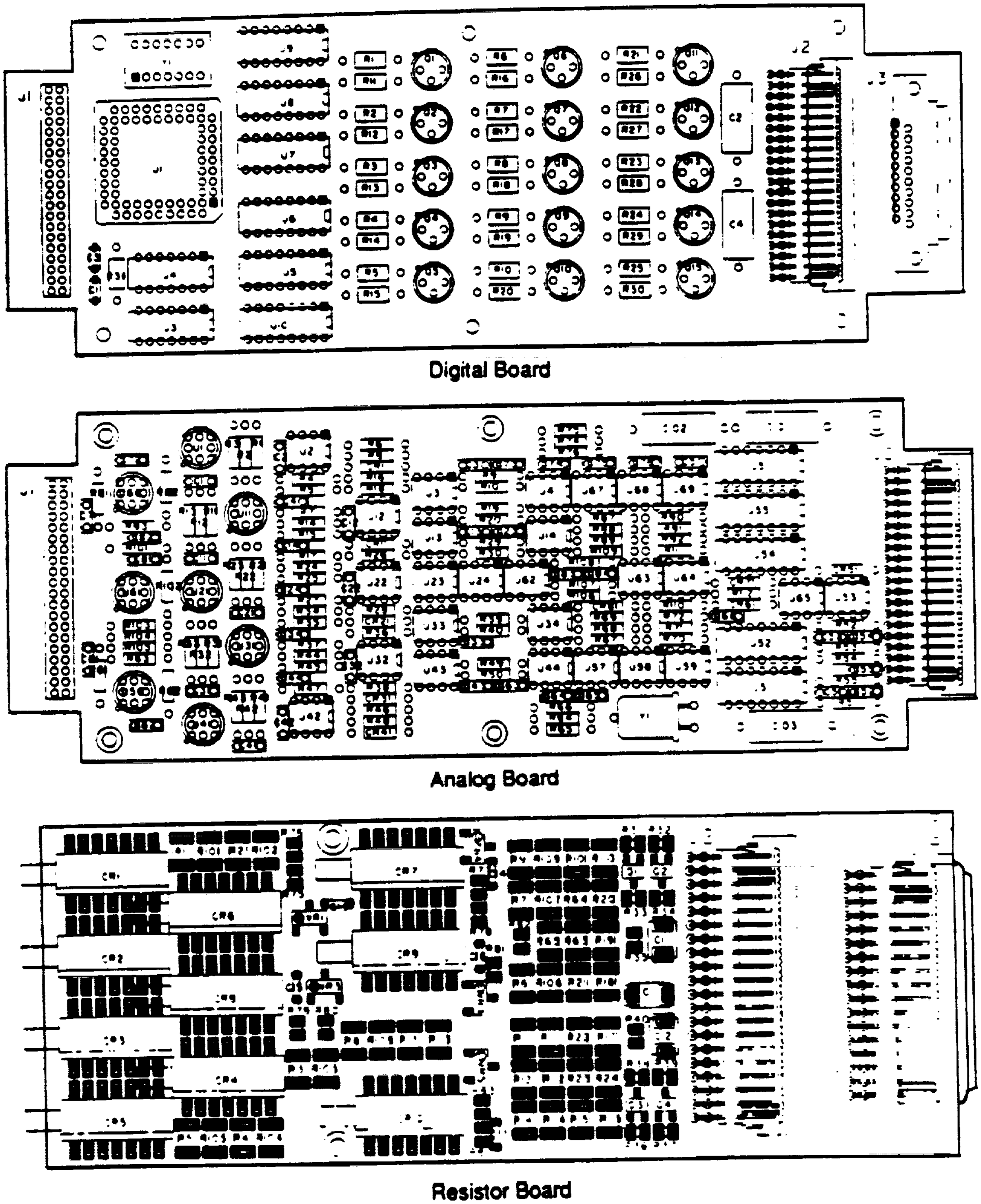


Figure 41. Electronic Printed Circuit Board Layouts for the Primary Opto-Electronic Module.

Figure 39 is a layout of the primary module assembly. The EOI, containing front-end electro-optics, and the resistor PC board are mounted on a web between the other two PC boards, containing front end electronics (transimpedance amplifiers and other early signal processing components) and digital output electronics. The close proximity of some of these components is necessary for good signal-to-noise ratio. Some of the necessary digital electronics are already part of the current electronic control module circuitry, and could be removed if this type of packaging is used. Figure 40 is a interconnection diagram for the module. Figure 41 shows PC layouts of each board.

The opto-electronic module for the secondary channel duplicates most of the items in the primary, with all of its components common. Its PC layouts, EOI component, and assembly drawing would be of the exact form as the primary, only containing fewer components.

7.3 THE ELECTRO-OPTIC INTEGRATED (EOI) COMPONENT

As shown in Figure 38, the displacement sensors, low range temperature sensors, speed sensors, and torque motors associated with the primary and secondary control channels require optical coupling and splitting functions with source(s) and detector(s). When these functions are combined in one component, the design becomes physically simpler, easier to maintain, and significantly lower in weight and volume, compared to placing each electro-optic component separately in its own package. Some manufacturers are developing this sort of integrated electro-optic package.

7.3.1 Physical Description

This EOI component design concept couples and routes optical signals to and from the electronic control module chassis connectors. It consists of embedded optical pathways accommodating all necessary couplers, filters, and other optical components, on a glass substrate, including an area at one end to mount the sources and detectors. The integration uses the combination of a planar optical waveguide with hybrid source and detector mounting techniques.

Figure 42 shows a planar waveguide design concept sized for the primary control channel. The displacement sensors use eight separate sources (8 bits), each excited and sent to all five position sensors sequentially, and returned to five dedicated detectors. The two low range temperature sensors each have a separate source coupled back to a single detector. A similar scheme is used for the three speed sensors.

Figure 43 shows a design for the completed EOI package with optical fiber pigtails transitioning to optical termini that would insert into the electronic controls chassis connector.

The EOI component design for this contract includes outside dimensions and a description of its electrical and physical characteristics. The specific internal embodiment of the functions is not described.

