FINAL REPORT

FIBER-OPTIC ENGINEERING SENSOR SYSTEM

CONTRACT N00014-87-C-2033

OPTECH™

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1. INTRODUCTION

1.1. Introduction

This report presents the conceptual design for a fiber-optic engineering sensor system that will find application in many Navy systems. The sensor system, illustrated in Figure 1.1-1, consists of the following components.

- (1) A variety of amplitude type fiber-optic sensors, each designed to measure a different physical parameter.
- (2) Optoelectronic circuitry to control the fiber-optic sensors.
- (3) A local fiber-optic telemetry subsystem that communicates sensor data to other ships' equipment.

Details of the sensor system design along with the advantages and potential risks of the proposed system are discussed herein. Primary advantages are the introduction of standard interface between existing ship's equipment and a large variety of sensor types, increased performance and system flexibility, and reduced sensor size, weight, and cost. The major risks that have been identified concern as yet unproven engineering details.

This report also presents an evaluation of the sensor and data telemetry requirements of the propulsion control system of the DDG-51. Specifically addressed is the Shaft Control Unit (SCU) of that system. The SCU has been selected as the design model for this study because it represents the current state of control system architecture and appears to be an ideal application for the introduction of fiber-optic systems. The focusing of this conceptual design on the SCU requirements insures that these design efforts result in the development of sensor and telemetry capabilities suited to shipboard installation and testing. The resulting sensor design, however, is generally applicable to other ships systems.

The conceptual design presented here is the first phase of a project that will prove the feasibility of using a fiber-optic sensor system in engineering applications aboard ship. The remainder of this project will be accomplished in three following phases. The fourth and final phase, platform testing of an Engineering Development Model (EDM) of the system described herein, will be preceded by the fabrication of a Laboratory Demonstration Model (LDM) in Phase II and an Advanced Development Model (ADM) in Phase III.

The first phase of this project has been a joint effort by Optical Technologies, Inc. (OPTECH) and General Electric Simulation and Control Systems Department (GE/SCSD). OPTECH has considerable experience in the design and implementation of fiber-optic sensors. GE/SCSD is a major supplier of Machinery Control systems for military ships. These systems include Auxiliary, Electric Plant, Damage, and Propulsion Control systems.

1.2. Goal of the Phase I Project

The goal of the first phase of this project is the development of a conceptual design that provides sufficient detail to confirm the applicability of the proposed fiber-optic systems to ship-board use. The conceptual design is to include the following details.

- Specification of performance requirements
- Identification of problems with existing sensor systems
- Description of the design approach
- Evaluation of system cost and technical risks
- Discussion of trade-offs and risk limiting alternatives
- Evaluation of potentials for improved performance and cost characteristics.

The major emphasis of this project is the development of fiber-optic sensors. The telemetry aspects of the final system, though addressed in sufficient detail to show the availability of subsystems able to meet shipboard data telemetry requirements, receive secondary consideration.

Specific goals for the sensor system design include the following.

- The establishment of a minimum number of optical modulation principles which can be applied to successfully implement a complete sensor suite for shipboard applications.
- The development of a standard sensor interface, thereby minimizing the number of different sensor-particular interfaces required aboard ship.
- The elimination of known problems with existing sensor systems.
- The use of optical fibers for all signal leads.

The goal for the telemetry subsystem is a standard architecture which is flexible and provides the necessary redundancy. The telemetry system designed under this project is to be suited to testing aboard a navy platform. The design is not to be of such detail or capability that it can be directly implemented as a primary data communication link aboard ship. Rather, the system is self contained and limited to sensor telemetry data. It will not interfere with the operation of other ship's equipment.

The telemetry system is to employ military grade and commercially available components to the maximum extent possible. For the purposes of this project, where both these conditions cannot be met commercial availability will take precedence over military qualification provided that the final design is sufficiently rugged for testing aboard a Navy Platform and the resulting design is not one that inherently excludes the eventual use of military grade components.

1.3. Goals of Subsequent Project Phases

The goal of Phase II is the fabrication, demonstration, and testing of a laboratory model. A preliminary specification for the sensor system is developed during this phase.

The goals of Phases III and IV are the progressive definition, specification, and fabrication of and Advanced Development Model and the ultimate testing of an Engineering Development Model aboard a Navy platform.

1.4. Review of an Existing Propulsion Control System

The propulsion control system of the DDG-51 has been selected as the model system for this project because it represents the current state of ship development and because of the familiarity which GE/SCSD has with its capabilities and requirements. The specific sensor and telemetry requirements of the DDG-51 propulsion control system are addressed in Section 2.

An overview of the DDG-51 machinery control system is shown in Figure 1.4-1. The propulsion system employs four LM2500 marine engine/turbines driving two propulsion shafts through reduction gears and variable pitch propellers. Each turbine is controlled by an Integrated Electronic Control (IEC) system which is in turn directed by one of two Shaft Control Units (SCU). Several critical turbine sensors are hardwired in a closed IEC-to-turbine loop. A much larger number of other auxiliary sensors providing engine performance data are wired to signal conditioning circuitry within the SCU. Twisted pairs of wire are typically used to carry these transducer signals which the SCU needs to program the IEC and to monitor turbine performance for fault conditions. The sensor data are also used by ship systems other than propulsion control and are displayed at various locations throughout the ship. Data are passed among a variety of systems (the propulsion, electrical, auxiliary and damage control systems) on che Ships Data Multiplexing System (SDMS).

1.5. Concept of an Improved Sensor System for Propulsion Control

There are three elements to the improved sensor system design presented here. First, current sensors are replaced as appropriate by fiber-optic sensors employing newly available technologies. Secondly, general purpose sensor controlling and multiplexing circuitry are introduced. Thirdly, local fiber-optic telemetry is used to communicate sensor data to shipboard systems. These points are introduced in the following sections.

1.5.1. Use of Fiber-Optic Sensors

Fiber-optic sensors have numerous advantages that have been detailed in other documentation and are well known to NRL personnel. Those advantages which are particularly relevant to the application addressed here include the following.

- o Inherent and complete EMI immunity in both the sensor and the telemetry links.
- o Total elimination of electrical grounding problems arising from conflicts of sensor, telemetry and power systems.
- o Flexibility of design that is not available in conventional sensors, e.g. pressure actuated diaphragms in reflection sensors do not have strain gauges bonded to them; they can be of arbitrary size.
- o Increased reliability due to the simplicity of the sensor.
- o Intrinsic safety of the sensor and telemetry link with regard to explosive atmospheres, shock hazards, etc.
- o Reduced life cycle system cost owing to the simplicity of the sensor and the resulting lower cost of replaceable parts.
- o Reduced weight of sensors and cables.

1.5.2. Introduction of Sensor Controlling Circuitry

The fiber-optic sensors described in this design are passive, purely optical devices. As such they require optoelectronic circuitry to interface them to other data processing and control equipment.

A microprocessor based electrooptical circuit, the Sensor Interface Controller (SIC), provides light to the fiber-optic sensors and processes the optical signals received from them. A Sensor Processing Unit (SPU) containing several SIC circuits operates a number of individual sensors of various types. The concept design address the use of sixteen sensor with each SPU. One SPU may have the capability of interfacing all the sensors associated with a given ships compartment or function. The SPU may be located aboard ship near its sensors, near to the ship's equipment with which it communicates, or at any more convenient location. Sensor data are transmitted from the SPU to various shipboard systems as required. Because the SPU is microprocessor based it provides "smart sensor" capabilities.

The advantages of this sensor interface approach include the following.

- o The SPU performs data reduction and monitoring functions, thereby reducing the data processing overhead of existing signal processing equipment.
- o The SIC's are capable of operating a variety of sensors and present a standard sensor interface for other ship's systems, thereby reducing significantly the variety of sensor interface hardware required aboard ship.
- o The microprocessor in the SIC provides "smart sensor" functions such as automatic self testing, calibration, data reduction, and fault analysis.

1.5.3. Use of Fiber-Optic Telemetry

The improved engineering sensor system will employ optical fibers to communicate sensor data between the SPU and an interface to other ship's systems. Specifically, a local fiber-optic telemetry system provides for this data to be passed onto an existing ship's data bus without interfering with the ship's current communication architecture.

The fiber-optic telemetry system takes advantage of recent and ongoing developments in commercial fiber-optic systems. The telemetry system ties the sensor controlling electronics, and other equipment as may be appropriate to a local sensor data bus, to a ships bus interface. That interface will be an intelligent device capable of performing some level of data management. The advantages of this approach include the following.

- o Reduced telemetry equipment size and weight
- o Reduced cable size and weight
- o Increased reliability and redundancy
- o Arbitrary placement of cables (no EMI pick-up).

1.6. Overview of the Development Models

The contract calls for three stages in the fabrication of prototype hardware. The Laboratory Demonstration Model (LDM), to be fabricated in Phase II, will be a tool for evaluation of the sensor and telemetry designs discussed in this report. The Advanced Development Model (ADM) and the Engineering Development Model (EDM) will be embodiments of the conceptual design described in this report. They will be fabricated during project Phases III an IV.

1.6.1. Laboratory Demonstration Model (LDM)

The (LDM) is intended to demonstrate feasibility of fiber-optic sensors and optical data telemetry as well as to provide hands-on experience prior to the final design of the ADM.

In order to minimize cost and development time, the LDM uses existing hardware to the maximum extent possible. OPTECH has already developed reflection type sensors and Sensor Management Controllers similar to those described in this report. These sensors will be demonstrated along with other reflection sensor concepts now at a prototype stage. One sensor controller circuit capable of operating two fiber-optic sensors will be used. Data generated by that circuitry is transmitted via optical fibers to a data logging and display console.

1.6.2. Advanced Development Model (ADM)

The ADM will employ reflection-type fiber-optic sensors to measure parameters selected during Phase II of this project. One parameter will be pressure. Other possible parameters include temperature, acceleration, vibration displacement, linear displacement, shaft speed, and shaft runout. This report reviews the conceptual design for each of these sensors. Fabrication of each of these sensors for inclusion in the ADM is not within the scope of this project as it is now defined. The ADM sensors will have common optical characteristics so that they will be interchangeable.

Two Sensor Processing Units (SPU's), each capable of operating eight fiber-optic sensors, will be included in the ADM. Fiber-optic telemetry will be used to communicate sensor data from the SPUs to a remote data logging and display console. Details concerning the telemetry and display subsystems are not yet resolved.

The ADM will be suited to installation and testing aboard a Navy platform. However, actual testing of the ADM outside of the OPTECH laboratory is not within the scope of this project as it is now defined.

Commercially available and military qualified components will be used in the ADM's fiber-optic telemetry system to the maximum extent possible. As described in Section 1.2, in the event that a military grade system is not commercially available the most appropriate industrial grade system that is available will be selected.

1.6.3. Engineering Development Model (EDM)

The Engineering Development Model (EDM) will be based upon the ADM to the maximum extent possible. When Phase III is completed the ADM hardware, following any necessary modifications identified during the ADM test phase, will be designated the EDM.

The EDM will be suited to testing aboard a Navy platform. It is OPTECH intention that the EDM will installed and tested parallel to an existing Shaft Control Unit (SCU) so that comparison data can be recorded.

2. EXISTING SHIPBOARD SENSOR AND DATA TELEMETRY SYSTEMS

2.1. Shipboard Measurement Requirements

Table 11.0-1 in Appendix A lists the sensors which are currently hardwired to the Shaft Control Unit (SCU) of the DDG-51. The various interfaces associated with these sensors are listed in Table 11.0-2 of Appendix A.

These data are presumed to be typical for a shipboard application. Other sensors known to be used in various ship's systems but not represented in the list of SCU devices include the following.

- o Acceleration
- o Vibration (displacement)
- o Smoke

Sensors of the first two of these parameters will also be discussed in this report.

2.1.1. Shipboard Data Rate Requirements

In most control system architectures data acquisition equipment operate in fixed cycles, sampling sensors at rates ranging from 100 to 200 milliseconds per cycle. Some sensors are sampled every cycle while others are sampled every second or every fourth cycle. A worst case analysis which assumes that each sensor is sampled once every 100 milliseconds is presented in Appendix B. That analysis shows that a communication protocol operating at a moderate data rate of 375 kHz is sufficient to accommodate approximately seventy SPUs and over one thousand sensors.

2.2. Deficiencies of existing sensor systems

In order to identify specific sensors to target for conversion to fiber optics, the following list of problem sensors was compiled. Included is a description of the sensor type, the specific problems related to the sensor, and some suggestions as to how fiber-optics can solve the problem.

2.2.1. Magnetic Speed Pickup

Magnetic pickups are currently being used to sense radial speeds within the LM2500 Gas Turbine. The current practice is to sense the passing of teeth on gears within the turbine. The speed of the Gas Generator and the Power Turbine sections are each monitored redundantly. Table 2.3-1 summarizes the speed ranges

Table 2.3-1. Magnetic Speed Pickup Speed Ranges

Parameter	Number of Teeth/Gear	Speed (RPM)	Freq. (Hz)
Gas Generator Speed (NGG)	47	0 - 12000	0 - 9400
Power Turbine Speed (NPT)	83	0 - 5000	0 - 6917

Two problems are associated with magnetic sensing of speed. The first is that in order to allow proper operation, the sensor must be positioned relatively close to the rotating gear. Often, during calibration procedures, the sensor is positioned too close to the gear thus causing damage to the sensor. This problem may not occur until the turbine reaches operating temperature and the expansions in both the gear and the sensor combine to reduce the specified gap.

The next problem is associated with the sensing of speed from a magnetic pickup. The signal conditioning circuit must be able to accurately detect the wide voltage ranges generated by the sensor. In order to accurately sense speeds at the high end of the range, which is more critical, accuracy is lost at the low end. In addition, the voltage levels at the low end approach the ambient electrical noise levels. In practice, speeds below 300 RPM for NGG and 100 RPM for NPT are not accurately measurable.

Both of these problems could be solved with the use of fiber optics. One technique would be to sense the passing of each tooth by positioning a light source and detector on either side of the gear. Each tooth would then break the beam as it passed. This technique is independent of speed in the specified ranges and immune to electrical noise.

A second technique which may work is to sense the passing of each tooth by reflecting a beam directly off of each tooth as it passes. This type of sensor could possibly use the same hole as the magnetic pickup.

2.2.2. Resistance Temperature Detector

Resistance Temperature Detectors (RTD) utilize the properties of certain types of metals to determine changes in temperature. The basic principal utilizes predictable nonlinear changes in resistance to compute the temperature. The major advantages to the use of RTDs are their stability, accuracy, and repeatability. The major problem is that the voltage drops and varying temperature coefficients incurred in the sense leads causes inaccurate readings. The solution to this problem is to provide a separate set of leads carrying no current to measure the voltage directly across the device. In most naval applications, platinum RTDs are used in three or four wire configurations. The use of platinum, which tends to be expensive, is primarily due to its stability and predictability.

The other major problem with the use of RTDs is that in order to achieve the needed accuracies, relatively stable currents are needed. The circuitry required to generate these currents tends to be bulky and expensive. Also, if the nonlinearities inherent with the use of RTDs is to be removed through the use of hardware, additional circuitry must be considered.

A fiber-optic temperature sensor targeted for this application must be able to achieve the stability, accuracy, and range of platinum RTDs, while significantly reducing the amount of circuitry required. Response is typically not a problem in this area because RTDs are not used in fast response applications (see thermocouples).

2.2.3. Thermocouples

Thermocouples are currently the preferred sensor where fast response or very high temperatures are being measured. The accuracy and linearity are reasonable. The basic principal in the operation of thermocouples uses the phenomenon that two dissimilar metals in isothermal contact causes a potential difference which is a function of temperature. Thermocouples therefore tend to be very low-level devices.

Signal conditioning for thermocouples tends to become expensive due to the need for low drift electronics to sense the low-level (millivolt) signals generated by the device. Additional circuitry may be necessary to linearize the signal if this is to be done in hardware.