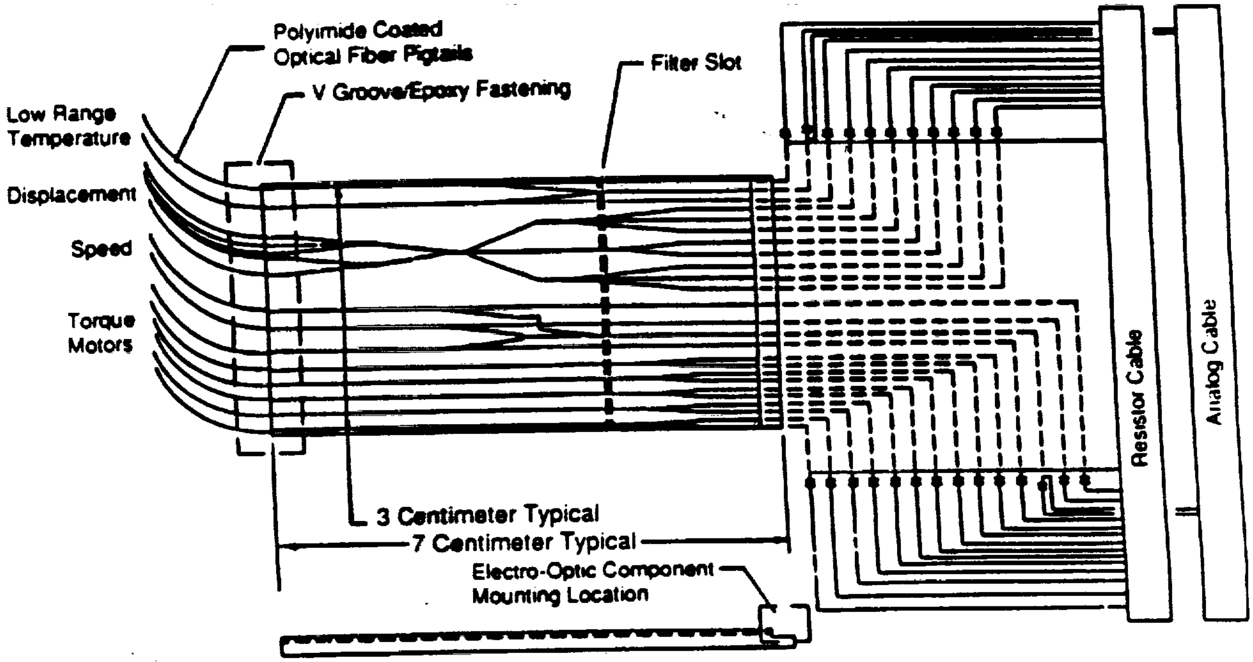


Figure 42. Planar Waveguide Design to Couple and Route Sources/ Detectors Optical Signals.

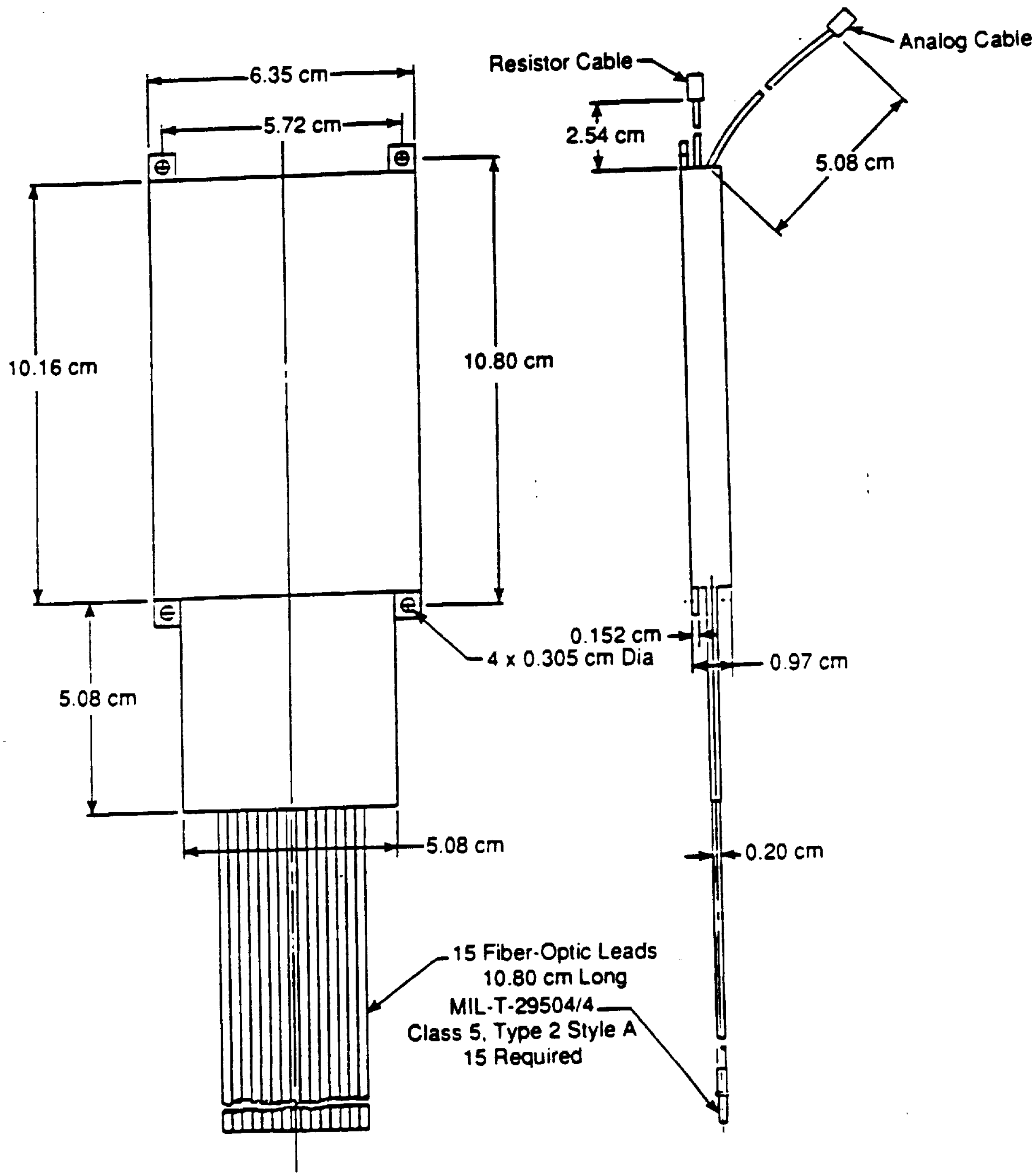
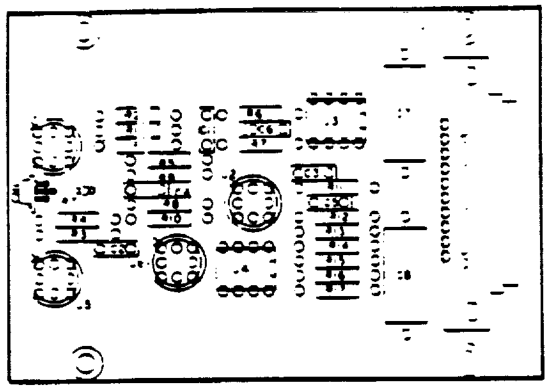
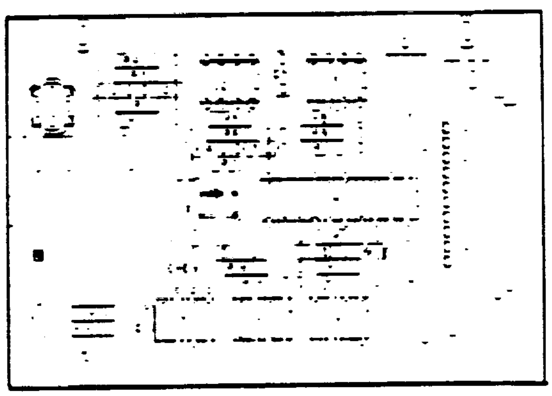


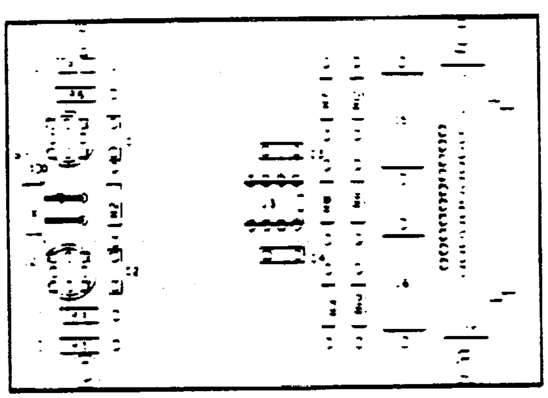
Figure 43. Electro-Optic Integrated Module Outline Drawing.