Since any two dissimilar metals will create a thermocouple, a critical part of any thermocouple design includes the elimination of unwanted thermocouples and the use of a temperature reference device. These two areas tend to increase the cost and complexity of most thermocouple applications.

A fiber-optic temperature sensor targeted for high speed applications must maintain a low thermal mass in order to provide adequate response. High temperature applications require rugged and reliable devices in order to withstand the severe environments typically encountered by thermocouples.

2.2.4. Accelerometers

The use of accelerometers in machinery control tends to be limited to mechanical vibration sensing. Current applications integrate the acceleration signal twice in order to get displacement. The displacement signal is then processed to determine if the vibration is excessive. In gas turbine applications, direct and induced vibrations are sensed at the current operating frequency of the turbine.

Since mechanical vibration is typically sinusoidal, the problems arise in the integration of the sinusoidal acceleration signal to a vibration velocity signal. This first integration is typically performed by a charge amplifier device in the engine module. The velocity signal is then transmitted to the control system where it is selectively filtered and integrated into the vibration displacement signal.

A fiber-optic displacement sensor in the engine module could be used to eliminate much of the circuitry needed to perform the complex integrations and signal processing. However, some questions remain as to how effective direct measurement will be as compared to the measurement of acceleration.

2.2.5. Linear Variable Differential Transformer

The Linear Variable Differential Transformer (LVDT) is an electro-mechanical device used to measure the precise position of valves and actuators. An LVDT is essentially a series of stationary coils (usually one primary and two secondaries) with a rod-shaped core which moves longitudinally within the coil. An AC excitation voltage is applied to the primary which induces voltages in the secondary which are proportional to the rod position. In addition, when the difference between the secondary voltages are either in phase or out of phase with the primary, the direction of the movement is indicated.

Aside from electrical noise on the inputs, one of the primary problems with the use of LVDTs is the need for a highly stable oscillator voltage on the input. Since the output of the LVDT depends on the input, instabilities with respect to time, temperature, and variations in load impedance must be held to a minimum. LVDT specifications usually require precise cable characteristics such as resistance, inductance, and capacitance per foot of cable, as well as the number of wires per cable and the maximum distance from the transducer to the signal conditioning.

LVDTs are designed to measure displacements from fractions of millimeters up to several centimeters. Some applications such as engine control require 12-bits or more across the linear range of the LVDT. As an example, the LVDT used to measure fuel valve position in the LM2500 gas turbine has a stroke of approximately 13 millimeters. The process control is required to provide an accuracy of at least +/- 0.5% of full scale, or approximately 0.065 millimeters

2.2.6. Fluid Level

Sensing of fluids such as fuel oil, lube oil, and water is typically performed through the use of a mechanical rod with a number of discrete contact closures. As a float traverses the rod, it mechanically activates one of the contacts, causing a change in the resistance of the rod. The resistance change is proportional to the fluid level. The contacts are positioned in a non-linear fashion in order to adjust for variations in the shape of the tank.

The primary problem involves the fouling of the bar and/or contacts, thus resulting in faulty readings. In addition, some applications require the sensing of the interface between two fluids such as sea water and fuel oil. In these applications, the proper selection of float material is critical. In other applications, the same float must be used for fuel oil or sea water at different times.

A fiber-optic solution to this problem might utilize two fiber cables and an exposed prism. When the prism is not covered by the fluid, most of the light is reflected by the prism back to the detector. When the prism is covered, most of the light is absorbed by the fluid. This technique will also work for the two-fluid interface because the differences in the index of refraction of the two fluids will reflect more or less light back to the detector.

2.2.7. Torsionometer

Torsionometers are currently used to determine the torque of the main propulsion shaft(s). Horsepower is then derived from the shaft torque and shaft speed. Current designs use a bar approximately three feet in length attached linearly along the shaft. Strain gage sensors on each end of the bar measure the strain-induced bending in the bar. The leads from the strain gages are carried through the shaft by the rotor/stator combination. Electronics are then used to convert the signals into shaft torque.

Some problems typically found with torsionmeters include sensitivity to transverse and longitudinal vibrations, as well as high levels of EMI induced error caused by transmitting the signals through the rotor/stator combination. The relatively large housing for the stator assembly also tends to become expensive. In general, the torque values obtained from this type of system are not considered to be reliable enough to be used for control applications.

Two optical techniques may be used to measure torsion in the propeller shaft. The first uses a pair of optical encoders attached to the shaft at a known distance from each other. Optical or electrooptical sensors may then be used to measure the phase difference between the signals from each sensor. The phase difference os proportional to the angular displacement which is in turn proportional to the torsion in the shaft. Torque is then determined by computing the amount of torque required to produce the measured displacement. A similar technique would use longitudinal markings on the shaft itself. Two reflection type fiber-optic sensors then measure the phase difference between the shaft markings.

2.2.8. Discrete Inputs

Discrete inputs in the form of contact closures, limit switches overpressure switches present a class of problems where a false indication can have potentially drastic consequences. In the case of most analog signals, a certain amount of validity checking is often performed, usually in the form of range and rate checks. These techniques do not apply to discrete signals since this category of sensors typically indicate one of two possible states. The integrity of some discrete signals is so important, the technique of providing a supervised contact is often used.

2.2.8.1. Contact Closures

Contact closures are most often provided by switches or by a spare set of dry contacts on an existing relay. In either case, the primary problems are contact bounce and dirty contacts. The signal conditioning circuit generates a signal which is returned when the contacts are closed.

Contact bounce may be eliminated either through hardware or through software. Hardware solutions add unwanted hardware to the signal conditioning circuits, and software solutions take away processing time. Recent solutions tend to favor software debounce in order to reduce the failure rate of the equipment by reducing the amount of hardware.

The problem of dirty contacts is typically solved by providing adequate current in the driver circuit to overcome the worst case contact resistance expected in the lifetime of the equipment. This typically results in oversized power supplies and added heat dissipation in the cabinet. Too much current, however, will cause arcing across the contacts, resulting in additional contact resistance.

One optical solution to this problem is to sense the mechanical closure by breaking or reflecting an optical beam. The reflection method has advantages since a single optical fiber may be used.

2.2.8.2. Supervised Contact Closures

In cases where the sensing of a contact is critical, supervised contact closures are often utilized. This technique places a resistor of known value across the contact. The signal conditioner is then able to determine if the signal path to the contact is open or if the contact itself is open.

Supervised contacts solve the problem of open wires in the circuit but do not solve the generic problems associated with contact closures. The additional circuitry required to sense the open contact current adds to the failure rate, as does the resistor at the contact. In addition, spare parts for both supervised and non-supervised switches and contacts must be stocked.

Several techniques may be used to ensure the integrity of the optical cable for critical discretes. One such technique utilizes a semitransparent mirror in the sensor which reflects a small percentage of the light in the open contact state. The amplitude of the reflected light is then used to determine the state of both the cable and the contact. A dual wavelength technique involving a dichroic mirror could also be used.

2.2.8.3. Limit Switches

Limit switches are typically used to detect the fully open and/or fully closed position of valves, dampers, or doors. Most applications utilize a mechanical contact closure for indication while others utilize magnetic proximity detectors.

In general, the problems associated with this type of detection lies in the mechanical nature of the contact closure as previously outlined above.

2.2.8.4. Pressure Switches

Pressure switches are used to generate a discrete signal upon particular pressure transitions. Typical construction techniques utilize a snap-diaphragm to actuate a mechanical contact whenever the pressure changes above or below a preset pressure setting.

Fiber-optics could be used to sense the position of the diaphragm in order to eliminate the mechanical contact and the electrical uplink signal. The pressure snap-diaphragm technique could still be used.

2.2.8.5. Temperature Switches

Like pressure switches, temperature switches are used to detect particular temperature transitions. The construction of temperature switches typically consists of bimetallic contacts which open or close at preset temperature settings.

2.3. Deficiencies of Existing Data Telemetry Systems

2.3.1. Electromagnetic Interference (EMI)

Electromagnetic Interference (EMI) has always been a major problem for electronic systems in the shipboard environment. However for typical electronic systems used for propulsion control, emission is less of a problem than susceptibility. The EMI emission and susceptibility requirements for surface ships are outlined in MIL-STD-461B Part 5 for Class A4 equipment. A summary of the specific requirements which apply to digital systems is shown in Table 2.3-2.

Table 2.3-2. EMI Test Requirements

Requirement	Applicability
CE01	DC, AC and interconnecting leads (narrowband)
CE03	DC, AC and interconnecting leads (broadband)
CS01	Equipment and subsystem power leads (limited)
CS02	Equipment and subsystem power leads
CS06	Equipment and subsystem power leads (spike)
CS09	Operating frequency (limited)
RE01	Radiated Emissions (magnetic field emissions)
RE02	Radiated Emissions (Electromag. field emissions)
RS01	Magnetic field susceptibility
RS02	Voltage spike and power frequency current suscept.
RS03	Radiated electric field susceptibility

The above requirements apply to both the enclosure itself and all interconnecting cabling outside of the enclosure. Since the design of the enclosure is equally critical in systems with and without fiber-optic cables, only those problems related to the cables themselves and the ingress and egress of those cables will be discussed.

The primary technique for the protection of analog signals is to use groups of signal cables in a "twisted/shielded pair" or "twisted/shielded triplet" configuration. Several of these cables are then grouped in a large bundle within an outer protective shield. One or two wires in each twisted pair/triplet is used for the signal and the other is connected to "logic ground". The shield is used to protect the signal from externally generated EMI and to prevent the emission of EMI from the signal to its neighbors in the cable. The entire cable is then encased in an overall protective shield and a waterproof armored jacket.

This type of cable fabrication technology typically results in large stiff cables in order to handle the large quantity of sensors in a typical control system application.

A major problem arises in the application of grounding techniques to each of the shields within the cable, as well as the overall outer shield. Various experts in the field offer wide solutions to this grounding problem. One of which is to attach each shield to chassis ground at one end of the cable and to leave the other end floating. Inside the enclosure, the shields would be continued on the cable but isolated from the chassis ground. A second technique would ground the shield to the chassis while maintaining shield continuity within the enclosure.

When the logic is allowed to float with respect to the ship's hull, the ground isolation between the logic and the hull becomes critical. When the ground path to the ship's hull becomes corroded, the cabinet will float at some potential above ship's ground. Each cabinet may therefore be floating at a different level with respect to each other, as well as with respect to the logic within the cabinet. Various ground loops are then created when failures occur in the cables or transducers. Failures of this type then cause damage in areas which are often remote from the original problem area and hence difficult to isolate.

The second technique uses a common ground for the cabinet and logic, connecting both at a single point to the ship's hull. This technique, while still susceptible to corrosion at the single point ground, has the additional problem of allowing noise spikes on the ground lines to enter the logic assembly. This problem tends to be very disruptive to digital circuitry.

The use of fiber-optic cables and sensors would virtually eliminate this type of problem due to the fact that each transducer is optically isolated from the electronic enclosure and hence from each other.

2.3.2. Cable Installation Cost

The cost of using optical fiber cables should differ dramatically from that of typical armored cables used aboard ship. While the cost per foot may be similar, the number and type of cables should differ widely. A recent analysis of the number of cables used in the FFG-7 class ship (Todd) showed that 1359 cables of 110 different types were used for a total of 81,809 feet of cable. These figures include signals for Ship Support and Combat Systems subsystems.

Cable length estimates for the DDG-51 program, for the Ship Support subsystem alone, range from 104,015 ft. at a cost of $23.40/ft. (Lockheed) to 167,708 ft. at a cost of $25.41/ft. (Todd).

Two approaches for the conversion to fiber-optics must be considered. The first is to replace all of the existing copper cables with fiber-optics. This approach has the advantages of EMI protection but would fall short of any improvements in cost. In order to fully utilize the capabilities of fiber-optics, the entire system must be analyzed. This is where the second approach comes in to effect.

Due to the increased bandwidth capabilities of fiber-optics, many signals may be multiplexed onto a single optical fiber. It follows therefore that a distributed approach to the use and transfer of signals between ship subsystems is the desired goal for the use of fiber-optic data transfer. Various types of high speed Data Transfer Networks (DTN) may be utilized to connect the major Ship Support Consoles (i.e. Propulsion, Electric Plant, and Damage control). Each subsystem could then interface to the various individual equipments via local fiber-optic data buses.

Designs which utilize the various DTNs and Local Busses would allow the most optimum use of fiber-optics for Ship Support subsystems. The number of cables could then be greatly reduced. All of the other advantages of fiber-optics may now be achieved.

2.3.3. 4-20 Ma Loop Telemetry

The problems associated with many sensors are often associated with the use a 4-20 milliamp loop to transfer data from the sensor to the signal conditioner. Typical sensors which use this technique are pressure, temperature, and tank levels. A DC excitation voltage is applied to the sensor from the signal conditioner. This voltage is used to generate a signal whose current is proportional to the sensed parameter.

The main problem with this technique is the susceptibility of the signal to external EMI. This problem is typically resolved by using a differential signal transmitted over a twisted shielded pair. This solution adds additional circuitry while providing some EMI protection.

Fiber-optics in this area could greatly reduce the EMI problems, while reducing and standardizing the circuitry needed to process the signal.

3. FIBER-OPTIC SENSOR SYSTEM DESIGN

3.1. Design Approach

Considerations in the design of the fiber-optic sensor system include the following.

- Designs should be such that a variety of sensors can be operated by a common sensor interface controller. Interchangeability of reflection-type sensors for pressure, temperature, acceleration, etc. is highly desirable. Likewise it is desirable to operate multiple types of sensors, i.e. reflection and microbend, from the same sensor controller circuit.
- Designs should be inherently simple, thereby assuring reliability, economy, and easy installation and maintainance.
- Problems with existing sensors are to be addressed. Characteristics of existing sensors are to be met or exceeded.

3.2. Sensor Specifications and Requirements

The Military Specifications applicable to the various sensors being considered in this report are listed in Table 3.2-1. Certain exceptions to these specifications will be in order since the fiber-optic sensors are passive optical devices that neither require optical power nor produce electrical output signals. The general performance requirements to be met by fiber-optic pressure and temperature sensors are listed in Tables 11.0-3 and 11.0-4 of Appendix A.

Table 3.2-1. Military Sensor Specifications

Measurement	Applicable MIL-SPEC
Pressure	MIL-P-24212 MIL-D-24304
Temperature	MIL-T-24387 MIL-T-24388
Liquid Level	MIL-L-23886 MIL-L-24407
Acceleration	MIL-T-83174
Shaft Speed	MIL-P-15554
Torque	TBD
Contact Closure	TBD
Smoke	TBD
Linear Displacement	TBD
Angular Displacement	TBD

3.3. Review of Fiber-Optic Sensors

This is a brief introduction to two types of fiber-optic sensors. This discussion is included to make this report self-contained and to define terms that will be used in sections to follow. No attempt is made educate the reader in the details of fiber-optic sensor since detailed information is available elsewhere and most of the personnel for whom this report is being written are already experts on the subject.

3.3.1. Reflection-Type Sensor Design

3.3.1.1. Principle of Operation

A reflection type sensor is shown conceptually in Figure 3.3-1. In its simplest form the sensor consists of a single optical fiber that is positioned near and perpendicular to a moveable reflective surface. The optical fiber carries light from a light emitting diode (LED) source located in a remote optoelectronic subsystem (the Sensor Interface Controller (SIC) discussed in Section 5.4). That light is emitted from the fiber, illuminates the moveable surface, and is partially reflected back into the optical fiber. The amount of light reentering the fiber is a direct indication of the separation between the fiber face and the reflecting surface. A photodetector located with the LED source in the SIC measures the amount of light thus returned from the sensor.

Reflection type sensors can be fabricated using any optical fiber. Early work at OPTECH demonstrated sensors using a large variety of fibers including 200 um core plastic clad silica (PCS) fibers, all plastic fibers, and with two 100 um core hard clad silica (HCS) fibers qualified for U.S.N. shipboard and U.S.A. aircraft applications. Other experiments have shown that single mode fibers and laser sources could conceivably be used to fabricate a reflection sensor.