Gas Temperature Pyrometer



Flame Sensor



Blade Temperature Pyrometer

What would it take to combine all 3 functions on one board?

Figure 44. **Printed Circuit Board Layouts for the Electro-Optics Associated with the Analog Sensors.**

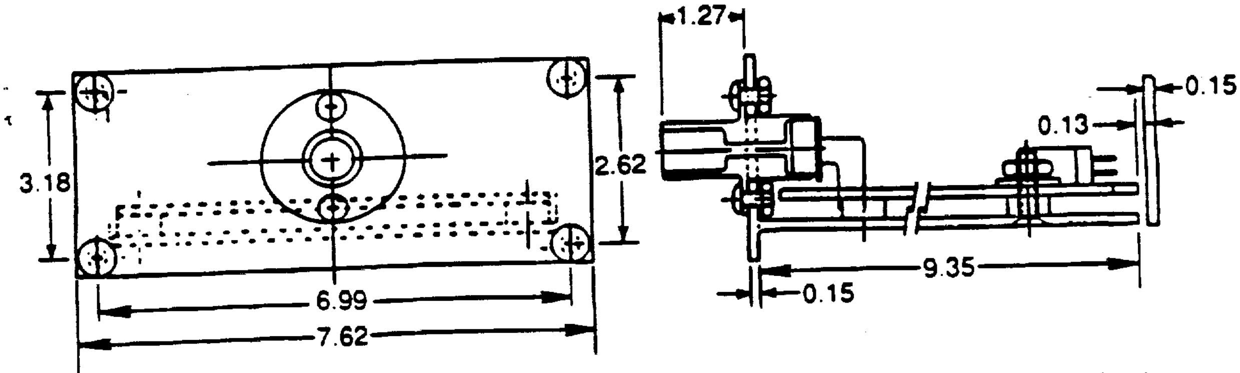


Figure 45. Blade Temperature Pyrometer Electro-Optic Module.

7.3.2 Design Considerations

One serious design consideration is the need to dissipate heat generated by the optical sources. Each optical source generates energy, the majority of which is heat. The primary EOI component contains twenty-three optical sources as listed below. Because the duty cycle of most sources is not 100%, the total power is about 940 milliwatts average power.

Displacement: Eight sources pulsed at 200 milliwatts with a 1/8 duty cycle	200 milliwatts
Low Temperature: Two sources at 100 milliwatts With a Sine Wave	140 milliwatts
Speed: Three sources at 100 milliwatts with a 1/3 duty cycle	100 milliwatts
Torque Motor: Ten sources at 100 milliwatts averaging a 50% duty cycle	500 milliwatts ?
Total:	940 milliwatts

For this reason, it was decided that those sources and detectors that do not require optical circuitry (coupling functions), such as the solenoids/relays, be mounted separately.

Another design consideration is crosstalk. The detectors must be well shielded from both electrical and optical noise because of their high gain amplification. To prevent crosstalk, it may be necessary to mount sources and detectors in different physical locations, rather than at one edge of the waveguide.

7.4 ANALOG MODULES

The three remaining modules service the analog fiber optic sensors: pyrometer, flame detector, and high range temperature, as shown in Figure 35. They have no separable optical connector, being continuous from the collection optics/head to an electrical connector. Electronics for optical signal detection and conditioning is in a rectangular package with an optical cable, housing, and electrical connector associated with each. Figure 44 shows each PC board layout. Figure 45 is an outline drawing of the pyrometer electro-optics module.

8.0 CONCLUSION

The subject of this report concerned the identification and description of preferred electro-optics architecture for servicing sensors and actuators in a fiber optic propulsion control system.

A model FADEC propulsion control system was described using a system layout, system schematics, and sensor lists. It was then used to identify and configure a system of fiber optic sensors and the electro-optics that service the sensors.

Candidate fiber optic sensors for each measurand were identified and broken down into comprised components and attributes under the categories of sources, detectors, fibers, protocols, optical elements, transduction techniques, and electronics.

A trade study identified the favored fiber optic sensor candidate for each measurand. Each candidate's components and attributes were rated using reliability, maintainability, cost, and weight/volume criteria. Those having digitally compatible signals and relatively simple electronics were favored; interferometric, analog, or contamination sensitive types were discouraged. The resulting sensor set was then applied to the system architecture design. Sensor performance, environmental, and physical requirements were specified, including estimates of optical power budgets.

A fiber optic propulsion system was constructed using the favored sensor choices and system architectural ground rules advocated by the Contractor. A considerable reduction in signal conductors over the electrical system resulted.

A design of the fiber optic system, integrating favored sensors and electro-optics architecture, was accomplished, resulting in a five module assembly. Minimizing fiber optic connections was a key design driver. A planar optical waveguide component provided electro-optic interfacing between the FADEC external connector and the optical sources/detectors.

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Appendix A
Fiber-Optic Sensor Specifications

APPENDIX A
FIBER-OPTIC SENSOR SPECIFICATION

SPECIFICATION FOR FIBER-OPTIC DISPLACEMENT SENSOR

This sensor uses an absolute optical encoder working with two fibers: one for interrogation and the other to carry the displacement information back. A block diagram is shown in Figure 19. The necessary accuracy is 1/100; eight bits will be used in the sensor. In the remote engine control, a set of IRED's and optical fibers will emit separate spectra which will be guided in one fiber per sensor. Each spectrum part will interrogate a separate bit in the sensor.

1. **Performance** (each bit):

Transmission (worst)	-10 dB
Modulation (minimum)	10 dB
Crosstalk (between bits)	-30 dB

2. **Physical** (entire sensor):

Number of Bits	8
Wavelengths	700 to 900 nanometers; 20 nanometer/bit minimum
Excess Loss	3 dB maximum separation of bits
Fibers	two: one in, one out; 100/140 step index
Size	2.5 cm x 5.0 cm x (stroke + 2.5 cm)
Connector	MIL-C-38999, Series III; 2 dB/contact loss maximum

3. **Environment** (entire sensor):

Temperature	extremes -55° to 260°C operating -55° to 204°C
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Must meet performance with oil, fuel, and water in sensing area.

SPECIFICATION FOR FIBER OPTIC SPEED SENSOR

This sensor will respond to a rotating feature(s) of ferrous metal in the engine. The Faraday effect will be used in the sensor to modulate optical energy in response to a magnetic field which will be generated/modulated by the rotating feature. The sensor will be interrogated through fiber optics by an IRED in the remote engine control. A block diagram is shown in Figure 20.

1. **Performance** (each channel):

Transmission (worst)	-24 dB (includes connection loss)
Modulation (minimum)	3 dB
Response Time (maximum)	1 microsecond

2. **Physical** (entire sensor):

Redundancy	Two channels per sensor
Fibers	One per channel; 100/140 step index
Size	1.25 cm diameter x 10 cm long probe 3.8 cm diameter x 5 cm long mount
Connector	MIL-C-38999, Series III
Wavelength	Within 600 to 940 nanometers

3. **Environment** (entire sensor)

Temperature	Extremes -55° to 260°C Operating -55° to 204°C
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Must meet performance with oil, fuel, water in sensing area.