The manner in which the reflected optical signal varies with the separation between the fiber face and the moveable surface depends upon the particular fiber in use; specifically, on the numerical aperture (NA) of the fiber, i.e. on the radiation pattern of the light leaving the fiber, and on the diameter of the fiber core. Typical data, taken with a 200 um core PCS fiber, are shown in Figures 3.3-2 and 3.3-3. There it can be seen that the reflection signal drops to twenty percent of its maximum value at a separation of approximately four hundred micrometers. This range of measurable displacement is approximately the same for all multimode fibers that OPTECH has tested. In the design of a particular sensor the reflecting surface is required to move a distance suited to the fiber employed.

OPTECH's reflection type sensor designs place a graded index-of-refraction (GRIN) rod at the end of the optical fiber. Light leaving the fiber passes first through the GRIN rod and then intercepts the moveable surface. Reflected light passes through the GRIN rod to reenter the fiber. GRIN rods are essentially short stubby lengths of optical fiber (2 mm diameter, 10 mm long) that can be designed to have specific optical properties. The GRIN rod chosen for reflection sensor applications is referred to as a half-pitch rod. Its optical performance is such that when placed directly on the end of an optical fiber it has no effect whatsoever on the pattern of light leaving and entering that fiber. Thus the performance of the sensor itself is not affected by the presence of the GRIN rod.

Detailed calculations related to the grin rod selection are given in Appendix C.

Sensors employing a GRIN rod at the fiber termination are designed such that the GRIN rod is built into a standard optical connector on the sensor body. An optical cable attached at that connector automatically has its fiber properly positioned with respect to the GRIN rod.

Inclusion of the GRIN rod in the sensor's design has several advantages. One is the provision of an optical surface upon which a dichroic (optical wavelength selective) mirror can be placed. The dichroic mirror and other GRIN rod advantages are discussed in Section 3.4 where the design of a reflection type pressure sensor is described.

3.3.1.2. Technical Risks and Alternatives

3.3.1.2.1. Surface Corrosion

Corrosion of the sensors reflective surface would obviously cause a reduction in the returned light level. If the corrosion occurred while the sensor was in use, the effect of the corrosion would be indistinguishable from an increase in the fiber-to-reflector gap. Very minor corrosion that occurred during storage of the sensor might be accounted for by calibration (zero and span) of the sensor at installation. Extensive corrosion would make the sensor inoperative.

The same can be said for the seepage of contaminants into the reflection space. Frost, oil films, etc. would all have similar effects on the reflection from the surface.

The solution to this problem is to hermetically seal the sensors reflection space and to fill that space with a dry gas. This requirement has been addressed in the OPTECH sensor designs.

3.3.1.2.2. GRIN Rod Surface Contamination

Contamination of the surface of the GRIN rod at the Fiber to GRIN rod interface would impede the passage of light to and from the sensor. Degradation of the sensor performance would clearly result. Contamination might occur both during the storage and the use of the sensor.

This problem is addressed by proper packaging of the sensors in storage and by proper cleaning of the sensors at installation. Post installation contamination is prevented by the use of environmentally tight optical connectors.

3.3.1.2.3. Improper Fiber Termination

In the reflection type sensors described here, the optical fiber connecting the sensor to the remote optoelectronic controller, though it be a standard fiber-optic cable, is an integral part of the sensing mechanism. That fiber, through the GRIN rod, illuminates the reflecting surface and receives the light from it. Improper termination of that fiber might cause a degradation of the sensors performance; the fiber must couple light into and out of the GRIN rod efficiently.

OPTECH has not experienced this problem. Indications are that normal care in the termination and handling of the sensor fibers is sufficient to insure proper operation of the sensor. This problem is addressed by the implementation of good fiber handling practices.

3.3.1.2.4. Thermal Effects

Temperature sensitivities of either the GRIN rod itself or of the dichroic mirror plated on its inner surface would effect the performance of the sensor at high temperatures.

Discussions with vendors indicate that neither component exhibits significant temperature sensitivities over the operating temperature range of the sensor. OPTECH is conducting experiments to verify this.

3.3.1.2.5. Fiber Attenuation Effects

A major problem with amplitude type sensors is the effect of attenuations in the fiber joining the sensor to its source and detector module. If no mechanism provides for a distinction between signal changes due to bending in that fiber, for example, and variations in the output of the sensor itself then major errors in the evaluation of the sensor signals may result.

This problem is addressed by an attenuation compensation technique described in Section 3.3.3

3.3.2. Microbend Type Sensors

3.3.2.1. Principles of Operation

Microbend type sensors consist of two sets of sawtooth-like deformers which have an optical fiber placed between them. Relative displacements of the deformers cause a microscopic bending of the fiber which in turn causes light from the fibers optical core to be coupled into the fiber classing cladding where it is subsequently attenuated. A properly designed fiber-deformer system causes the loss of light in the fiber to be directly proportional to the relative separation of the deformers.

This type of sensor is very simple and very rugged. The only optics required are an LED source, a photodetector, and an optical fiber to transmit the light. The deformers are usually solid pieces of metal with raised machined teeth. The only electronics required are the LED driver and photodetection circuitry.

Motions as small as 0.05 Å combined with a linear range of 100 dB have been recorded with these sensors. The upper limit of motion for these detectors is approximately one micrometer and, to that extent, the device is a zero-motion detector. That property, along with its large dynamic range and flexibility of design, makes it useful in devices such as the accelerometer, force gage, pressure sensor, zero movement switch, etc. Also, the overall stiffness of the system can be controlled to give a wide range of operational frequencies.

Most current microbend devices have the power and demodulation electronics located near the deformers. This prevents any false signal generated by the movement of a lead fiber that brings light to the sensor. However, future designs could place the LED and demodulation system a large distance (up to 500 meters) from the sensor.

3.3.2.2. Technical Risks and Alternatives

Microbend sensors that have the optics and electronics in close proximity have few technical difficulties. The biggest problem is the possibility of a force overload breaking the fiber. This is easily prevented, however, by designing in a mechanical stop to keep the teeth from meshing to the point where the fiber breaks.

Because the sensor is an intensity-modulated device, any change in detected light level will be seen as a signal. Thus, if the LED changes intensity due to temperature changes or supply power drift, the readings from the device will vary. It should be stressed, however, that this is not a significant problem with A.C. devices such as accelerometers. D.C. devices, such as pressure sensors, will require source stabilization.

If the microbend sensor is to be operated as a remote unit, much research must be conducted to optimize the light delivered to the sensor and reduce the signal noise (manifested as random light loss due to bending along the fiber leads). The fiber attenuation compensation technique discussed in Section 3.3.3 can also be applied to microbend type sensors to eliminate these effects.

3.3.3. Fiber Attenuation Compensation

3.3.3.1. Principle of Operation

A common problem experienced with amplitude type sensors such as the reflection and microbend devices described above is the effect of varying attenuations in the fiber that joins the sensor to its remote source and detector module. The most likely source of these varying cable attenuations are bending or pinching of the fiber, thermal effects in fiber and connectors, and variations in the coupling efficiency of a connector that has been opened and reconnected. In each of these cases the optical signal passed by the fiber can vary by as much ten percent. If no provision is made to adjust for these effects the resulting change in optical signal is indistinguishable from a change in the parameter being measured, e.g. the position of the reflecting surface in a reflection type sensor.

The apparent error in the sensor measurement is compounded by the fact that a given percentage change in the optical signal generally corresponds to a far greater change (a factor of two to four) in the parameter being measured.

Many techniques for detecting fiber attenuation effects have been presented in the literature. The technique that OPTECH employs is described below. This particular discussion uses the example of a reflection type sensor. Other amplitude type sensors are compensated in a similar way.

Two independent optical sources (LEDs) emitting light at different optical wavelengths are used to illuminate the single optical fiber leading to the fiber-optic sensor. A dichroic mirror placed within the fiber-optic sensor distinguishes between these two light beams as illustrated conceptually in Figure 3.3-4. Ideally, one beam (the Measure beam) is wholly transmitted by the dichroic mirror. It enters the sensor and is modulated appropriately. The other beam (the Reference beam) is, ideally, wholly reflected by the dichroic mirror. Its light returns to the photodetector without being affected by the sensor. Both beams, however, experience identical fiber and connector attenuations. By analyzing the reference beam signal, one can identify and evaluate attenuation effects in the fiber. This information is then used to correct the measurement signal and eliminate those effects.

In order for this technique to work, the two beams of light must experience identical attenuations due to bending, connector variations, etc. This requires that those two beams be as close in wavelength as practical. Light beams at 830 nm and 1300 nm wavelengths, for instance, are known to demonstrate significantly different bending attenuation characteristics. Equally important, however, is a separation in wavelengths sufficient for the dichroic mirror to effectively distinguish the two light beams. The choice of operating wavelengths is determined by a trade off of these two requirements and by the selection of available components. An evaluation of wavelength dependance on bending effects is given in Appendix D.

OPTECH has selected two LEDs that emit light at nominal wavelengths of λ_1 nm and λ_2 nm, separated by about 50 nm. LEDs are broadband sources and, consequently, the spectra of these two sources overlap significantly. The result is that each beam is partially transmitted and partially reflected at the dichroic mirror, as illustrated in Figure 3.3-5. Typical gap dependant reflection data for a dual wavelength sensor having a dichroic mirror is shown in Figure 3.3-6. Because of the partial transmission and reflection of each beam by the dichroic, the attenuation correction algorithm is less accurate than it might be if the two beams were wholly distinguished by the dichroic mirror. Experimental work at OPTECH has shown that the information necessary to distinguish between sensor modulations and bending effects does reside in the optical measure and reference signals. OPTECH is now working to model the sensor system and to determine the best algorithm for processing these two signals to obtain fiber-attenuation independent values for the sensor output.

3.3.3.2. Technical Risks and Alternatives

As with all modeled systems one potential problem is the incompleteness of the initial data on which the model is based. Future data may not be covered by the model and would give erroneous results. Another problem is the possibility that the system itself may change in some small but unrecognized way that invalidates the model. Again, erroneous results would be obtained. Variables might include the wavelength or spectra of the optical sources, characteristics of the dichroic mirrors, characteristics of the sensor fibers, and modal properties of the light beams.

OPTECH is addressing these potential problems by a comprehensive plan to obtain complete data for the building and initial testing of the model. A similar plan covers subsequent testing of the model in realistic situations.

3.4. Reflection-Type Pressure Sensor

3.4.1. Current Sensor Design

OPTECH's reflection type pressure sensor is illustrated in Figure 3.4-1. The main body of the sensor is made of two machined parts. The first has a standard pipe fitting and a pressure actuated corrugated diaphragm that serves as a reflective surface. That diaphragm is linearly displaced by pressures applied to the cell, although linearity of the pressure induced displacement is not a requirement of the design. The diaphragm is designed such that at full scale pressures the diaphragm undergoes a displacement of approximately 350 um, a distance suited to the optical fiber and GRIN rod that is currently employed. The design of sensors for various pressure ranges requires only a selection of diaphragms giving appropriate displacements.

The second part of the main body of the sensor contains the required GRIN rod and has a standard SMA type connector machined into it. The SMA connector causes the optical fiber connected to the sensor to be properly positioned with respect to the GRIN rod.

A feature of the sensor design is the ability to set the initial GRIN rod to diaphragm gap through the use of shims. This removes the criticality of fabrication tolerances in both the diaphragm and the sensor body. The zero pressure spacing between the diaphragm and the GRIN rod is set to approximately 50 um.

In addition to contributing to the optical properties of the sensor, the GRIN rod provides a hermetic optical feedthrough that insures the environmental integrity if the reflection space. Moisture and other contaminants that might enter the gap between the Grin rod and the diaphragm, particularly during storage or installation when that space would be open to the environment, are thereby excluded. An o-ring seal prevents moisture from entering the same space through the junction of the two main body parts.

A gauge port is provided by a hole in GRIN rod side of the main body. The hole is protected from leakage of moisture and contaminants by a large flexible rubber boot. The boot is in turn protected by a perforated metal covering.

Typical performance data recorded using the pressure sensor described above and developmental sensor controlling circuitry are illustrated in Figure 3.4-2. These data were collected on two consecutive days during which the equipment was not adjusted or recalibrated. The observed rms error in the pressure reading was approximately 0.1%. During this experiment the optical fiber connecting the sensor to its electronic controller was not subjected to bending variations.

3.4.2. Proposed Design Modifications

Several modifications to the present design will be incorporated in a more rugged model suited to shipboard application. These modifications include the following.

- Incorporation of a military grade fiber-optic connector and extensive strain relieving of the fiber-optic cable.
- Addition of a contoured backstop that matches the shape of the corrugated diaphragm, thereby providing extended overpressure sustaining capability.
- Addition of an appropriate mounting bracket.

3.4.3. Technical Risks and Alternatives

A common problem with pressure sensors is the failure of the gauge reference port with respect to the exclusion of moisture or other contaminants. The ability of the rubber boot in OPTECH's design to exclude harsh environments and still pass atmospheric pressure has not been proven. Also, temperature effects to be expected in the GRIN rod, dichroic mirror, and diaphragm remain to be quantified.

OPTECH is preparing to undertake experiments to prove the worthiness of this design.

3.5. Reflection-Type Temperature Transducer

3.5.1. Principle of Operation

The reflection-type temperature transducer works on the same principle as the reflection-type pressure sensor. In this case the force that moves the diaphragm comes from the thermal expansion of a fluid constrained in the body of the transducer.

A prototype of the transducer is shown in Figure 3.5-1. The inner cup holds the fluid and acts as clamping device for a flat Mylar diaphragm. As the temperature increases or decreases, the fluid expands or contracts, changing the gap between the diaphragm and the end of the fiber. The larger the volume of fluid in the cup, the greater is the diaphragm displacement for a given change in temperature.

This design is simple but the choice of the sensing fluid is very important. It must have a high thermal expansion coefficient and show good stability over the operational and storage temperature ranges of the sensor. Several fluids and compounds are suitable for this application and among the ones tested were silicone RTV compounds (which are sometimes used as actuators because of their thermal expansion properties) and silicone oils. The material finally selected for a prototype sensor will be one with a high thermal expansion coefficient and a very low compressibility.

3.5.2. Preliminary Performance Data

Figure 3.5-2 shows the response of the sensor to an instantaneous change in temperature from twenty-two to forty degrees centigrade. The time constant of this sensor is twelve seconds. The time constant depends on the mass of the sensor and the thermal conductivity of the fluid. Future versions of the sensor will optimize both these parameters.

Figures 3.5-3 and 3.5-4 show the output of the sensor plotted against the actual temperature of the sensor. This output will be linearized by the demodulation electronics in the sensor interface controller.

3.5.3. Technical Risks and Alternatives

Although the design of the transducer is simple and easy to reproduce, the response time of the system is slow compared to present RTD and thermocouple type sensors. This is because of the relatively large mass of the casing and the fluid. This problem is being addressed in the miniaturization of the current temperature sensor design.

An alternative design to the one described above uses reflective bimetallic discs that change shape as a function of temperature. This sensor would be less accurate than the fluid filled sensor but would also be less expensive and not dependant on the selection of appropriate fill fluids.

3.5.4. Preliminary Design for Next Generation Transducer

The second generation design for the transducer will include improvements shown in Figures 3.5-4 and 3.5-5. These improvements include using a GRIN rod interface between the fiber and the diaphragm and selecting the best material for the diaphragm and fill fluid. The volume of the cup will depend on the temperature range and the thermal expansion coefficient of the fluid.

3.6. Reflection-Type Accelerometer

3.6.1. Principles of Operation

The reflection-type accelerometer illustrated in Figure 3.6-1 consists of a reflective mass suspended between two springs. That mass moves relative to the sensor housing which supports an optical fiber and GRIN rod combination opposite the reflector as was described for the pressure sensor. The sensor interface controller used with the reflection-type pressure sensor also operates the accelerometer, effectively measuring the separation between the GRIN rod and the suspended mass.

The response characteristics of the accelerometer are determined by the mass of the reflector and the spring constant of its supports. If these are chosen such that the resonant frequency of the sensor is much greater than the frequency of the vibration to be measured, then the recorded displacement of the mass relative to the sensor case is directly proportional to the sensors acceleration. This approach is not practical for most machinery monitoring applications because of the high frequencies of interest, typically several hundred hertz or greater. The displacements that can be obtained with reasonable masses and springs are too small for reflection measurements.

An alternative and more attractive design has the resonant frequency of the sensor set much lower than the excitation frequency. In this case the reflective mass will be stationary with respect to the vibrating sensor case. The resulting signal will be a measure the displacement of the case, the parameter actually required in most machinery monitoring applications.

3.6.2. Technical Risks and Alternatives

A potential problem with the vibration displacement measuring sensor described above is its inclination sensitivity; the relatively weak springs necessary to obtain a low resonant frequency allow the mass to change position as the case is tilted. Also, although the vibration frequencies of interest may be high, the mass may still be driven to oscillate at the lower resonant frequency. These problems will be addressed by signal processing software in the sensor interface controller.

3.7. Reflection-Type Displacement Transducer

3.7.1. Principle of Operation

The basic reflection sensor described in Section 3.3.1 is suited to measuring displacements over a span of approximately four hundred microns with a resolution of approximately one micron. Typical reflection data were shown in Figures 3.3-2 and 3.3-3. Applications exist where it is necessary to measure substantially greater displacements. Linear Variable Displacement Transformers (LVDTs) on the LM2500 marine engine/turbine, for instance, are used to measure the position of fuel metering valves and variable pitch stator vanes. The LVDTs used for these applications have strokes of 0.5" and 3.4" respectively. The required measurement accuracy in each case is +/- 0.5% of the full scale displacement.

A displacement sensor capable of making large stroke measurements, yet using the same optics as employed in the pressure and temperature sensors described above is shown in Figure 3.7-1. The large stroke sensor has a reflecting wedge which is moved according to the displacement to be measured. A standard arrangement of GRIN rod, dichroic mirror, and optical fiber is positioned above the wedge and perpendicular to its reflecting surface. Displacement of the wedge causes a proportional change in the separation between its reflecting surface and the GRIN rod with that separation being appropriate to the reflection optic's requirements. The measurement range is adjusted by simply changing the slope of the reflecting wedge. In any case, the resolution of the measurement as a fraction of the full scale displacement is equal to that of the reflector to Grin rod separation measurement, or approximately 0.2%.

An alternate arrangement that could be used to greatly improve the resolution of the displacement sensor is shown in Figure 3.7-2. Here multiple wedges are used in series to record displacement. This configuration is complicated by the need to detect and record the transition from one wedge to another, a function that could be accomplished by the signal processing software.

3.7.2. Technical Risks and Alternatives

3.7.2.1. Wedge Vibration

Minor displacements of the reflecting wedge in the direction of the GRIN rod will be interpreted as relatively large changes in the measured displacement. The wedge or actuator shaft must be securely constrained against cross axis motion. This will be addressed in the detailed design of the sensor.

3.7.2.2. Non Uniform Reflectivity

Any non uniformity in the reflectivity of the wedge surface would cause a variation in the reflected light which would, in turn, result in erroneous displacement readings. This will be addressed in the design of the reflection wedge.

3.7.2.3. Contamination

The reflection sensor requires that the space between the reflector and GRIN rod be hermetically sealed in order to protect the reflecting surface. In the present sensor design this will require a hermetic feedthrough for the actuator shaft.

3.8. Reflection-Type Rotation Speed Transducer

3.8.1. Principle of Operation

The reflection-type rotation speed sensor consists of a fiber and GRIN rod assembly of the type that was described in Section 3.3.1 which is positioned opposite and perpendicular to the teeth of a movable gear. The sensor is illustrated in Figure 3.8-1. When the gear is in a position such that a top land is opposite the sensor a substantial amount of light is reflected back into the GRIN rod and is photodetected. When a bottom land is opposite the sensor then, because of the increased separation between the sensor and the gear surface, only an insignificant amount of light is reflected and photodetected. As the gear turns the photodetection circuitry produces a square wave signal with a frequency proportional to the speed of the gears rotation. This sensor performs equally well at high speeds and at low speeds where conventional devices become insensitive.

Because the measurement to be by this sensor is essentially a digital one, i.e. a determination that a top land of the gear is or is not present opposite the device, the sensor optics can be modified to improve its performance and ease of installation. This is done by substituting a quarter-pitch GRIN rod for the half-pitch rod used in other sensors. A quarter-pitch GRIN rod causes the light leaving the sensor to be collimated rather than diverging. This makes the reflection signal insensitive to minor changes in the reflector position but leaves it sufficiently sensitive to detect changes equal to the height of a gear tooth. An advantage of the quarter-pitch rod is that, because of the collimated beam, the separation between the GRIN rod and the gear can be increased over the few hundred micron separation normally used in a reflection sensor. Installation of the sensor is therefore less critical. The quarter-pitch rod improves the performance of this sensor by using a larger area of the reflecting surface to generate the returned light. Variations in the reflectivity of the gear surface are thereby minimized through an effective averaging over that surface.

Variations in the reflection signals are further eliminated by comparing the signal to a reference value using an electrical comparator. The reference value is between the reflection signals corresponding to top and bottom lands of the gear.

Preliminary data taken with a rotation sensor of this type are shown in Figure 3.8-2. These were taken using a quarter-pitch Grin rod and the gears of a drill chuck collet. The drill chuck was turning at 450 rpm. Both the optical signal and the comparator output are illustrated.

3.8.2. Technical Risks and Alternatives.

3.8.2.1. Reflector Quality

If this sensor is to be used in conjunction with existing mechanical gears, e.g.the gears in a transmission, then grease or other contaminants might foul the reflection surface or the surface of the GRIN rod. This problem is eliminated by the use of special gears or shaft encoders dedicated specifically to speed measurement. Dedicated gears are now used with conventional speed sensors.

3.8.2.2. Response Rate

Speed sensors of the type discussed here are typically used by fault detection circuitry that prevents turbine run-away in the event of a break in the turbine shaft. The response time of the sensor must therefore be very fast. The ability of the sensors electronic system to provide an adequate response time has not been verified. This will be addressed in the detailed system design.

3.9. Microbend-Type Accelerometer Transducer

3.9.1. Principle of Operation

Figure 3.9-1 shows a microbend-type fiber-optic sensor that can be operated in conjunction with the SIC electronics. This implementation differs from typical microbend sensors in that a full mirror is plated onto the end of the sensor fiber. The fiber light thus passes twice through the sensors deformer and returns to the electronics subsystem on the single optical fiber joining the sensor and the SIC. The dichroic mirror necessary for attenuation compensation is plated onto one of a pair of quarter-pitch GRIN rods in the sensors fiber-optic connector.

The sensor shown in Figure 3.9-1 is based upon a borehole seismometer designed and fabricated at OPTECH. That particular device was designed to measure horizontal accelerations as small as 5 ug at 1Hz, to have a bandwidth from 1 to 100 Hz, and to have a dynamic range of 100 dB. Other sensitivities and bandwidths can be obtained by redesigning the mass and spring components of the sensor.

Typical data taken with the OPTECH microbend accelerometer are shown in Figure 3.9-2.

3.9.2. Technical Risks and Alternatives

The design of this accelerometer has not been carried out in sufficient detail to identify or address the technical risks associated with it.

3.10. Other Amplitude-Type Sensors

Other sensors to which this design would be applicable, but which OPTECH has not yet considered in detail include the following.

- o Liquid level
- o Smoke
- o Flow (turbine with a shaft encoder)
- o Contact Closure

4. OPTICAL SOURCE AND DETECTOR DESIGN FOR AMPLITUDE-TYPE SENSORS

4.1. Design Approach

The optical module required in a single-fiber reflection sensor system is a nonstandard component. Considerations in its design are the reliability, cost efficiency, and the ability of the design to be adapted to various sensor fibers. Equally important is the manufacturability and ultimate availability of the final product.

4.2. Requirements and Specifications

The sensor controller alternatively provides light of two wavelengths over a single optical fiber. The controller must also detect light returning on the same fiber. Because the sensor is an amplitude device, the ability to regulate the light levels is a feature of the optical design.

The optoelectronics package must ultimately meet the requirements of the following specifications and standards as they apply to shipboard installation.

MIL-S-901	Shock Tests, H.I. (High Impact); Shipboard Machinery, Equipment and Systems Requirements For.

MIL-STD-167-1	Mechanical Vibrations of Shipboard Equipment (Type I - Environmental and Type II - Internally Excited).
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment.
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement Of.
MIL-E-16400(Navy)	Electronic, Interior Communication and Navigation Equipment, Naval Ship and Shore, General Specification For.
DOD-STD-1399(Navy)	Interface Standards for Shipboard Systems.
MIL-E-6051D	Electromagnetic Compatibility requirements, Systems.

Detailed specifications for the optical module will be developed during Phase II of this project.

4.3. Present Optical Module Design

The optical source and detector module that OPTECH presently employs in amplitude type sensors is illustrated conceptually in Figure 4.3-1. That module uses a 3x1 coupler to place two LEDs and one photodetector on the fiber that goes to the fiber-optic sensor. As described in Section 3.3.3, fiber attenuation compensation requires that LED sources with different but close wavelengths be used. The two selected LEDs are "hot-spot" types that are particularly efficient at coupling light into optical fibers. The Signal photodetector receives light reflected from the fiber-optic sensor.

Each LED has two optical fibers pigtailed to it. One goes to the 3x1 coupler. The other goes to a reference photodetector that monitors the output of the LEDs. Feedback circuitry uses this photodetector to maintain the LED output at a constant intensity. In practice, the two LEDs are alternately illuminated. Since only one LED is turned on at a time, single reference and signal photodetectors can serve both LEDs.

The 3x1 coupler that OPTECH currently uses is fabricated by placing three 112/125 um fibers side-by-side in one standard SMA connector which is mated to a second SMA connector containing a 200/230 um fiber. The overlapping of the cores of the 112/125 and 200/230 fibers is such that light is efficiently coupled between them. In the forward (3 to 1) direction better than 95% of the light passes through the coupler. In the reverse (1 to 3) direction geometrical mismatch of the fibers allows only 10% of the reflected light to pass from the sensor fiber to the photodetector fiber.

4.4. Technical Risks with the Current Design and Alternatives

Several technical risks associated with the current optical module design are listed below. Each of these is addressed by the alternative design described in the following section.

The temperature sensitivity of the modules used in testing at OPTECH has been excessive Typically, the output intensity of a regulated module varies by approximately 0.2 percent per degree centigrade. Analysis of this problem indicates that a thermal shift in the two fibers attached to an LED is causing differential changes in the amount of light coupled into them. This shift is exaggerated by the regulating circuitry which maintains constant light intensity at the reference photodetector.

Another problem that OPTECH has experienced with these modules is the variability among units. The manufacturability of the devices is questionable; they are now mostly hand made. Also, only one vendor willing to produce these devices has been identified.

One further short coming of the current module design is its specific use of a 200 um core fiber as its output. This results from an earlier OPTECH decision to use this particular fiber in some of its reflection sensor systems. The use of this module with fibers having smaller core diameters has been difficult.

4.5. Alternative Optical Module Design

An alternative design to the module described above is shown in Figure 4.5-1. It employs a multimodal 3x3 coupler to connect the required two LEDs and one photodetector to an output fiber. In this case the reference photodetector is connected to an output of the coupler, as is the sensor itself. Specific advantages of this design include the following.

- Only one fiber is connected to the LEDs and photodetectors, greatly simplifying fabrication of the optical module.

- The Reference photodetector measures the actual light coupled from an LED into the optical fiber. Variations in that coupling efficiency or in the output of the LED would be detected and properly corrected by the intensity regulating circuitry. This eliminates the major problem experienced with the current modules, i.e. the temperature sensitivity of the LED-to-multiple-fiber connections.

- Several manufacturers produce multimodal 3x3 couplers of the type required for this design. Also, couplers fabricated with many types and sizes of fiber are available. The design therefore does not require the use of any particular sensor fiber.

4.6. Technical Risks with the Alternative Design

4.6.1. Ruggedness of the Optical Module

Optical module is not military qualified. OPTECH has selected LEDs and photodetectors that have the most appropriate optical properties. Although these devices are of standard commercial quality and may be as rugged as any, their availability in military qualified versions has not been verified. The components that need to be ruggedized are the following.

- o LED's
- o Photodetectors
- o Pigtailing of fibers to LEDs and Photodetectors
- o 3x1 and 3x3 couplers

4.6.2. Temperature Sensitivity

The temperature sensitivity of the fiber couplings at the LED . ave been described. The 3x1 coupler itself shows a similar, but less severe effect. This problem is being addressed in the 3x3 coupler design discussed above.

3x3 couplers will also show some temperature sensitivity in their splitting ratio. This is an effect that is not compensated by the regulating circuitry. Vendor literature and preliminary experiments at OPTECH indicate that this may not be a significant effect. OPTECH is performing further experiments to quantify the extent of the problem.

4.6.3. Modal Sensitivity

Sensitivity of the 3x3 couplers splitting ratio to the modal content of the light it divides has been observed. This sensitivity requires that appropriate mode mixing be performed within the module. This is being addressed in the optical module design.

4.6.4. Reproducibility

The manufacturability of the current optical module, and an ability to obtain reproducible and interchangeable devices, has not yet been proven. Nothing in the design of the alternative optical module, however, puts it beyond the capabilities of fiber-optic component manufacturers.

4.6.5. Availability

The 3x1 coupler based module described above is available from only a single vendor. Other vendors willing to undertake manufacture of a similar device have not been identified.

The 3x3 coupler based module will be easily manufactured. A number of vendors produce its major component, the 3x3 coupler itself, and OPTECH is capable of fabricating the finished optical module.

5. SENSOR INTERFACE ELECTRONICS DESIGN

The sensor interface electronics provide light for the fiber-optic sensors, detect and process the optical signals received from those sensors, and convey sensor data to other display and control equipment.

5.1. Design Approach

Specific considerations in the design of the sensor interface electronics include the following.

- The system capabilities must be applicable to numerous sensors and sensor types. This is driven be a need for simplified sensor systems, increased maintainability, and a reduction in spare parts requirements. The system must also present a common interface between ship's systems and a variety of sensors.

- The circuitry must have a flexibility in its hardware design that allows different firmware to adapt the same circuitry to various applications.

- The sensor controller must provide intelligent sensor functions such as data reduction and built-in testing and fault detection.

5.2. Requirements and Specifications

5.2.1. Applicable MIL-SPECS

The sensor controller must ultimately meet the requirements of the following specifications and standards as they apply to shipboard installation.

MIL-S-901	Shock Tests, H.I. (High Impact); Shipboard Machinery, Equipment and Systems Requirements For.
MIL-STD-167-1	Mechanical Vibrations of Shipboard Equipment (Type I - Environmental and Type II - Internally Excited).
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment.
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement Of.
MIL-E-16400(Navy)	Electronic, Interior Communication and Navigation

Equipment, Naval Ship and Shore, General Specification For.

DOD-STD-1399(Navy)	Interface Standards for Shipboard Systems.
MIL-E-6051D	Electromagnetic Compatibility requirements, Systems.

A detailed specification for the electronics system will be developed during Phase II of this project.

5.3. Design Overview

The sensor controlling electronics consist of two main components. The first is a Sensor Processing Unit (SPU) that supplies light to remote optical sensors, receives and processes the light returned from those sensors, and transmits the measurement results via optical telemetry. The optical telemetered data is received by the second main component, the Data Acquisition Unit (DAU) which is an interface between the optically transmitted data and the ships Shaft Control Unit (SCU).