SPECIFICATION FOR FIBER OPTIC TEMPERATURE SENSOR
(Low Range)

This temperature sensor measures the time constant of fluorescent emissions from ruby. Energy from an LED emitting at 565 nm is directed to the ruby where fluorescence occurs. The LED is sinusoidally modulated at 120 Hz. The sinusoidal fluorescent emission from the ruby occurs at about 690 nm and mimics the modulation from the excitation except for a phase difference caused by the emission's time constant. The time constant is a well behaved function of temperature, so that the phase difference is, as well. A block diagram is shown in Figure 21.

1. **Performance:**

Temperature Range	-55° to 260°C
Modulation Frequency	50 to 150 Hz
Phase Change Total	0 to 1 millisecond, full temperature range
Energy Convers. Effic.	-20 dB (including optical loss)
Thermal Response	0.5 second (sensing element only)
Crosstalk (spectral)	-40 dB from low band to detector

2. **Physical:**

Fiber	one, bidirectional
Size	0.6 cm diameter x less than 5 cm long
Connector	MIL-C-38999, Series III, stainless; 2 dB per contact loss maximum

3. **Environment:**

Temperature	-55° to 260°C
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Must meet performance with oil, fuel water in sensing area.

SPECIFICATION FOR FIBER OPTIC GAS TEMPERATURE PYROMETER

This sensor has a probe in the gas stream which glows when hot. The optical emissions from the glow are conducted in an optical fiber to the engine control, where an InGaAs detector is used to measure the radiation. The probe is likely to be nonmetallic, given the high temperatures expected.

In this application, there will be two sets of pyrometer probes. Each set will combine fibers at the detector. A block diagram is shown in Figure 24.

1. **Performance:**

Gas Temperature Range	260° to 1650°C
Accuracy	10°C above 800°C
Numerical Aperture	0.20 + 0.01
Transmission (including emissivity)	50% average, 0.7 to 1.7 μm; average stable within 2%; spectrum stable within 5%
Response Time	0.3 second rise time

2. **Physical** (entire sensor):

Fibers	one fiber/probe; four probes/set 200/240 μm diameter; step index, NA ≥ 0.22; gold hermetic layer to 300 μm maximum diameter, 20 μm minimum thickness
Size	1.25 cm inch diameter at root; 5 cm long

3. **Environment** (entire sensor):

Temperature	-55° to 1650°C at probe -55° to 600°C at fiber termination -55° to 260°C fiber cable
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Sealed against fuel, oil, water, cleaning solvents, and detergents

SPECIFICATION FOR FIBER OPTIC BLADE PYROMETER

This sensor has an optical probe assembly which accepts optical energy emitted by turbine blades due to their temperature. The optical emissions are conducted to the engine control where a silicon detector is used to measure the radiation. A block diagram is shown in Figure 23.

There is one pyrometer probe on the engine. The probe is permanently connected to its optical cable. The optical cable will comprise multiple fibers to enable a large enough signal to the detector and still allow reasonable cable bending without an intolerably high mechanical stress in the fiber silica. The amount of optical area to carry from blade image to the detector is about 1 square millimeter. The magnification of the blade from the object to fiber aperture will be between 1 and 0.25, depending on engine configuration.

1. **Performance:**

Blade Temperature Range	540° to 1000°C
Accuracy	10°C above 700°C
Numerical Aperture	0.20 + 0.01
Transmission	50% average, 0.4 to 1.1 μm; average stable within 2%, spectrum stable within 5%
Response Time	17 microseconds

2. **Physical:**

Fibers	200/240 step index; gold hermetic layer to 300 μm maximum diameter, 20 μm minimum thickness; total core(s) area 1 mm^2
Size	3.0 cm diameter at root

3. **Environment:**

Temperature	-55° to 1000°C at probe -55° to 600°C at fiber termination -55° to 260°C fiber cable
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Purge air available from 450° to 650°C for continuous clean optic

SPECIFICATION FOR FIBER OPTIC FLAME SENSOR

This sensor has an optical assembly which accepts energy emitted by the afterburner pilot flame. The optical emissions are conducted to a fluorescent material which absorbs the UV and re-emits longer wavelength energy. The longer wavelengths are conducted with significantly higher transmission in silica fiber to the engine control, where a solid state detector is used to measure the radiation. Above a certain level the sensor is to indicate "on," and below that level "off." A block diagram is shown in Figure 26.

There is one flame sensor on the engine. The probe is permanently connected to its optical cable. The optical cable will comprise multiple fibers to enable a large enough signal to the detector and still allow reasonable cable bending without an intolerably high mechanical stress in the fiber. The amount of optical area to carry from the flame image to the detector is at least one square millimeter.

1. **Performance:**

Threshold Flame Energy	3.3 nanojoules/sr
Hysteresis	0.3 nanojoules/sr
Numerical Aperture	0.20 + 0.01
UV Transmission	40% minimum at any wavelength, 0.2 to 0.3 μm to wavelength shift device; average stable within 5%; spectrum stable within 10%
Fluorescence	Total efficiency 30% minimum; sensitivity, 180 to 300nm
Transmission	80% at fluorescence spectrum
Response Time	1 millisecond

2. **Physical:**

Fibers	200/240 step index; hermetic layer to 300 μm maximum diameter; 20 μm minimum thickness.
Size	3.0 cm diameter, 2.5 cm long

3. **Environment:**

Temperature	-55° to 350°C at probe -55° to 260°C fiber cable
Vibration	10 to 2000 Hz, to 20 g's
Contamination	Must meet performance with oil, fuel, water in sensing area.

Appendix B
Discussion on Sensor Evaluation Criteria Values

APPENDIX B
DISCUSSION ON SENSOR EVALUATION CRITERIA VALUES

Sources

In general, IRED's are the most reliable optical sources. They are solid state, about 5% electrical-to-optical efficient, and being small, they are efficiently launched into optical fibers. The amount of life ranks high to low, as seen in the literature, from surface emitter to edge emitter to superluminescent, although launch efficiency improves in the same direction because of size and NA. Some manufacturers state a life for edge emitting diodes of 10,000 hours at 125°C. At room temperature, a life of a million hours has been claimed. Although there are differences in life of the surface and edge emitter, theirs are close together, and they have about 10X the life of a laser diode at any given temperature (Reference 8). The life of a superluminescent diode is midway between those two extremes. All the solid state devices are considered resistant to the vibration levels seen in engine electronics. Cost ranges from $20 to $1000 or more from surface type to superluminescent. Device sizes are similar among the three.

Xenon lamps are not made as small as IRED's and their life is not as long. They are more electrically efficient, but the plasma is relatively large and not nearly as efficiently launched into fiber. They generate EMI which needs to be shielded. They are not expensive. Their output does not change as dramatically with temperature compared to IRED's.

A tungsten lamp filament needs to run at high temperature, at least 2000°K (about 1700°C) to emit near IR. They are generally not as long lived as IRED's, although some are rated at 100,000 hours at room temperature. Physically they can be small, but the source is large and poorly launched into fiber. Their output does not change as much with temperature compared with IRED's, but they are more vibration sensitive, especially as life is consumed. They are inexpensive.