The SPU contains several Sensor Interface Controller (SIC) cards each of which handles two sensors. The maximum number of SIC cards which can be placed in a single SPU enclosure has not been determined. At least eight cards, providing sixteen sensors per SPU, is achievable. Another circuit card in the SPU, the Sensor Management Controller (SMC), handles data transmissions between the SICs and the DAU. SIC to SMC communications are conducted on an electrical bus within the SPU. A fiber-optic transceiver on the SMC provides an interface to the DAU. Except for power supply lines, the only penetrations through the SPU enclosure are optical; one fiber going to each sensor plus the fibers required for telemetry to the DAU.

Fiber-optic telemetry is discussed in Section 6. The SIC and SMC circuits are described below.

5.4. Sensor Interface Controller

5.4.1. Sensor Interface Controller Design

A block diagram of the Sensor Interface Controller (SIC) is shown in Figure 5.4-1. The SIC supports two sensors. Dual optical modules (described in Section 4) with associated LED drivers and photodetector amplifiers provide light to the sensors and process the optical signals returned from them. The LEDs are under the direct and individual control of the microprocessor so that there is a flexibility in their timing, sequencing, etc. Optical signals from the two sensors are multiplexed to an A/D converter, also under microprocessor control. Microprocessor determines the value of the measures parameter, e.g. pressure, as indicated by optical signals. Measurement data is then transmitted as appropriate over an internal SPU data bus to the Sensor Management Controller (SMC). An RS-232 output for each SIC is available for a local indication of the sensor reading or can be used to test the sensor and controller for proper operation.

5.4.2. Sensor Interface Controller Operation

The operation of the SIC is determined by the firmware which the microprocessor executes. Thus the operation varies according to the type of sensor being used and the physical parameter being measured.

5.4.2.1. Operation for Low Frequency Continuous Range Measurements

Low frequency continuous range measurements include pressure, temperature and linear displacement. The required frequency response for these sensors extend to approximately 20 Hz. Operation of the SIC for these types of signals is as follows.

Interrupt driven microprocessor routines control the LEDs and record signal values in the following sequence. Two separate routines are alternately executed at each interruption of the controllers microprocessor.

At an interrupt the microprocessor does the following:

Record channel 0, k1 LED signal (reference)
Turn channel 0, k1 LED off
Turn channel 0, k2 LED on

Record channel 1, k1 LED signal (reference)
Turn channel 1, k1 LED off
Turn channel 1, k2 LED on

At alternate interrupts the microprocessor does the following:

Record channel 0, k2 LED signal (measure)
Turn channel 0, k2 LED off
Turn channel 0, k1 LED on

Record channel 1, k2 LED signal (measure)
Turn channel 1, k2 LED off
Turn channel 1, k1 LED on

The interrupts are triggered by a system clock. For pressure and temperature measurements they occur every 1 ms. At this sampling rate a set of reference and measure values is obtained every 2 ms. This is sufficient to capture parameter signals with frequencies up to 100 Hz, thus exceeds the system requirements.

As its foreground task the microprocessor analyzes the optical signals to determine the value of the parameter measured by the sensor, e.g. the applied pressure. This will be done using a numerical model which calculates the value of the parameter from the recorded measure and reference signals. The model may be specific to the particular sensor type (e.g. pressure or temperature) and will require ZERO and SPAN calibration values to define it completely. The ZERO and SPAN operations will be similar to those performed with sensors currently in use.

5.4.2.2. Controller Calibration for Pressure and Temperature Sensors

The procedure for system calibration will be developed during Phase II of this project.

5.4.2.3. Operation for High Frequency Continuous Range Measurements

Some measurements require sampling rates greater than the 100 Hz possible with the technique described above. Mechanical vibrations and shaft speed are two examples. In order to make these measurements, the SIC is programmed (in firmware) for another mode of operation wherein the LEDs are left on for longer periods of time while the photodetector output is repeatedly sampled at a high rate. The relative length of time that the reference and signal LEDs are left on is determined by the particular measurement being made and the signal processing algorithm being employed. Signals with frequencies up to 10 KHZ can be measured in this way.

5.4.2.4. Operation for Discrete Range Measurements

The signal processing necessary to detect discrete switch closures will be far simpler than that necessary for other sensors. It essentially is a comparison of the attenuation-compensated optical signal with a preprogrammed set point to determine the state (on, off, or fault) of the discrete sensor.

5.4.2.5. Built-in Test Functions

The microprocessor in the sensor controller is programmed to detect several fault conditions that might occur during operation of sensor system. These tests are carried out either upon power-up of the controller or at regular intervals during its normal operation, depending in the nature of the test. Built-in test functions capable of detecting the following failure modes have been demonstrated on a developmental sensor controller circuit.

- Analog-to-Digital convertor failure
- Programmable gain and multiplexing amplifier failure
- LED failure

- o Photodetection circuitry failure
- o Fiber-optic cable failure

Fault conditions, when detected, are reported to the appropriate ships equipment. This can be done either through an immediate transmission of a error message or in response to a status inquiry. The system can also be designed to indicate fault conditions at the controller itself through the use of, for example, LEDs visible to service personnel.

5.4.2.6. Design Alternatives

Several alternatives to the current SIC design are being considered. These design changes have the potential for reducing the cost and increasing the application flexibility of the sensor system. Alternatives being considered include the following.

- o Changing the number of sensors per SIC card from two to four or one. Having more sensors per card might decrease the per-sensor cost of the SIC. Having a single sensor per card would decrease the card size and reduce the per-card replacement cost.
- o Using custom integrated or hybrid circuitry. This would reduce the system size, cost, and power requirements.
- o Alternative schemes for the transmission of data from the SIC to SMC equivalent circuitry are being considered.

5.4.2.7. Technical Risks and Alternatives

The SIC makes use of fully developed electronic technologies. Therefore there are no unaddressed technical difficulties expected in either its development or use.

5.5. Sensor Management Controller

5.5.1. Sensor Management Controller Design

The Sensor Management Controller provides a single interface between the SPU with its multiple SICs and the ships Data Acquisition Unit (DAU).

The SMC has not yet been designed. Its function is extremely straight forward and will be easily implemented using standard digital and fiber-optic telemetry designs and components.

A block diagram of the SMC is shown in Figure 5.5-1. The SMC consists basically of an interface to the local SPU bus, an interface to the sensor systems fiber-optic data telemetry bus, and microprocessor circuitry to execute the required data transfers.

5.5.2. Sensor Management Controller Operation

The microprocessor based Sensor Management Controller (SMC) is firmware programmed to poll the SICs within the SPU as required to obtain measurement data. This data is then transmitted as appropriate over fiber-optic data lines to the DAU. "As appropriate" implies that the interface circuitry is capable of responding to specific requests from the DAU for measurement status or data. Potential requests include the following.

- Current measurement for a specific sensor.
- Average of measurements sensor since last average value request.
- Maximum or minimum measurements
- Status of all measured values with respect to formerly defined set points.
- SIC, SMC, or SPU status

Application flexibility is designed into the interface card so that operational changes can be implemented by a change in the firmware executed by the microprocessor.

5.5.3. Design Alternatives

The principle alternatives to be considered in the SMC design have to do with the two data busses to be implemented; the internal SPU bus and the fiber-optic data telemetry bus. Fiber-optic telemetry is discussed in Section 6. Options for the SPU bus include a parallel Multibus protocol or a serial point-to-point connection between the SMC and each of the SICs using the RS-232 protocol.

5.5.4. Technical Risks and Alternatives

Because the SMC makes use of fully developed technologies, there is no significant risks associated with its development.

6. TELEMETRY SYSTEM DESIGN

This section briefly outlines the telemetry design developed for the improved fiber-optic sensor system.

6.1. Requirements and Specifications

The general and detailed specifications to be met by the telemetry system will be determined (or developed as required) during Phase II of this project.

6.2. Telemetry System Design Overview

The Shaft Control Unit (SCU) portion of the propulsion control system is used as the baseline for this design. These units are integral parts of the typical Machinery Control System (MCS) used aboard recent US Navy ships. The DDG-51 is a good example of a MCS which uses a distributed control philosophy where the various control consoles are interconnected by a redundant high-speed serial data bus. The specific bus used aboard the DDG-51 is referred to as the Data Multiplexing System (DMS), but a more generic term for this concept is a Data Transfer Network (DTN).

Figure 6.3-1 shows an example of a MCS implemented with a generic DTN. The DTN also provides an interface to other shipboard DTNs such as those which might be used in the navigation system or the weapons system. In this figure, the SCUs provide the middle to low levels of control for the engines and power train. Each SCU provides an interface to a single shaft and propeller; two LM2500 gas turbine engines which drive the shaft; and most of the associated auxiliary equipment.

An example of a fiber-optic sensor bus implementation for the SCU is shown in Figure 6.3-2. Table 6.3-1 lists the types of subsystems supported by each SCU in the DDG-51 and the number of sensors associated with each.

Table 6.3-1. Subsystems Within a Typical SCU

Subsystem	Acronym	No. of Sensors
Propulsion Engines	PE	88
Power Train	PT	53
Lube Oil	LO	33
Fuel Oil	FO	28
Bleed Air	BA	12
Fresh Water	FW	12
Compressed Air	CA	10
Sea Water	SW	9
Air Conditioning	AC	6
Waste System	WS	5
Fire Main	FM	4
Total		260

In this example, the sensor interface is provided by the SCU. Alternate configurations use a Data Acquisition Unit (DAU) to accumulate the sensor data and transfer the data to the MCS bus. Each DAU might have a similar mix and quantity of sensors, depending upon the type of machinery at its interface.

Some of the consoles shown in Figure 6.3-1 only perform sensor I/O while others only process data from the DTN. Other consoles do both. For those consoles which perform direct sensor I/O and for the Data Acquisition Units (DAU), a local fiber-optic sensor telemetry link is used to simplify and organize the interface to the sensors. Figure 6.3-3 shows a generic arrangement for a sensor telemetry system which utilizes a fiber-optic sensor bus for gathering and distributing data from both fiber-optic and electrical sensors. This type of arrangement could be used with an SCU, DAU, or other console. Sensor Processing Units (SPU) process the optical sensor data into an optical serial bit stream which is transferred to the DAU or console via the Fiber-Optic Sensor Bus.

Each fiber-optic sensor is connected to a sensor controller card located either in the SPU or directly in the DAU or console. In addition, existing electrical sensors may be locally converted into fiber-optic signals and subsequently treated as a normal fiber-optic sensor input. Any sensors which connect directly to the DAU or console are not part of the fiber-optic sensor bus. The DAU or console is responsible for controlling the communications to and from the SPUs in a deterministic communications scheme.

As shown in Figure 6.3-2 the basic configuration for the fiber-optic sensor bus utilizes a dual-redundant counter-rotating ring implementation. Dual redundancy was selected due to cost and size constraints but higher levels of redundancy are possible. This type of bus configuration is fault tolerant in that single-point failures in any of the components will not cause degradation in the operation of the system. Further details on this implementation is provided in Section 6.6.1.

6.3. <u>Telemetry System Interfaces</u>

6.3.1. Sensor Processing Unit Interfaces

6.3.1.1. Sensor Input Interface

The SPU is designed to provide an interface for up to 16 fiber-optic sensors, each of which requires at least one dedicated fiber-optic cable to perform the actual measurement.

6.3.1.2. Primary Input Power Interface

The primary input power to each SPU is 115 VAC, 60 Hz, three-phase provided by the ship service generators. Suitable isolation and filtration will be provided which conforms to the requirements of DOD-STD-1399 Section 300.

6.3.1.3. Backup Power Interface

In order to save space in the SPU, backup power in the form of 155 VDC will be provided by the DAU or console. A suitable switching network will be provided within the SPU to enable the DC voltage in the event of a loss of the primary input power.

6.3.1.4. Fiber-Optic Sensor Bus Interface

The interface to the sensor bus consists of two (or more) electro-optical bus transceivers designed to interface to a redundant counter-rotating fiber-optic ring bus. Under normal operating conditions, only one ring will be active at any given time. The optical signal enters the transceiver through an optical to electrical converter. The message is then repeated electronically and re-transmitted through an electrical to optical converter back onto the bus. The repeater function is typically part of the bus transceiver device but may be part of the sensor bus interface card. For fault tolerance, the bus transceiver should remain powered on when the SPU is down for any reason.

Alternate designs provide an optical bypass in the event the electronics within the transceiver fail. While this alternative has merit, the losses due to the bypass must be considered in the overall optical budget. These losses will decrease the maximum number of nodes on the bus.

6.3.2. Console Interface

6.3.2.1. Backup Power Interface

The console will constantly provide 155 VDC backup power to each SPU. Adequate power will be available to allow full operation of the SPUs for a minimum of 30 minutes.

6.3.2.2. Fiber-Optic Sensor Bus Interface

The interface at the DAU or console consists of the same electro-optical interface used in the SPUs. The commonalty only applies to the bus interface hardware. The hardware and software used to implement the communications protocol will be different for the DAU or console and the SPUs.

6.3.2.3. Console Processor Interface

Once the incoming data is converted from optical format to electrical, the data is stored in common memory until processed by the main computer in the DAU or console. Since the data is processed on a cyclic basis, data from each SPU is stored once per cycle for use during the next processing frame. The specific implementation of the interface to the main computer in the DAU or console is dependent upon the type of computer used. For instance, if the AN/UYK-44 computer is used, the NTDS-FAST interface is a possible choice.

6.4. Telemetry Subsystem Requirements

6.4.1. Sensor Processing Unit Requirements

6.4.1.1. Sensor Controller Cards

The current design of each sensor controller card allows up to two reflection-type fiber-optic sensors to be used.

6.4.1.2. Sensor Management Controller Card

The sensor management controller accumulates the data from up to eight sensor controller cards for a total of 16 fiber-optic sensors. In addition, this card handles the top-level protocol for communications with the DAU or console across the fiber-optic sensor bus. The electrical to optical interface may reside on this card or it may be located elsewhere in the cabinet, depending upon the specific hardware available during the detailed design phase.

6.4.1.3. Logic Assembly

The logic assembly holds all of the cards necessary to process up to 16 fiber-optic sensors and perform communications with the fiber-optic sensor bus. Card spacing and orientation will be such that conventional convection cooling may be used. However, if the reliability analysis shows that convection cooling is not adequate, the use of forced air cooling will be considered. Spare slots will be provided to allow future expansion.

6.4.1.4. Power Supplies

US Navy Standard Power Supplies conforming to NAVSEA SE 010-AA-SPN-010 will be used in a redundant configuration. The primary input power will be 115 VAC, 60 Hz, three-phase with 155 VDC backup power for a minimum of 30 minutes.

6.4.1.5. Cabinet

The cabinet for the SPU is intended to be deck mounted in a centralized location relative to the sensors which it controls. Aside from the primary and backup power inputs, all signal ingress and egress for the cabinet will be by means of fiber-optic cable. All fiber-optic connections will occur within the enclosure. Environmentally sealed orifices will be provided with strain relief where the cable passes through the cabinet. The fiber-optic connectors will be positioned for maximum accessibility.

Rigid doors or panels will be provided for easy access to the electronics and connectors. Louvers will be provided to allow convection or forced air cooling.

6.4.2. Console Requirements

6.4.2.1. Backup Power

Backup power for the SPUs in the form of 155 VDC +/- 30% will be provided by the console. Adequate power will be available to allow full operation of the SPUs for a minimum of 30 minutes after the loss of the primary AC power.

6.4.2.2. Fiber-Optic Sensor Bus Interface

A minimum of two redundant bus connections will be available for communications to the SPUs. Failure of the SPU will not cause the degradation of the fiber-optic sensor bus. However, power must remain available to the bus transceiver circuitry in the event of a SPU failure.

Each message on the bus will be either electrically repeated or optically bypassed as it passes through the bus transceiver. Electrical repeater circuitry is preferred since no optical power losses are incurred in passing through the bus transceiver. However, in smaller systems, optical bypassing may be a valid approach.

6.4.3. Interconnection Requirements

6.4.3.1. Fiber-Optic Cable

The fiber-optic cable used to interconnect the individual nodes on the fiber-optic sensor bus shall conform to the requirements of PMS-400-XYZ-1 for shipboard fiber-optic cable.

6.4.3.2. Connectors

Fiber-optic connectors shall meet the applicable requirements.

6.4.3.3. Installation

The installation requirements for fiber-optic cable differ somewhat from electrical cable. For example, the bend radius and tensile loads during cable pulling operations must not exceed the capability of the cable. One-hundred meter lengths of fiber-optic cables conforming to PMS-400-XYZ-1 should have the capability of being pulled 90 degrees over a sheave with a minimum radius of five times the finished cable diameter at a rate of 30 feet per minute with a tensile load of 175 pounds per inch of diameter maximum. Any increases in attenuation referenced to its initial value will not exceed 0.5 db for cables conforming to the above specification.

6.5. Fiber-Optic Telemetry Design

The following sections describe three possible implementations for the fiber-optic telemetry link. Included are descriptions on ring bus, star network, and a point to point implementations.

6.5.1. Ring Bus Implementation

The preferred method of communications between the SPUs and the DAU console is the ring bus. For the purpose of describing the ring bus operation and failure modes, the DAU or console is referred to as the Bus Controller (BC) and the individual SPUs are referred to as Data Terminals (DT).

The basic operation of a fiber-optic ring bus consists of two or more devices which transmit and receive all messages on a series of single fiber point-to-point optical cables. Only one device is permitted to transmit data on the bus at any given time in order to prevent message collisions. A common technique used to prevent message collisions utilizes a deterministic communications protocol. In a deterministic system, a single BC decides which DT will transmit data at any given time. Messages may be sent to or received from individual DTs, or messages may be sent from one DT to another. Redundancy is implemented in the form of multiple parallel rings for the bus and a backup or secondary BC in the event of a failure in that area. Redundant rings are usually implemented in a counter-rotating scheme where one ring transmits data in a clockwise direction with respect to the BC, and the other ring transmits data in a counter-clockwise direction.

The normal operation of the ring bus uses the primary ring for all communications. The following failure modes are examples of the types of failures expected in a ring bus.

- o In the case of a single point cable break in the primary ring or a single point interface circuit failure in either the BC or the RTs, the BC simply reconfigures the system to communicate on the secondary bus.

- In cases where an the RT ceases to operate entirely, or both cables break at the same point, the BC reconfigures the system to transmit and receive on alternate rings as required by the location of the fault. As an example, suppose that both the primary and secondary cables break between RT #3 and RT #4 in Figure 6.6-1. The BC, upon detecting and analyzing the fault, commands RTs #1,2, and 3 to receive on the secondary ring and transmit on the primary ring. RT #4 is commanded to receive on the primary ring and to transmit on the secondary ring. Figure 6.6-2 shows an example of the switching network required to implement this approach.

The expansion capability of the a ring system is limited primarily by the processing time required to process all nodes on the ring. This parameter plus the maximum transmission rate, number of parameters per message, and the overhead per message are required before determining the maximum capability of the bus. Appendix B provides a complete analysis for a system with a maximum data transmission rate of 375 K-bits per second, a maximum of 19 16-bit words per message (16 sensors plus overhead), and a total message transfer time of approximately 1.4 milliseconds. With such a system, up to 69 SPUs may be serviced in a typical 100 millisecond data frame resulting in the processing of up to 1104 sensors.

The above numbers represent the absolute maximum number of sensors based on data rate. In reality, the number of SPUs and sensors should be less in order to allow time for the transmission of command messages, fault processing, and other overhead functions. If 30_% of the frame is reserved for overhead functions, and 20_% is reserved for spare, the frame time is effectively half, or for the example, 50 milliseconds. Therefore, the maximum number of SPUs is 34 for a maximum sensor count of 544.

6.5.2. Star Implementation

A fiber-optic star multiplexer is a device which combines the light from one of N input fibers onto one or more output fibers. Stars typically operate in both directions, where one or more sources may transmit to N destinations while each of the N destinations may, in turn, transmit to one or more sources. In a deterministic system, the source is the BC described in section 6.6.1 and the destinations are the RTs. Stars work well in deterministic systems because only one RT will ever transmit at any given time. Figure 6.6-3 shows an example of a simple redundant star network using 4x4 star multiplexers.

A passive star network utilizes star multiplexers which simply combine the fibers from the multiple inputs to one or more output fibers. The losses incurred in the multiplexer must be considered in the overall optical budget. These losses may become excessive if multiple stars are used in series, resulting in the need for more sensitive receivers. An active star network is less susceptible to losses because each star boosts the optical signal prior to re-transmission. Power is therefore required at each star in the network.

Star networks have specific limitations such as a maximum of two levels of multiplexing and an unexpandable number of sensors for a given size star multiplexer. Only two levels of multiplexing are possible due to the recombination of signal paths above the second level. Assuming the maximum sensor count per SPU is 16 and the maximum number of inputs per star is (N), the following formulas apply:

Max SPUs = N**2 / 2 (N even)

or

Max SPUs = ((N**2 - N) / 2) + 1 (N odd).

Therefore,

Max Sensors = Max SPUs * 16

and

Number of Stars = N + 2 (N even)

or

Number of Stars = N + 1 (N odd).

The above formulas only apply to systems where each star is the same size. Table 6.6-1 applies these formulas to various star sizes.

Table 6.6-1. Star Network Size (All Stars Same Size)

No. Inputs	No. SPUs	No. Stars	Max No. Sensors
2	2	2	32
3	4	4	64
4	8	6	128
5	11	6	176
6	18	8	288
7	22	8	352
8	32	10	512
16	128	18	2048
32	512	34	8192

For systems where the second level of star multiplexers have twice as many inputs as the first level (up to a maximum of 32 inputs), the number of SPUs and sensors per system is shown in Table 6.6-2.

Table 6.6-2. Star Network Size (Different Sized Stars)

No. Inputs Level 1	No. Inputs Level 2	No. SPUs	Max No. Sensors
2	4	4	64
3	6	9	144
4	8	16	256
5	10	25	320
6	12	36	384
7	14	49	448
8	16	64	512
16	32	256	4096
32	32	1024	8192

In addition to the need for intermediate multiplexers, the star network requires additional optical hardware at each node. Since each node must transmit and receive using a single fiber, an optical Y-tap is required to couple the light from the fiber into the optical detector and from the optical transmitter into the fiber. The optical losses incurred through the use of the Y-tap must be considered in the overall optical power budget.

6.5.3. Point-to-Point Implementation

The above systems all utilize bus and multiplexing techniques to simplify and organize the sensor to controller interface. In a point to point system, the multiple sensor output from the SPU is transferred directly into the DAU or console as shown in Figure 6.6-4. Each input is handled separately by the main CPU or by independent sensor input controllers. If the main CPU is used for communications, the overhead needed to process the incoming data may become too great. If this is the case, the use of independent sensor controllers may be used to reduce this overhead.

Implementation of a point to point system may be accomplished with a single fiber-optic cable and Y-splitters at each end. Data transmission occures bi-directionally in this case. Alternate designs use a dual cable configuration with separate circuits for transmit and receive. This case is feasible if the cost of a dual cable is less than the cost of a single cable and the Y-splitters.

In order for a point to point system to be feasible for systems with large number of sensors, each SPU would need to handle more sensors than the present design allows. This would reduce the number of fiber-optic inputs to the console.

6.6. Technical Risks and Alternatives

Technical risks present in the proposed telemetry design will be identified and evaluated during the detailed design phase of this project. Alternate telemetry schemes to be considered include a ring network, a star network, and point-to-point fiber optic links for each local sensor multiplexer.

7. DESIGN ANALYSIS

7.1. Sensor Cost Analysis

A comparison of the system cost for conventional and fiber-optic sensors uses the cost models shown in Figures 7.1-1 and 7.1-2. The conventional system consist of the transducer itself, electrical cabling, and the electrical circuitry necessary to power the transducer and to condition the signals received from it. The circuitry needed to input the conditioned sensor signal to the SCU or DAU microprocessor is not included in the cost model. Cost data on conventional systems were obtained through GE/SCSD.

The fiber-optic system consists of the sensor, fiber-optic cable, and the SIC electronics. Because the SIC serves two fiber-optic sensors, only half its cost is included in the per-sensor cost estimation. The cost of the DAU, which corresponds to the interface electronics excluded from the conventional system model, are not included in the cost estimate for the fiber-optic system. Cost data for the fiber-optic sensor, cable, and SIC were estimated by OPTECH and are based on recent vendor proposals.

A summary of cost data is presented in Table 7.1-1. There it is seen that the fiber-optic system both increases and decreases the cost of interfaces and cables, depending on the particular sensor being considered. The cost of the actual sensors, however, is universally and substantially decreased.

Detailed backup data for conventional sensor costs are presented in Appendix E. Data on telemetry link hardware costs are also presented there.

Table 7.1-1. Sensor System Cost Summary

		Transducer Cost ($)		Interface Cost ($)	
Sensor Type	Qty	Current	Fiber-Optic	Current	Fiber-Optic
Speed	5	1568	50	1936	970
Temperature (RTD)	45	317	65	749	970
Temperature (TC)	2	120	65	2838	970
Pressure (g)	14	608	150	418	970
Pressure (a)	6	150	150	418	970
Pressure (d)	6	1020	300	418	970
TOTAL EXTENDED COST		40625	8105	59929	75660
AVERAGE COST PER SENSOR		520	104	768	970

7.2. Telemetry System Cost Comparison

7.2.1. Telemetry Hardware

The following data is used to determine the relationship between cost and the total number of nodes for the following three telemetry systems.

- o Ring Bus
- o Star Network
- o Point to Point

In order to provide an accurate comparison of the three systems a model must be developed for each system. Figures 6.6-1, 6.6-3, and 6.6-4 show the basic configurations for the three systems. Figure 7.2-1 shows the models used for the three configurations and the type of equipment needed for each implementation. The equipment and costs used in the analysis are listed in Table 7.2-1. Since the costs are based on currently available industrial equipment the data has been normalized to allow comparisons to future military systems.

Table 7.2-1. Required Hardware for Cost Comparisons

Item	Cost ($)	Normalized Cost
32x32 Star Mux	8495	1.000
16x16 Star Mux	4395	0.518
8x8 Star Mux	2300	0.271
4x4 Star Mux	1300	0.153
Y-Splitter (1)	200	0.200
Serial I/O Board (2)	500	0.500
Connector (3)	50	0.050

Notes:
(1) The cost for the Y-splitter is an estimate. Included is the cost of a permanent installation onto an I/O card.
(2) The serial I/O card is an industrially available stand-alone card for speeds up to 375 Kbaud. An electrical to optical interface is included in the estimated cost.
(3) The connector cost includes nominal labor cost for factory installation onto prefabricated cable.

The following assumptions have been made to allow equal comparisons among the three systems.

- The serial card for each system is a stand-alone interface with a microcontroller to handle the serial protocol. The hardware for the primary I/O card and each secondary I/O card are equivalent.
- The star network is implemented using two levels of optical multiplexing. The first level only uses 4x4 optical multiplexers and the second level uses different size multiplexers for each configuration. For the four node system the second level of multiplexing is not used.
- The point to point and star networks use a Y-splitter to allow the use of a single optical fiber for the bi-directional communications.

Table 7.2-2 itemizes the total number of devices needed to implement each network using duplex redundancy. Data have been accumulated for systems with four to 64 nodes.

Table 7.2-2. Equipment Quantities

Type	Nodes	BC	RT	CON	Y	4x4	8x8	16x16	32x32
Ring	4	2	8	20	0	0	0	0	0
	8	2	16	36	0	0	0	0	0
	16	2	32	68	0	0	0	0	0
	32	2	64	132	0	0	0	0	0
	64	2	128	260	0	0	0	0	0
Star	4	2	8	18	6	2	0	0	0
	8	2	16	50	10	6	0	0	0
	16	2	32	98	18	8	2	0	0
	32	2	64	194	34	16	0	2	0
	64	2	128	386	66	32	0	0	2
P-P	4	8	6	16	16	0	0	0	0
	8	16	16	32	32	0	0	0	0
	16	32	32	64	64	0	0	0	0
	32	64	64	128	128	0	0	0	0
	64	128	128	256	256	0	0	0	0

Applying the cost data from Table 7.2-2 to Table 7.2-1 gives the normalized equipment data shown in Table 7.2-3. The data are graphically represented in Figure 7.2-2.

Table 7.2-3. Normalized Equipment Cost Data

Nodes	Ring	Star	Point to Point
4	0.03125	0.05052	0.05729
8	0.05625	0.11094	0.12500
16	0.10625	0.21094	0.25000
32	0.20625	0.41198	0.05000
64	0.40625	0.81302	1.00000

7.2.2. Cable Length Comparisons

In order to perform a valid comparison of the relative cable lengths of the three telemetry configurations, the following assumptions must be made.

- All nodes are the same distance from each other.
- All nodes are equidistant from the DAU or console. This distance is assumed to be equal to one.

- Each configuration is implemented over the same area. For example, the four node system and the 16 node system both cover the same area such that the distance between the nodes is smaller for the 16 node system.
- Only the cable lengths for the telemetry system are considered. Not included are the cable lengths from the node to the sensor.
- For the star network four nodes are located equidistant from the second level multiplexer and each multiplexer is located a unit distance from the DAU or console. Also, the distance from the nodes to the second level multiplexer is equivalent to the distance between the nodes on the ring bus system.
- For the star network the distance from the first level multiplexer to the DAU or console is negligible.

Figure 7.2-3 graphically depicts the configuration of a 16 node system for each of the three network systems. The relative total cable lengths for each of the three configurations are shown in Table 7.2-4. Normalization of the data in Table 7.2-5 produces the normalized cable data listed in Table 7.2-5 and depicted graphically in Figure 7.2-4.

Table 7.2-4. Relative Cable Lengths

Nodes per	Inter-Node	Relative Cable Length		
System	Distance	Ring	Star	P-P
4	1.4142	6.24	5.66	4.00
8	0.7654	7.36	8.12	8.00
16	0.3902	7.85	10.24	16.00
32	0.1960	8.08	14.27	32.00
64	0.0981	8.18	22.28	64.00

Table 7.2-5. Normalized Cable Length Comparison

Nodes	Ring	Star	P-P
4	0.0975	0.0884	0.0625
8	0.1150	0.1269	0.1250
16	0.1227	0.1600	0.2500
32	0.1262	0.2230	0.5000
64	0.1279	0.3481	1.0000

7.3. **Reliability Analysis**

A formal reliability analysis for the mechanical and electrical hardware designed under this project is not yet available. A circuit analysis will be performed in the Phase II of this project.

8. FUTURE PLANS

During the System Design Review conducted at the conclusion of Phase I of this project, comments made by NRL personnel indicated the following.

- OPTECH should concentrate on the development of fiber-optic sensors.
- Telemetry of the type described in Section 6 of this report should not be considered in detail nor implemented in the hardware models to be fabricated under this project.
- The contractual requirements for data telemetry are satisfied by the transmission of analog optical signals from the fiber-optic sensor to the Sensor Interface Controller.
- The contractual requirements for an interface between the sensor system and ship's equipment are satisfied by an RS-232 output from the Sensor Processing Unit.

These clarifications have caused OPTECH to greatly reduce GE/SCSD's involvement in Phases II, III, and IV of this project and restructure the program with more emphasis on sensors.

8.1. **Phase II Plans**

8.1.1. Detailed Design

Detailed designs will be developed for the following components of the fiber-optic engineering sensor system.

- Pressure Sensor
- Temperature Sensor
- RPM (Gear Speed) Sensor
- Sensor Interface Controller
- Sensor Management Controller

8.1.2. Laboratory Demonstration

A Laboratory Demonstration Model (LDM) for the fiber-optic engineering sensor system will be fabricated, tested, and demonstrated to NRL personnel. The LDM, illustrated in Figure 8.1-1, will consist of the following.