In general, sources are one of the weakest reliability links in the sensor architecture. Attribute A6 applies to a sensor that does not require a source such as a pyrometer or some flame sensors. Such a source is simpler and should have a higher score in the source category compared to, for example, a high temperature Fabry Perot cavity. Attributes A7 and A8 apply to sensors that require more than one source.

Detectors (Reference 9)

The silicon PIN photodiode is commercially available with bandwidth to 100 MHz. That is enough for most of the sensor types considered in this work. Even if a fast sensor time response is not necessary, the transduction or multiplexing schemes sometimes dictate fast circuits. Time delay techniques cans easily require 100 MHz. The silicon PIN photodiode costs between $10 and $100, depending on the area and performance. It can be linear over six decades of signal level and has sensitivity from 200 to 1100 nm.

The silicon avalanche photodiode can be 100X more sensitive than the PIN type, depending on bias voltage. Although it is nonlinear, it can also perform much faster. It is several times more expensive and usually is used with several hundred of volts bias which must be closely controlled as a function of temperature.

The InGaAs avalanche photodiode behaves similarly to the silicon PIN except that its sensitivity is from 800 to 1700 nm. It is more expensive than silicon. It is also similar to the silicon avalanche photodiode, but with sensitivity from 800 to 1700 nm.

Photomultipliers and electron gain devices have broad sensitivity, from 100 to 1500 nm (across many types) and are superior in the UV and visual ranges. They have competitive sensitivity in IR with cooling. They are relatively expensive, require high voltages, have medium speed, and are of relatively large volume/weight.

Fibers (Reference 10)

There are applications for optical cable on engine in two general zones: temperatures from -55° to 200°C and from -55° to above 200°C, as high as 600°C in some cases. The higher temperature applications vary depending on the sensor. These would include some displacement sensors, the pyrometric sensors, and the flame sensor.

A short bend radius is desirable, but that desire conflicts with life. Life models show that a 5 to 1 proof-test-to-service-test ratio will yield life of 100,000 hours or more at elevated temperatures, depending upon n value (a measure of resistance to fiber environment). The n value is a function of such things as overcoating hermeticity, temperature, and controls during drawing. Even for smaller fibers (125 μm silica OD) a 12-mm radius is probably the lower limit. This must be accommodated in cable and routing design. Fiber of 400 μm core is considered a reasonable upper diameter limit. It would need to have a minimum radius of at least 50 mm or require higher proof test levels.

Larger fiber size can be reliable and more readily maintainable at the connector to some degree, because connections will degrade less as tolerance is consumed. Acceptable fiber core diameters are 100 to 400 μm. Sizes from 50 to 85 μm are more difficult to connect and offer no life or reliability benefit because standard outer diameters are 125 μm for 85 μm core or less.

For -50° to 200°C, polyimide-coated silica is suitable and relatively inexpensive. For -50° to 400°C, aluminum-coated silica is suitable and medium expensive. For -50° to probably 650°C, gold-coated silica is suitable, but very expensive. For bundle applications and -50° to 600°C or more, uncoated silica is possible. There is at least one fiber available which has promise over the entire temperature range without a coating, but the current diameter is a nonstandard 70 μm OD with about a 60 to 63 μm core diameter.

Other optical materials besides silica are possible for fiber; for example, borosilicate, sapphire, and zirconium fluoride. Very little has been reported in the literature about the life or reliability of these materials as optical fiber. They are still emerging as products.

Protocols

The protocols are ranked with respect to reliability and maintainability because of their resistance to environmental effects and/or the added difficulty in maintaining the system to an as-installed performance level. The direct-digital techniques are preferred because they are either on or off and the system does not need to measure the amount of light or how long it is on. Digital parallel lines are considered a superior protocol because the signals are kept separate. Wavelength encoding is considered slightly better than time delay encoding because it will be insensitive to such things as cable length differences from engine to engine and changes due to maintenance action. For multimode systems, the threat of color effect in the connectors (Fabry Perot interference) is not of concern.

The next most robust protocols are those that still do not need to know how much light, such as frequency or phase measurement, when some threshold is crossed and timing begins or ends. The amount of light changes the precision because of signal to noise effects on threshold detection. Wavelength shift is similar in that the amount of light affects precision but not accuracy. Knowing a peak wavelength within a range is not as easily detected as digital spectral codes because the peak position is of interest, and it will be more susceptible to connector effects and spectral mode effects in the cable.

Modulated intensity is ranked near the bottom because the amount of light is measured. It is slightly better than pure analog level because the modulation allows synchronous detection (or phase locked loop) which rejects d.c. noise, the largest noise component. The least desirable is a system which needs to know the amount of light because it will be very susceptible to many effects such as source changes, cable changes, and connector changes. However, a pyrometer, at least, has no source effects, as it has none.

Optical Elements

Optical elements are considered more reliable than electro-optic or electronic elements because they are passive. Added optical elements are not penalized as severely as, for example, added optical sources. It is assumed that the elements are designed and installed to resist the appropriate environment, for example, glass lenses at low temperatures to quartz and sapphire lenses at high temperatures. A component that depends on index gradation can change gradient, or filters which depend upon interference coatings will degrade in time. Connectors are not considered as reliable as, for example, a lens because the vibration is often higher and more components are involved.

Transduction Techniques

The rating of transduction techniques, like protocol ratings, is intended to depend on the maturity of the technique and its inherent environmental resistance, independent of hardware used.

- Reflection is a simple robust technique with fairly low losses (although strongly dependent on distance). Any exposed reflection surface is vulnerable to contamination and will require periodic inspection. A sealed reflection system scores significantly higher for this reason.

- The Faraday effect can be susceptible to errant magnetic fields and usually has high absorption losses. Faraday materials are expensive.

- The microbend technique is rated a little lower in reliability because it stresses the fiber, but is very optically efficient and relatively inexpensive. Macrobend transducers are ranked the same.

- Absorption change is used in some sensors, sometimes with spectral content being important. It is considered reliable and usually low cost.

- Fluorescence decay has considerable experience and is rated well.

- Moire pattern is a lossy technique, better suited to full imaging systems, but is probably inexpensive.

- RF signal interferometry has been demonstrated but requires high bandwidth for short distances (80 MHz for 4 inches).

- Transmission, sealed or unsealed, is considered better than reflection because there are competing connector reflections.

Electronics

The bandwidth threshold is seemingly low because many of the sensors return a lower signal than commonly seen in digital fiber systems, so the gain-bandwidth product of the electronics becomes stressed. A high speed op-amp such as 10^8 can see 10^6 of that consumed by the gain factor. Depending upon the connector arrangement, the amount of returned energy can easily be as low as 10 nanowatts when the source also degrades with high temperature and life.

Because of the low energy levels from some sensors due to such things as multiple connectors required and high transducer losses, high speed circuitry is considered a liability. The detection front end must not limit speed; with small signals and high speed the development and manufacturing effort to yield satisfactory performance is high.