- o Two Fiber-Optic Pressure Sensors
- o One Sensor Interface Controller
- o Data Display and Recording Equipment
- o Conventional Sensors for Comparison

The display and recording equipment will be based on an IBM PC.

The LDM will be fabricated of existing materials owned by OPTECH, thus making it a nondeliverable item. This will conserve both time and project money.

8.1.3. Documentation

Documentation generated in accordance with contractual requirements will include the following.

- o System Specification
- o Level 1 Drawings for the LDM
- o Operating Instructions for the LDM
- o Management Plan
- o System Test Plan
- o Level 3 Work Breakdown Structure

8.2. Phase III Plans

8.2.1. Design

Revised designs for the fiber-optic engineering sensor system based upon the LDM design and incorporating change requirements identified during Phase II testing and review will be developed.

8.2.2. Fabrication and Testing

An Advanced Development Model (ADM) of the fiber-optic engineering system will be fabricated and tested at the OPTECH facility. The ADM, illustrated in Figure 8.2-1, will consist of the following.

- Pressure Sensors
- Temperature Sensors
- Two Sensor Processing Units
- Eight Sensor Interface Controllers
- Two Sensor Management Controllers
- Data Display and Recording Equipment

Because the testing of the ADM will be performed at OPTECH, the display and recording equipment used in Phase II will also be used in Phase III.

8.2.3. Documentation

Documentation generated in accordance with contractual requirements will include the following.

- Critical Item Development Specification
- Program Management Plan
- System Test Procedure
- Configuration Management Plan
- Electromagnetic Compatibility Plan

8.3. Phase IV Plans

8.3.1. Design Update

Any required design changes identified during Phase II testing and review will be completed.

8.3.2. System Modification

Any modification of the ADM required in accordance with the design revision will be completed. The resulting hardware will be designated the Engineering Development Model (EDM).

8.3.3. Testing

The EDM will be tested aboard a Navy platform identified by NRL. OPTECH will recommend that this testing be carried out at a land based test site operated by NAVSSES in Philadelphia.

8.3.4. Documentation

Documentation generated in accordance with contractual requirements will include the following.

- o Critical Item Product Specification
- o Level 2 Drawings
- o Configuration Management Plan
- o Integrated Logistics Support Plan
- o Program Management Plan
- o System Test Procedures
- o Electromagnetic Compatibility Plan

9. CONCLUSIONS

The fiber-optic sensor system presented in this report addresses many of the shipboard measurement requirements of the U.S. Navy. The system provides a universal interface between a wide variety of sensors and existing ship's equipment. The simplicity of the fiber-optic sensors and the flexibility of the sensor interface circuitry promise a reliable, cost effective, and widely applicable sensor system.

The machinery control philosophy for machinery control systems aboard U.S. Navy ships has previously been limited to top-level systems such as propulsion, electric plant, and auxiliary control systems. Below that level the sensor processing and data telemetry has been centralized. The use of fiber-optic telemetry of sensor data from Sensor Processing Units to the ship's consoles extends this distributed control philosophy to this lower level.

10. REFERENCES

Lewis, Richard M., "Application of Fiber Optics in Marine Vessel Engine Rooms," Marine Propulsion Technology Conference, Washington, D.C., May 12-14, 1986.

Lockheed Shipbuilding and Construction Company, DDGX Producibility Study. Surface Combatant Data Bank NAVSEA 03D3, 1981.

Todd Pacific Shipyards Corporation, DDGX Producibility Study. Los Angeles Division, 1982.

11. APPENDIX A - DDG-51 SENSOR REQUIREMENTS

Table 11.0-1. Sensor Inputs to DDG-51 SCU

Sensor Type	Sensor Range	Qty	Interface
Speed	0 to 5,000 RPM	2	0-10V
	0 to 12,000 RPM	2	0-10V
	0 to 200 RPM	1	Frequency
Temperature (RTD)			
	-40 To 150°F	2	0-10V
	-40 To 260°F	28	RTD
	-40 To 500°F	2	RTD
	0 To 160°F	1	RTD
	0 To 300°F	2	RTD
	0 To 400°F	10	RTD
Temperature (Thermocouple)			
	0 To 2,000°F	2	Thermocouple
Torque			
	0 To 2,000,000 Ft-Lbs	1	4-20ma
Liquid Level		2	Variable Resistance
		2	4-20ma
Linear Displacement		4	LVDT
Angular Displacement		2	0-10V
		1	Variable Resistance
Pressure			
	0 To 16 psia	2	0-10V
	0 To 30 psig	1	4-20ma
	0 To 60 psig	3	4-20ma
	0 To 60 psid	6	4-20ma
	0 To 75 psia	2	0-10V
	0 To 100 psig	1	0-10V
	0 To 300 psia	2	0-10V
	0 To 300 psig	6	4-20ma
	0 To 1,500 psig	2	0-10V
	0 To 6,000 psig	1	4-20ma
Discrete Measurements (Pressure/Temp/Other)		3	0-10V
		157	Contact Closure
		12	Tri-Level
TOTAL		262	

Table 11.0-2. Interface Circuit Requirements of the DDG-51 SCU

Interface Type	Number of Circuit Boards
0-10v	17
4-20ma	20
RTD	43
Thermocouple	2
Frequency	1
Contact Closure	157
0/10V	3
Tri-level	12
Variable Rsistance	3
LVDT	4
TOTAL	262

Table 11.0-3. Pressure Monitoring System Specifications

Static Error	± 1% full scale (f.s.)
Repeatability	0.5% f.s.
Threshold/Deadband	Less than 0.2% f.s.
Ripple	Less than 0.15% f.s.
Warmup Time	Less than 30 min.
Temperature Coefficient	Less than 0.02% f.s./°C
Pressure Ranges	0-15 psi to 0-6000 psi
Over Pressure	200% for 1 hour
Frequency Response	0.01-20 Hz, ± 0.5 db

Table 11.0-4. Temperature Monitoring System Specifications

Accuracy	± 2% full scale (f.s.)
Ripple	0.15% full scale
Warmup Time	Less than 30 min
Ambient Temperature Error	0.1% f.s. per °F
Temperature Ranges	-40 - 260°F to 0 - 1000°F
Response Time	3 seconds to reach ± 2% of reading after a change of 10% to 90% full scale temperature.

12. APPENDIX B - RING BUS THROUGHPUT ANALYSIS

Throughput Analysis using the 8751 Microcontroller

12.1. 8751 Background

The M8751 is the EPROM version of the M8051 family of microcontrollers manufactured by the Intel Corporation. The devices are manufactured in military temperature ranges and are currently DESC qualified (Defense Electronics Supply Center). The following features are all integrated into a single 40-pin DIP or LCC package:

- 8-bit microprocessor
- Programmable full duplex serial port
- 4K bytes UV-EPROM
- 128 bytes RAM
- 32 discrete I/O lines
- 2 16-bit timer/counters
- 5 interrupts with 2 levels
- Hardware multiply and divide
- Boolean processor with bit-addressable RAM
- operation up to 12 MHz

The 8751 serial port operates in one of the following four modes:

- Mode 0 - 8-bit communications baud rate fixed at the oscillator frequency divided by 12 for a maximum baud rate of 1 MHz.

- Mode 1 - 10-bit communications with programmable baud rates up to a maximum of 62.5 KHz.

- Mode 2 - 11-bit interprocessor communications with a baud rate fixed at the oscillator frequency divided by either 32 or 64 for a maximum baud rate of 375 KHz.

- Mode 3 - 11-bit interprocessor communications with programmable baud rate up to a maximum of 62.5 KHz .and list

Mode 2 seems to the best suited for a bus application due to the use of a 9th bit attached to each byte. When the master controller sends an address message across the bus, the 9th bit is set to a 1. Each slave controller is interrupted in order to decode the address of the message. One slave then prepares for the data which is sent with the 9th bit set to a 0. The other slaves automatically ignore any messages where the 9th bit is a 0.

12.2. Throughput Analysis

The maximum baud rate in mode 2 is 375 KHz when a 12 MHz crystal is used. for an 11-bit transmission, the following formula holds:

$$\frac{375\ \text{K-bits}}{\text{sec}} * \frac{1\ \text{Byte}}{11\ \text{bits}} = 34.1\ \text{K-Bytes/sec.}$$

This may be converted to the transmission time for each byte:

Transmission Time = 29.3 microseconds/Byte.

The following is an example of one protocol which may be used by the DAU or console to request data from one of the Sensor Processing Units (SPU). The protocol is similar to that used by MIL-STD-1553B. The maximum message size is assumed to be 16 16-bit words with three words of overhead (status, checksum, etc.) for a total of 19 words or 38 bytes.

Operation	Max # Bytes	Xmit time (uS) at 375 KHz
Transmit Request from DAU	1	29.3
Response Delay	-	200.0
Receive Status and Data	38	1113.4
Intermessage Gap	-	100.0
Total transmit time (uS)		1442.7

In most control system architectures, the DAU or console operates in a fixed cycle. The cycle for systems at SCSD range from 100 to 200 milliseconds. Some sensors are sampled each cycle where others at every other cycle or every fourth cycle. For a worst case analysis, assume that each sensor is sampled once every 100 millisecond cycle. Also note that the communications controller operates in parallel with the main controller such that while the main controller is processing data for the previous frame, the communications controller is gathering data for the next frame.

Therefore, the following equations summarize the maximum number of SPUs which may be processed per 100 millisecond frame and the corresponding maximum number of sensors.

Max number of SPUs = 100 mS / 1442.7 uS = 69

and

Max number of Sensors = 69 SPUs * 16 sensors/SPU = 1104.

These numbers assume that there is only a single type of message format and that data is transferred only from the SPUs to the DAU or console. In reality, other message formats must be considered, such as data to a specific SPU, broadcast data to all SPUs, and perhaps SPU to SPU data. Further analysis must be performed for specific applications in order to determine the actual number of SPUs allowed. In addition, the Response delays and Intermessage gaps may need to be lengthened if these times prove to be too short. A more realistic SPU count may therefore be in range of 10 to 16 for maximum sensor counts of 320 to 512.

13. APPENDIX C - GRIN ROD VERIFICATION

The PMS employs a GRIN lens to serve as a substrate for the dichroic mirror. In addition, the lens protects the pressure sensitive diaphragm located within the body of the transducer. The selection of the length, NA, and pitch of the lens was based on component availability and reasons discussed below.

The locus of a ray passing through a SELFOC GRIN lens is shown in Figure 13.0-1.

The refractive index at any point, r, from the optical axis is given by

$$N(r) = N_o(1 - Ar^2/2), \text{ where}$$

$N(r)$ = refractive index at any point r
N_o = refractive index on the optical axis
A = refractive index gradient constant
r = radial distance from the optical axis

From this equation, the following ray matrix may be derived

$$\begin{bmatrix} r_2 \\ \beta \end{bmatrix} = \begin{bmatrix} \cos\sqrt{A}z & \sin\sqrt{A}z/N_o\sqrt{A} \\ -N_o\sqrt{A}\sin\sqrt{A}z & \cos\sqrt{A}z \end{bmatrix} \begin{bmatrix} r_1 \\ \alpha \end{bmatrix}$$ where

r_1 = distance between incident point and the optical axis
r_2 = distance between the emitting point and the optical axis
α = the incident angle
β = the emitting angle
z = the length of the lens

From the ray matrix, it can be seen that

$$r_1\cos(\sqrt{A}z) - \alpha\sin(\sqrt{A}z)/N_o\sqrt{A} = r_2$$

and

$$r_1N_o\sqrt{A}\sin(\sqrt{A}z) + \alpha\cos(\sqrt{A}z) = \beta$$

The fractional pitch, P, is defined as $P = z\sqrt{A}/2\pi$ therefore

$$r_2 = r_1\cos(2\pi P) - \alpha z\sin(2\pi P)/N_o2\pi P$$

and

$$\beta = r_1N_o2\pi P\sin(2\pi P)/z + \alpha\cos 2\pi P$$

It is obvious from these two equations that if $P = 1/2$, then

$$r_2 = -r_1 \text{ and } \beta = -\alpha$$

This shows that the exit angle, β, has a magnitude equal to the entrance angle, α. The minus sign indicates inversion. Similarly, the exit point r_2 has the same magnitude as the entrance point r_1 but it is also inverted. Thus, the GRIN rod does not affect the incidence angle or exit distance, but merely inverts the input conditions.

Suppose now that an optical fiber illuminates the GRIN rod end as shown in Figure 13.0-2.

The entrance point r_1 can be seen to be equal to

$$r_1 = r_{co} + x\tan\theta_c$$

where r_{co} is the fiber core radius and x is the distance between the fiber and GRIN rod. The entrance angle α has a magnitude of θ_c if there is perfect alignment. Thus, the ray matrix equations are modified as follows:

$$r_2 = (r_{co} + x\tan\theta_c)\cos(2\pi P) - \theta_c z\sin(2\pi P)/N_o2\pi P$$

$$\beta = (r_{co} + x\tan\theta_c)N_o 2\pi P\sin(2\pi P)/z + \theta_c\cos 2\pi P$$

Substituting P = 1/2 as before yields

$$r_2 = -(r_{co} + x\tan\theta_c)$$

$$\beta = -\theta_c$$

Thus, $\Delta\beta/\Delta x$ (longitudinal displacement) is equal to 0 and the output angle β is therefore constant with x. Also, $\Delta r/\Delta x = -\tan\theta_c$ which indicates that the emitting distance from the optical axis is a linear function of x. Finally, the exit angle β is not a function of r_1 but only depends on θ_c (and the angular misalignment error). Since the output angle strongly affects the transducer response, a 1/2P GRIN rod appears to be a logical choice.

14. APPENDIX D - WAVELENGTH DEPENDENCY OF BENDING EFFECTS

14.1. Bend Loss Analysis

Since the FMS is based on amplitude measurement, it is impossible to determine if a change at the detector output is due to a real sensor signal or some other effect, such as bend loss. In an attempt to isolate the sensor output, two (or more) sources of different center wavelengths may be employed. If the sensor can be made to discriminate one source from another, the output signal may be operated on to correct for bend-induced optical loss.

A dichroic mirror may be employed as the isolation element. If an optical lead that propagates light from two different sources experiences a bend which attenuates the light equally, it becomes possible to discriminate the sensor signal from bend-induced effects, since both wavelengths experience the bend loss but only one wavelength experiences sensor-induced loss.

Once the above is assumed, a determination of the source wavelength separation must be made. The choice of source wavelengths is affected by the following.

- a maximum tolerance (to be determined) between the bend-induced loss at λ_1 and λ_2 at "normal" bend radii of curvature;
- source availability at λ_1 and λ_2;
- source price;
- dichroic fabrication ability and,
- dichroic price.

It is assumed that the further the separation between λ_1 and λ_2, the easier (and therefore less expensive) it is to fabricate the dichroic; however, it is expected that the degree of bend-induced loss cancellation becomes worse as λ_1 and λ_2 become further separated.

Calculations can be made to address factor (1) above. For example, the fundamental mode on a weakly guiding, bent fiber can be replaced by a model of a current carrying antenna of infinitesimal thickness which radiates in an infinite medium of index equal to the cladding refractive index of the fiber. Then far-field antenna radiation theory can be applied to calculate the radiation once the current on the antenna is specified. The calculation is rigorous if a single-mode fiber is assumed since there is only one value of propagation constant $\beta = nk$ allowed. In a multimode fiber, many values of β are allowed and thus the total power lost is a sum over all allowed values of β. Furthermore, each mode would require a different spatial extent or "spot size" in the above calculation. Thus, it becomes extremely difficult to calculate bend-induced loss in a multimode fiber. The single-mode approach is useful, for at least an idea of how fast (with respect to bend radius) the power is attenuated as a function of λ and bend radius may be obtained.