Added and ancillary devices, such as those requiring temperature control, impose a penalty. Cooling is less efficient and more expensive than heating, and not very effective above 100°C. A nonstandard voltage such as for PM tubes, flashtubes, or avalanche photodiodes is a penalty because it is higher than the airframe or engine generated power, requiring dedicated components to step it up. Standard analog electronics would be used with, for example, a speed sensor or phase measurement where the amount of light is not to be measured. Fluorescent decay time, even though time-based, must measure light amount, as must all the analog sensors. The chief difference is cost. Synchronous detection for very small signals uses a specialized set of four op-amps to measure the energy of a chopped signal; it can be done with one monolithic component.

Appendix C
Evaluation Scores for Fiber-Optic Sensor Candidates

APPENDIX C
EVALUATION SCORES FOR FIBER-OPTIC SENSOR CANDIDATES

- Example Calculation: Spectrally Encoded Grey Scale Displacement Sensor.

Components/Attributes	Rating
IRED-Edge Source	162.5
Two Sources	134.2
Si PIN Detector	192.3
CCD Array	116.1
Polyimide/Silica Fibers	182.5
Two Fibers Required	170.3
Wavelength Encoding Protocol	172.5
Selfoc Lens	172.3
Metal or Glass Mirror	151.1
Metal or Glass Grating	129.5
Multicontact Connector	96.2
Four Optical Elements Required	134.2
Sealed Reflection Transduction	195.5
Electronic Bandwidth Less than 10 kHz	190.8
Electrical Power Less than 1 watt	185.3
Standard Analog Electronics	192.5
More than 8 Active Electronic Components	121.1
Total Average	158.8

Sensor Candidate / Component/Attribute		Spectrally Encoded Grey Scale	Subcarrier Frequency Interferometry	Wavelength Select Monochromator	Moire Pattern Pulse Delay	Temporally Encoded Grey Scale	Collimated Space Analog With Reference	Slanted Shaft (Angular) Analog Level
Sources:	IRED-Edge	162.5	162.5	162.5	--	162.5	162.5	162.5
	Tungsten Lamp	--	--	--	127.5	--	--	--
	Two Sources	134.2	--	134.2	--	--	--	--
Detectors:	Si PIN	192.3	192.3	192.3	192.3	--	192.3	192.3
	Si Avalanche	--	--	--	--	132.7	--	--
	CCD Array	116.1	--	--	--	--	--	--
	2 Detectors	--	156.1	156.1	--	--	156.1	156.1
	4 Detectors	--	--	--	134.7	--	--	--
Fibers:	Poly./Silica	182.5	182.5	182.5	--	182.5	182.5	--
	Aluminum/Silica	--	--	--	167.4	--	--	167.4
	1 Fiber	--	--	208.5	--	208.5	--	--
	2 Fibers	170.3	170.3	--	170.3	--	170.3	--
	Up to 8 Fibers	--	--	--	--	--	--	127.2
Protocols:	Wave. Encode	172.5	--	--	--	--	--	--
	Wave Shift	--	--	152.3	--	--	--	--
	Pulse Rate	--	202.5	--	--	--	--	--
	Pulse Delay	--	--	--	169.1	--	--	--
	Time Encode	--	--	--	--	129.1	--	--
	Intensity Ratio	--	--	--	--	--	117.5	--
	Intensity Var.	--	--	--	--	--	--	113.8
Optical Elements:	Selfoc Lens	172.3	--	--	172.3	--	--	--
	Wave. Coupler	--	--	--	--	--	166.1	166.1
	Bulk Lens	--	151.1	151.1	151.1	--	151.1	--
	Mirror	151.1	--	151.1	--	151.1	--	151.1
	Taper Coupler	--	--	--	--	141.1	--	--
	Grating	129.5	--	129.5	129.5	--	--	--
	Separ. Filter	--	--	--	--	--	119.3	--
	Precis. Optics	--	--	--	--	67.4	67.4	--
	1 Contact	--	--	147.1	147.1	147.1	--	--
	Multi-Contact	96.2	96.2	--	--	--	96.2	96.2
	4 Elements	134.2	134.2	134.2	--	--	--	134.2
	8 Elements	--	--	--	91.5	91.5	91.5	--
Transduction Technique:	Mods. Source	--	--	--	--	--	202.8	--
	Reflec. Sealed	195.5	--	195.5	--	195.5	--	--
	Freq. Interf.	--	180.6	--	--	--	--	--
	Monochromator	--	--	125.6	--	--	--	--
	Reflec. Exposed	--	--	--	--	--	--	116.6
	Moire Interf	--	--	--	109.1	--	--	--
Electronics:	Bandw. <10 KHz	190.8	--	190.8	190.8	--	190.8	190.8
	Bandw. >1 MHz	--	126.0	--	--	126.0	--	--
	Power < 1 Watt	185.3	185.3	185.3	185.3	185.3	185.3	185.3
	Temp. Measure	--	--	--	--	--	146.0	--
	Device Heater	--	--	125.8	--	--	--	--
	TE Cooler	--	--	124.3	--	--	--	--
	Standard Anal.	192.5	--	--	192.5	192.5	--	--
	Low Noise/Offset	--	127.4	127.4	--	--	127.4	127.4
	8 Active Comp.	--	--	147.6	147.6	--	147.6	--
	>8 Active Comp.	121.1	121.1	--	--	121.1	--	121.1
	Total Average Score	158.8	156.3	156.2	154.9	148.9	148.5	147.2

Evaluation Scores for Fiber Optic Displacement Sensors.

Sensor Candidate / Component/Attribute		Fluorescence Temporal Phase Change	Fluorescence Decay Time	Wavelength Encoded TIR	Fabry Perot Wave. Select with Multimode	Absorption Analog with Reference	Fabry Perot Wavelength Select
Sources:	IRED-Edge	162.5	—	—	162.5	162.5	162.5
	IRED-Superlumin.	—	—	135.9	—	—	—
	Xenon Lamp	—	124.8	—	—	—	—
	Two Sources	—	—	134.2	—	—	—
Detectors:	Si PIN	192.3	192.3	192.3	192.3	192.3	192.3
	2 Detectors	156.1	—	—	156.1	156.1	156.1
	Detector Array	—	118.1	118.1	—	—	—
Fibers:	Poly./Silica	182.5	182.5	—	—	—	182.5
	Aluminum/Silica	—	—	167.4	167.4	167.4	—
	2 Fibers	170.3	170.3	170.3	170.3	—	—
	Up to 8 Fibers	—	—	—	—	127.2	127.2
Protocols:	Wave. Encode	—	—	172.5	—	—	—
	Wave Shift	—	—	—	152.3	—	152.3
	Pulse Rate	—	—	—	—	202.5	—
	Pulse Delay	169.1	169.1	—	—	—	—
	Intensity Ratio	—	—	—	—	117.5	117.5
Optical Elements:	Wave. Coupler	—	—	—	—	166.1	166.1
	Bulk Lens	—	151.1	151.1	—	151.1	151.1
	Mirror	—	—	—	151.1	—	151.1
	Grating	—	—	129.5	—	—	—
	Separ. Filter	119.3	119.3	—	—	—	—
	Precis. Optics	—	—	—	—	67.4	—
	1 Contact	147.1	147.1	—	147.1	—	—
	Multi-Contact	—	—	96.2	—	96.2	96.2
	2 Elements	165.5	165.5	—	165.5	—	—
	4 Elements	—	—	134.2	—	134.2	134.2
Transduction Technique:	Total Int. Refl.	—	—	210.5	—	—	—
	Mods. Source	—	—	—	—	202.8	—
	Reflec. Sealed	—	—	—	195.5	—	—
	Fluoresce. Decay	168.6	168.6	—	—	—	—
	Monochromator	—	—	—	—	—	125.6
Electronics:	Bandw. <10 KHz	190.8	190.8	190.8	190.8	190.8	190.8
	Power < 1 Watt	185.3	185.3	185.3	—	185.3	185.3
	Power > 1 Watt	—	—	—	110.9	—	—
	Temp. Measure	—	—	—	146.0	—	—
	Device Heater	—	—	—	125.8	—	—
	TE Cooler	—	—	—	124.3	—	—
	Low Noise/Offset	127.4	127.4	127.4	127.4	127.4	127.4
	Non-Stan. Volt.	—	84.4	—	—	—	—
	4 Active Comp.	172.3	172.3	—	—	—	—
	8 Active Comp.	—	—	—	—	147.6	147.6
	>8 Active Comp.	—	—	121.1	121.1	—	—
	Total Average Score	164.9	154.3	152.3	153.3	152.6	150.9

Evaluation Scores for Fiber Optic Low Range Temperature Sensors.

Sensor Candidate / Component/Attribute		Blackbody Cavity (1)	Blackbody Cavity (2)	Blackbody Cavity (3)	Blackbody Cavity (4)	Blackbody Cavity (5)	Blackbody Cavity (6)	Blackbody Cavity (7)
Sources:	No Source	265.0	265.0	265.0	265.0	265.0	---	265.0
	IRED-Edge	---	---	---	---	---	162.5	---
Detectors:	Si PIN	---	---	---	192.3	---	192.3	---
	InGaAs PIN	185.7	185.7	186.7	---	185.7	---	185.7
	2 Detectors	---	---	---	---	---	156.1	---
	4 Detectors	---	---	134.7	134.7	134.7	---	---
	Detector Array	---	---	---	---	---	---	118.1
Fibers:	Gold/Silica	132.5	132.5	132.5	132.5	132.5	132.5	132.5
	Up to 8 Fibers	127.2	127.2	127.2	127.2	127.2	127.2	---
	Up to 20 Fibers	---	---	---	---	---	---	85.9
Protocols:	Intensity Var.	113.8	113.8	113.8	113.8	113.8	---	113.8
	Intensity Ratio	---	---	---	---	---	117.5	---
	Wavelength Shift	---	---	---	---	---	152.3	---
Optical Elements:	Wave. Coupler	---	---	---	---	---	166.1	---
	Blackbody	161.0	161.0	161.0	161.0	161.0	---	161.0
	Bulk Lens	151.1	151.1	151.1	151.1	151.1	151.1	151.1
	Mirror	---	---	---	---	---	151.1	---
	No Connector	214.3	214.3	214.3	214.3	214.3	---	---
	Multi-Contact	---	---	---	---	---	96.2	96.2
	4 Elements	---	---	---	---	---	134.2	---
	8 Elements	91.5	91.5	91.5	91.5	91.5	---	91.5
Transduction Technique:	Mods. Source	202.8	202.8	202.8	202.8	202.8	---	202.8
	Monochromator	---	---	---	---	---	125.6	---
Electronics:	Bandw. <10 KHz	190.8	190.8	190.8	190.8	190.8	190.8	190.8
	Power < 1 Watt	185.3	185.3	---	---	---	185.3	---
	Power > 1 Watt	---	---	110.9	110.9	110.9	---	110.9
	Temp. Measure	146.0	146.0	146.0	146.0	146.0	---	146.0
	Synchronous Det.	---	146.0	---	146.0	146.0	---	---
	Low Noise/Offset	127.4	127.4	127.4	127.4	127.4	127.4	127.4
	2 Active Comp.	205.4	205.4	---	---	---	---	---
	8 Active Comp.	---	---	147.6	---	---	147.6	---
	>8 Active Comp.	---	---	---	121.1	121.1	---	121.1
	Total Average Score	166.7	165.4	156.4	154.6	154.2	148.0	143.7

(1) 4 Probes, Single InGaAs Detector, Without Synchronous Detection
(2) 4 Probes, Single InGaAs Detector, with Synchronous Detection
(3) 4 Probes and InGaAs Detectors, Without Synchronous Detection
(4) 4 Probes and Si Detectors, with Synchronous Detection
(5) 4 Probes and InGaAs Detectors, with Synchronous Detection
(6) 4 Probes, Single Si Detector, Without Synchronous Detection
(7) 4 Probes and Dual Detectors, Without Synchronous Detection

Evaluation Scores for Fiber Optic High Range Temperature Sensors.

Sensor Candidate Component/Attribute		Blackbody Effect (Ratio)	Blackbody Effect Analog Level	Blackbody Effect Analog Level	Blackbody Effect Spectr. Content
Sources:	No Source	265.0	265.0	265.0	265.0
Detectors:	Si PIN	192.3	192.3	—	—
	InGaAs PIN	185.7	—	185.7	—
	CCD Array	—	—	—	116.1
	2 Detectors	156.1	—	—	---
Fibers:	Uncoated Silica	137.5	137.5	137.5	137.5
	Over 20 Fibers	71.1	71.1	71.1	71.1
Protocols:	Intensity Var.	117.5	—	---	117.5
	Intensity Ratio	—	113.8	113.8	--
Optical Elements:	Bulk Lens	151.1	151.1	151.1	151.1
	Grating	---	—	---	129.5
	Precision Optics	67.4	67.4	67.4	—
	No Connector	214.3	214.3	214.3	--
	1 Contact	---	—	---	147.1
	2 Elements	165.5	165.5	165.5	--
	4 Elements	—	--	---	134.2
Transduction Technique:	Transmission (Not Sealed)	126.6	126.6	126.6	126.6
Electronics:	Bandw. >10 KHz	147.7	147.7	147.7	--
	Bandw. < 1 Watt	---	--	---	190.8
	Power < 1 Watt	185.3	185.3	185.3	185.3
	Temp. Measure	146.0	146.0	146.0	--
	Low Noise/Offset	127.4	127.4	127.4	127.4
	4 Active Comp.	---	172.3	172.3	--
	8 Active Comp.	147.6	—	---	--
	>8 Active Comp.	---	—	---	121.1
	Total Average Score	153.2	152.2	151.8	144.3

Evaluation Scores for Fiber Optic Blade Temperature Sensors.

Sensor Candidate / Component/Attribute		Spectral Ratio Absorption	Temporally Encoded Reflection	Spectrally Encoded Reflection	Separated Binary Lines Grey Code
Sources:	IRED-Edge	162.5	162.5	162.5	162.5
	Two Sources	134.2	—	134.2	—
Detectors:	Si PIN	192.3	192.3	192.3	192.3
	2 Detectors	156.1	—	—	—
	Detector Array	—	—	118.1	118.1
Fibers:	Poly/Silica	182.5	182.5	182.5	182.5
	2 Fibers	170.3	170.3	170.3	—
	Up to 20 Fibers	—	—	—	85.9
Protocols:	Wave. Encode	—	—	172.5	—
	Pulse Delay/Time	169.1	—	—	—
	Dig. Para. Lines	—	—	—	141.2
	Time Encode	—	129.1	—	—
Optical Elements:	Wave. Coupler	—	166.1	166.1	166.1
	Bulk Lens	151.1	—	—	—
	Mirror	—	—	—	151.1
	Grating	—	—	129.5	—
	Multi-Contact	96.2	96.2	96.2	96.2
	2 Elements	165.5	—	—	—
	4 Elements	—	—	—	134.2
	8 Elements	—	91.5	91.5	—
Transduction Technique:	Total Int. Refl.	—	—	—	210.5
	Reflec. Sealed	—	195.5	195.5	—
	Absorption	158.7	—	—	—
	Transmis. Expos.	126.6	—	—	—
	Reflec. Exposed	—	—	—	116.6
Electronics:	Bandw. < 10 KHz	190.8	—	190.8	190.8
	Bandw. > 10 KHz	—	147.7	—	—
	Power < 1 Watt	185.3	185.3	185.3	185.3
	Standard Anal.	—	192.5	192.5	192.5
	Low Noise/Offset	127.4	—	—	—
	8 Active Comp.	147.6	—	—	—
	>8 Active Comp.	—	121.1	121.1	121.1
	Total Average Score	157.3	156.4	156.3	152.9

Evaluation Scores for Fiber Optic Fluid Level Sensors.

Sensor Candidate / Component/Attribute		One Fiber Reflective Feature	One Fiber Magneto-Optic Switch	Two Fibers Magneto-Optic Switch	Multi-Fiber Reflective Feature
Sources:	IRED-Surface	---	---	---	185.7
	IRED-Edge	162.5	162.5	162.5	---
Detectors:	Si PIN	192.3	192.3	192.3	192.3
Fibers:	Poly./Silica	182.5	182.5	182.5	---
	Aluminum/Silica	---	---	---	167.4
	1 Fiber	208.5	208.5	---	---
	2 Fibers	---	---	170.3	---
	Up to 20 Fibers	---	---	---	85.9
Protocols:	Pulse Rate/Freq.	202.5	202.5	202.5	202.5
Optical Elements:	Wave. Coupler	166.1	166.1	166.1	---
	Bulk Lens	---	---	---	151.1
	Mirror	---	151.1	151.1	---
	Separ. Filter	---	119.3	119.3	---
	1 Contact	147.1	147.1	---	---
	Multi-Contact	---	---	96.2	96.2
	2 Elements	165.5	---	---	165.5
	4 Elements	---	134.2	134.2	---
Transduction Technique:	Faraday Effect	---	140.6	140.6	---
	Reflec. Exposed	116.6	---	---	116.6
Electronics:	Bandw. > 10 KHz	147.7	147.7	147.7	147.7
	Power < 1 Watt	185.3	185.3	185.3	185.3
	Standard Anal.	192.5	192.5	192.5	192.5
	2 Active Comp	205.4	205.4	205.4	205.4
	Total Average Score	175.0	169.2	163.2	161.1

Evaluation Scores for Fiber Optic Shaft Speed Sensors.

Sensor Candidate / Component/Attribute		UV Emission Fluorescent Spectr. Shift	UV Emission Analog Level	UV Emission Spectral Content
Sources:	No Source	265.0	265.0	265.0
Detectors:	Si PIN	192.3	---	---
	UV Tube	---	117.8	---
	CCD Array	---	---	116.1
Fibers:	Aluminum/Silica	167.4	167.4	167.4
	Over 20 Fibers	71.1	71.1	71.1
Protocols:	Intensity Varia.	113.8	113.8	113.8
Optical Elements:	Bulk Lens	---	---	151.1
	Grating	---	---	129.5
	Separ. Filter	119.3	---	---
	No Connector	214.3	214.3	214.3
	2 Elements	165.5	165.5	---
	4 Elements	---	---	134.2
Transduction Technique:	Transmis. Expos.	126.6	126.6	126.6
Electronics:	Bandw. < 10 KHz	190.8	190.8	190.8
	Power < 1 Watt	185.3	185.3	185.3
	Standard Anal.	---	192.5	---
	Low Noise/Offset	127.4	---	127.4
	Nonstand. Volt.	---	84.4	---
	4 Active Comp.	172.3	172.3	---
	> 8 Active Comp	---	---	121.1
	Total Average Score	162.4	159.0	151.0

Evaluation Scores for Fiber Optic Flame Sensors.

Sensor Candidate Component/Attribute		Analog Level Reflection	Analog Level Birefringence	Analog Level Microbend
Sources:	IRED-Edge	162.5	162.5	162.5
Detectors:	Si PIN	192.3	192.3	192.3
	2 Detectors	156.1	156.1	156.1
Fibers:	Aluminum/Silica	167.4	167.4	167.4
	2 Fibers	170.3	---	---
	Up to 8 Fibers	---	127.2	127.2
Protocols:	Intensity Ratio	117.5	117.5	117.5
Optical Elements:	Selfoc Lens	172.3	172.3	---
	Wave. Coupler	166.1	166.1	166.1
	Bulk Lens	---	151.1	---
	Mirror	151.1	---	---
	Separ. Filter	119.3	---	---
	1 Contact	147.1	---	---
	Multi-Contact	---	96.2	96.2
	2 Elements	---	---	165.5
	4 Elements	134.2	134.2	---
Transduction Technique:	Mods. Source	---	202.8	---
	Reflec. Sealed	195.5	---	---
	Microbend	---	---	169.2
	Fluores. Decay	168.6	---	---
Electronics:	Bandw. < 10 KHz	190.8	190.8	190.8
	Power < 1 Watt	185.3	185.3	185.3
	Low Noise/Offset	127.4	127.4	127.4
	8 Active Comp	147.6	147.6	147.6
	Total Average Score	159.5	156.1	155.1

Evaluation Scores for Fiber Optic Vibration Sensors.

Sensor Candidate / Component/Attribute		Fiber Motion Frequency with Temp.	Temporal Phase Difference Reflective	Temporal Phase Difference Magneto-Optic
Sources:	IRED-Surface	185.7	185.7	—
	IRED-Edge	—	—	162.5
Detectors:	Si PIN	192.3	192.3	192.3
	2 Detectors	—	—	156.1
Fibers:	Poly/Silica	182.5	182.5	182.5
	2 Fibers	170.3	170.3	—
	Up to 8 Fibers	—	—	127.2
Protocols:	Pulse Rate/Freq.	202.5	—	—
	Pulse Delay/Time	—	169.1	169.1
Optical Elements:	Bulk Lens	—	—	151.1
	Mirror	—	151.1	151.1
	Multi-Contact	96.2	96.2	96.2
	2 Elements	165.5	165.5	—
	4 Elements	—	—	134.2
Transduction Technique:	Mods. Source	202.8	—	—
	Faraday Effect	—	—	140.6
	Reflec. Exposed	—	116.6	—
Electronics:	Bandw. < 10 KHz	190.8	190.8	190.8
	Power < 1 Watt	185.3	185.3	185.3
	Standard Anal	192.5	192.5	—
	Low Noise/Offset	—	—	127.4
	4 Active Comp.	172.3	—	—
	8 Active Comp.	—	147.6	147.6
	Total Average Score	178.2	165.0	154.3

Figure 54. Evaluation Scores for Fiber Optic Muss Flow Sensors.

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