14.2. Loss Due to Constant Curvature

The material presented here is derived from theory contained in Optical Waveguide Theory by Snyder and Love (Chapman and Hall, 1983). A single propagating mode is assumed. Snyder and Love show that the radiation from a circular loop antenna can be given by

$$P_{rad}/P_{in} = XY, \text{ where}$$

$$X = \exp\,[-4R_c\Delta W^3/3\rho V^2]$$

and

$$Y = (\pi R_c \mu_o)^{1/2}(I_c V)^2 N_{co}/32a(\rho E_o)^{1/2} W^{3/2} N\Delta$$

where

R_c = curvature radius
ρ = fiber core radius
a = modal amplitude
V = V number $kn_{co}\rho(2\Delta)^{1/2}$
W = cladding parameter $\rho(\beta^2 - k^2 n_{cl}^{\,2})^{1/2}$
Δ = relative index difference $n_{co} - n_{cl}/n_{co}$
N = normalization

$$N = [(N_{co}/2)(E_o/\mu_o)]^{1/2}\int_A e_t^2 dA \quad (A = \text{cross-sectional area})$$

where e_t is the magnitude of the transverse electric field and

I_c is defined as

$$I_c = -2\pi i a n_{co}\rho V(2\Delta E_0/\mu_0)^{1/2}\int^{\infty}[1 - f(R)]F_0(R)dr$$

where

$$F_0(R) = \exp[-R^2/2r_0^2]$$

i.e. a Gaussian modal profile is assumed and r_0 is the spatial extent of the mode in the radial direction, i.e. the "spot size", and

$$\begin{aligned} f(R) &= 0 \quad \text{for} \quad 0 < R < 1 \qquad \text{(step index profile)} \\ &= 1 \quad \text{for} \quad 1 < R < \qquad R = r/\rho . \end{aligned}$$

Of interest is the fractional power loss per unit length, or power attenuation coefficient γ. γ is found by dividing the above equation for P_{rad}/P_{in} by the length of the loop $2\pi R_c$. Since γ is independent of z (length), the power at any position along the loop is given by

$$P(z) = P_{in}\exp(-\gamma z), \quad \gamma = P_{rad}/2\pi R_c P_{in}$$

The optical fiber does not extend infinitely into space. Thus, effects due to finite cross-sectional area must be determined. γ_c becomes equal to $\alpha\gamma$, where the area factor α is expressible as

$$\alpha = [\int^{\infty}(1-f)F_0(R)I_0(WR)RdR/\int^{\infty}(1-f)F_0(R)dR]^2 .$$

After evaluation of the integrals, the area factor α is found to be

$$\alpha = (U^2/[WV^2K_1(W)])^2, \text{ where}$$

$$U = \rho(k^2n^2_{co} - \beta^2)^{1/2},$$

$$W = \rho(\beta^2 - k^2n^2_{cl})^{1/2},$$

and K_1 is the first-order modified Hankel function. The final result of γ_c corrected for finite cross-section is

$$\gamma = \sqrt{\pi}U^2\exp[-4R_c\Delta W^3/3\rho V^2]/2(\rho R_c)^{1/2}W^{3/2}V^2K_1^2(W)$$

The exponential term obviously dominates γ.

A plot of P_{rad}/P_{in} as functions of bend radius and wavelength for a 10 cm length of fiber having an NA equal to 0.2 appears in Figure 14.2-1.

14.3 Transition Loss

In addition to the radiation loss associated with constant bending of a fiber, there is transition loss due to abrupt changes in curvature. In order to calculate the radiation due to an abrupt change in curvature, the modal fields of the bent fiber must be specified. There exist two types of transition: a straight to curved transition and two curves of differing bend radii.

14.3.1. Straight-to-Curved Transition

Snyder and Love show that the predominant effect of curvature on the fundamental mode is to shift the mode field distribution radially outwards in the plane of the bend a distance r_d from the fiber axis. For an arbitrary index profile,

$$r_d = (V\rho)^2 r_o^4/2\Delta R_c\rho^4, \ R_c >> \rho$$

Assuming the fiber is single moded, the fraction of incident mode power which remains bound is given by

$$P_o/P_{in} = [2\rho_s r_o/(\rho_s^2 + r_o)^2]^2 \exp[-r_d^2/(r_o^2 + \rho_s^2)], \text{ where}$$

$\rho_s = r_o + r_d$ and r_o is the "spot size" as before.

This is approximately equal to

$$P_o/P_{in} \approx \exp[-r_d^2/2r_o^2].$$

Thus, the fraction of power radiated is given by

$$1-P_o/P_{in} = 1 - \exp[-r_d^2/2r_o^2].$$

The spot size, r_o, can be calculated using the equation

$$\beta^2 = \int^\infty[k^2n^2(r)F_o^2 - (dF/dr)^2]rdr/\int^\infty rF_o dr,$$

where

$$F_o(r) = \exp[-r^2/2r_o^2] \text{ (i.e. a Gaussian)}$$

After performing the integration and the algebra, r_o is found to be equal to

$$r_o^2 = \rho^2/\ln[k^2\rho^2(n_{co}^2 - n_{cl}^2)]$$

This result may be substituted in the above equation for P_o/P_{in}.

A plot of P_o/P_{in} for a straight to curved transition as a function of bend radius and wavelength for a length of fiber having an NA equal to 0.12 appears in Figure 14.3-1.

14.3.2. Curve-to-Curve Transitions

For the case of a transition between two curved sections, the relative shift r_d is given by

$$r_d = (r_1^2 + r_2^2 - 2r_1r_2\cos x)^{1/2}$$

x is the angle between the planes containing each bend. When the bends lie in the same plane, $r_d = r_1 + r_2$ if the bends are in the opposite sense, or $r_d = r_1 - r_2$ if the bends are in the same sense. With R_c replaced by R_1 and R_2 respectively, the relative shift r_d is calculated to be

$r_d = R_1 \pm R_2\ \rho^2V^2r_o^4/R_1R_2 2\Delta\rho^4$ and $1 - P_o/P_{in}$ is found to be

$$1 - P_o/P_{in} = 1 - \exp[-r_d^2/2r_o^2] \text{ or}$$

$$1 - P_o/P_{in} = 1 - \exp\{-(R_1 \pm R_2)^2V^4r_o^6/(R_1R_2)^2 8\Delta^2\rho^4\}$$

Again r_o is the spot size defined above.

A plot of P_o/P_{in} for a curve-to-curve transition as a function of bend radius and wavelength for a fiber having an NA equal to 0.12 appears in Figure 14.3-2.

14.4. <u>Bend Loss Summary</u>

14.4.1. Constant Curvature of Bend Radius R

$$P_o = P_{in}\exp(-\gamma z) \text{ where}$$

$$\gamma = \frac{\sqrt{\pi}(n_{co}^2 - n^2)\exp\{-2Rk(n^2 - n_{cl}^2)^{3/2}/3n_{co}^2\}}{4\Delta R^{1/2}\rho^2k^{3/2}(n^2 - n_{cl}^2)^{3/4}n_{co}^2K_1^2\{\rho[k^2(n^2 - n_{cl}^2)]^{1/2}\}}$$

and

- z = length of bent fiber
- n = "arbitrary" refractive index for the mode investigated
- n_{co} = core index
- n_{cl} = cladding index
- k = wavenumber
- Δ = relative core/clad index difference
- ρ = core radius
- K_1 = modified Hankel function of order 1

Also,

$$\Delta P_o/\Delta R = P_{in}z\exp(-\gamma z)\gamma[2k(n^2 - n_{cl}^2)^{3/2}/3n^2_{co} + 1/2R]$$

14.4.2. Transition Loss

14.4.2.1. Straight-to-Curved Section

$P_o = P_{in} \exp(-\gamma)$ where

$\gamma = k^4 n^4_{co} \rho^6 / 2R^2 [\ln(k^2 \rho^2 n_{co}^2 - k^2 \rho^2 n_{cl}^2)]^3$

$\Delta P_o / \Delta R = P_{in} \exp(-\gamma) 2\gamma / R$

14.4.2.2. Curved-to-Curved Sections

Two Curved Section where $R_1 \neq R_2$ for bends in the same sense and where $R_1 = R_2$ is allowed for bends in the opposite sense.

$P_o = P_{in} \exp(-\gamma)$ where

$\gamma = (R_1 \pm R_2)^2 k^2 n_{co}^2 \rho^4 / (R_1 R_2)^2 2[\ln(k^2 \rho^2 n_{co}^2 - k^2 \rho^2 n_{cl}^2)]^3$ and

$\Delta P_o / \Delta R = -P_{in} \exp(-\gamma) \Delta\gamma / \Delta R$

$-P_{in} \exp(-\gamma) \Delta\gamma / \Delta R_1 \quad R_2 = \text{constant}$

$=$

$-P_{in} \exp(-\gamma) \Delta\gamma / \Delta R_2 \quad R_1 = \text{constant}$

If both R_1 and R_2 change, then

$\Delta P_o = (\partial P_o / \partial R_1) \Delta R_1 + (\partial P_o / \partial R_2) \Delta R_2$

For $R_1 = R_2$ (opposite sense bends), $\Delta P / \Delta R = P_{in} \exp(-\gamma) 2\gamma / R$

A single propagating mode was assumed in the above derivations. The quantities $\Delta P / \Delta R$ for the two wavelengths must be equal to assume total cancellation.

15. APPENDIX E - COST DATA

Table 15.0-1. Electronic Sensor Costs

Sensor Type	Supplier	Weight (Lbs)	Estimated Cost ($)	GE Selling Price ($)
Magnetic Pickup	GE	0.5	108.00(3)	162.00(1)
Tachometer	GE	20.0	4795.00(3)	7193.00(1)
CR-AL Thermocouple				
Thermowell	GE	1.0	80.00(3)	120.00(1)
RTD	GE	2.0	211.00(3)	317.00(1)
Switch - Pressure	GE	2.0	105.00(3)	158.00(1)
Switch - Pressure	Detroit Sw.		119.00	179.00(2)
Switch - Pres. Sup.	Detroit Sw.		139.00	209.00(2)
Switch - Temperature	GE	2.0	200.00	300.00(1)
Switch - Temperature	Detroit Sw.		139.00	209.00(2)
Switch - Temp. Sup.	Detroit Sw.		166.00	249.00(2)
Switch - Diff. Press.	Detroit Sw.		209.00	314.00(2)
Switch - Flow				
Switch - Level				
Transducer - Diff. Press.	GE	5.0	680.00(3)	1020.00(1)
Transducer - Pressure	GE	5.0	405.00(3)	608.00(1)
Transmitter - Level (VR)				

NOTES:

(1) GE selling price based on previous programs.

(2) GE selling price based on manufacturers list price plus typical adders.

(3) Estimated cost based on GE selling price.

Table 15.0-2. Electronic Signal Conditioning Costs

Board Name	# Circ /Board	Cost ($)	Cost per Sensor ($)	mA/Board 5/+15/-15V	mW/Bdm	W/Sen
RTD (-10VDC Reference)	5	660.00	132.00			
RTD (+10VDC Reference)	5	550.00	110.00	0/ 10/100	1650	330.0
Thermocouple (+meter output)	4	550.00	137.50	90/ 50/ 30	1650	330.0
Thermocouple (0-2000 DEGF)	1	2470.00	2470.00			
Thermocouple	18					
4-20 Ma to 0-10 VDC	11	540.00	49.09	0/ 20/ 85	1575	143.2
Pot Position (+ extra circuits)	1	1100.00	1100.00			
Potentiometer	16					
Contact Closure (Opto-isolated)	12	768.00	64.00			
Contact Closure Supervised	12	1350.00	112.50			
Contact Closure	32					
Speed to Voltage (200 RPM Max)	2	807.00	403.50	30/ 20/140	2550	1275.0
Speed to Voltage (2500 RPM Max)	2	680.00	340.00	30/ 20/140	2550	1275.0
Speed to Voltage (5.9 KHz Max)	2	2250.00	1125.00			
Diff. Receiver (+10 diff drvrs)	10	700.00	70.00	200/ 0/ 0	1000	100.0

Diff. Receiver (+7 single drvr)					
15	430.00	28.67	50/ 20/ 15	775	51.7
Diff. Receiver (+13 cc rcvrs)					
8	1025.00	128.13	200/ 0/ 0	1000	125.0
Analog Mux (32 to 1)					
32	1600.00	50.00	90/ 6/ 6	630	19.7
Analog Mux + A/D (12-bit)					
8	2530.00	316.25	400/ 45/ 50	3425	428.2
Analog Mux + A/D (12-bit + DAC)					
13	2180.00	167.69			
Analog Mux + A/D (12-bit)					
128	5000.00	39.06			
Discrete Input (0/5VDC)					
126					

Table 15.0-3. Time Division Multiplexer Costs

Item	Supplier	Qty	Part Number	Cost ($)
32 channel multiplexer	ODS	1-9	ODS 300	2800.00
16 channel multiplexer	ODS	1-9	ODS 301	2000.00
8 channel multiplexer	ODS	1-9	ODS 302	950.00

Table 15.0-4. Star Multiplexer Costs

Item	Supplier	Qty	Part Number	Cost ($)
4X4 10 db	Codenall	100	1295	
8X8 13 db	Codenall	100	2495	
16X16 17 db	Codenall	100	4395	
32X32 21 db	Codenall	100	8495	

Table 15.0-5. Electrical Cable Costs For SCU

Cable Type (1) Cost ($/ft)	Number (M24640)	Quantity	Gauge	Diameter (Max in.)	Cable Weight (lbs/1000 ft.)
24 twisted/shielded triplets	3XSOW-24	4	AWG 22	1.280	1649.0
19 twisted/shielded triplets	3XSOW-19	5	AWG 22	1.080	1231.0
10 twisted/shielded triplets	3XSOW-10	1	AWG 22	.879	738.0
30 twisted/shielded pairs 18.00(2)	2XSOW-30	9	AWG 18	1.280	1572.0
19 twisted/shielded pairs	2XSOW-19	4	AWG 18	1.020	984.0
12 twisted/shielded pairs	2XSOW-12	1	AWG 18	.859	721.0
15 twisted/shielded pairs with circuit integrity	TTXOW-15	2	AWG 22	.588	261.0

Notes:
(1) All cables are watertight and unarmored with an overall shield.
(2) Minimum quantity of 1000 ft.

Table 15.0-6. Cable Plug Costs For SCU

Plug Number (MS3406DJ-)	Cable Number	Cost Quantity	($/Ea.)
44B-52D	3XSOW-24	4	
40A-56D	3XSOW-19	5	
[illegible]10D	3XSOW-10	1	
[illegible]	2XSOW-30	9	
[illegible]	2XSOW-19	4	
28B-[illegible]	2XSOW-12	1	
28A-2[illegible]	[illegible]XOW-15	2	

Table 15.0-7. Console Receptacle Costs For SCU

Recep. Number (MS3402D-)	Cable Number	Quantity	Cost ($/Ea)
44-52S	3XSOW-24	4	108.00
40-56S	3XSOW-19	5	92.74
36-10S	3XSOW-10	1	66.78
44-52S	2XSOW-30	9	108.00
40-62S	2XSOW-19	4	76.17
28-21S	2XSOW-12	1	54.29
28-21S	TTXOW-15	2	54.29

Table 15.0-8. Fiber-Optic Cable Costs

Item	Supplier	Qty (ft)	Part Number	Cost ($/Ft)
50 um @ 5 db/km	ODS	1000+	503 duplex	0.78
100 um @ 6 db/km	ODS	1000+	505 duplex	1.25
200 um @ 7 db/km	ODS	1000+	507 duplex	1.02

Table 15.0-9. Fiber-Optic Connector Costs

Item	Supplier	Qty	Part Number	Cost ($)
SMA connector	ODS (1)			
Line splice (50 um)	ODS (1)			22.00
Line splice (100 um)	ODS (1)			12.00

Notes:
(1) Optical Data Systems

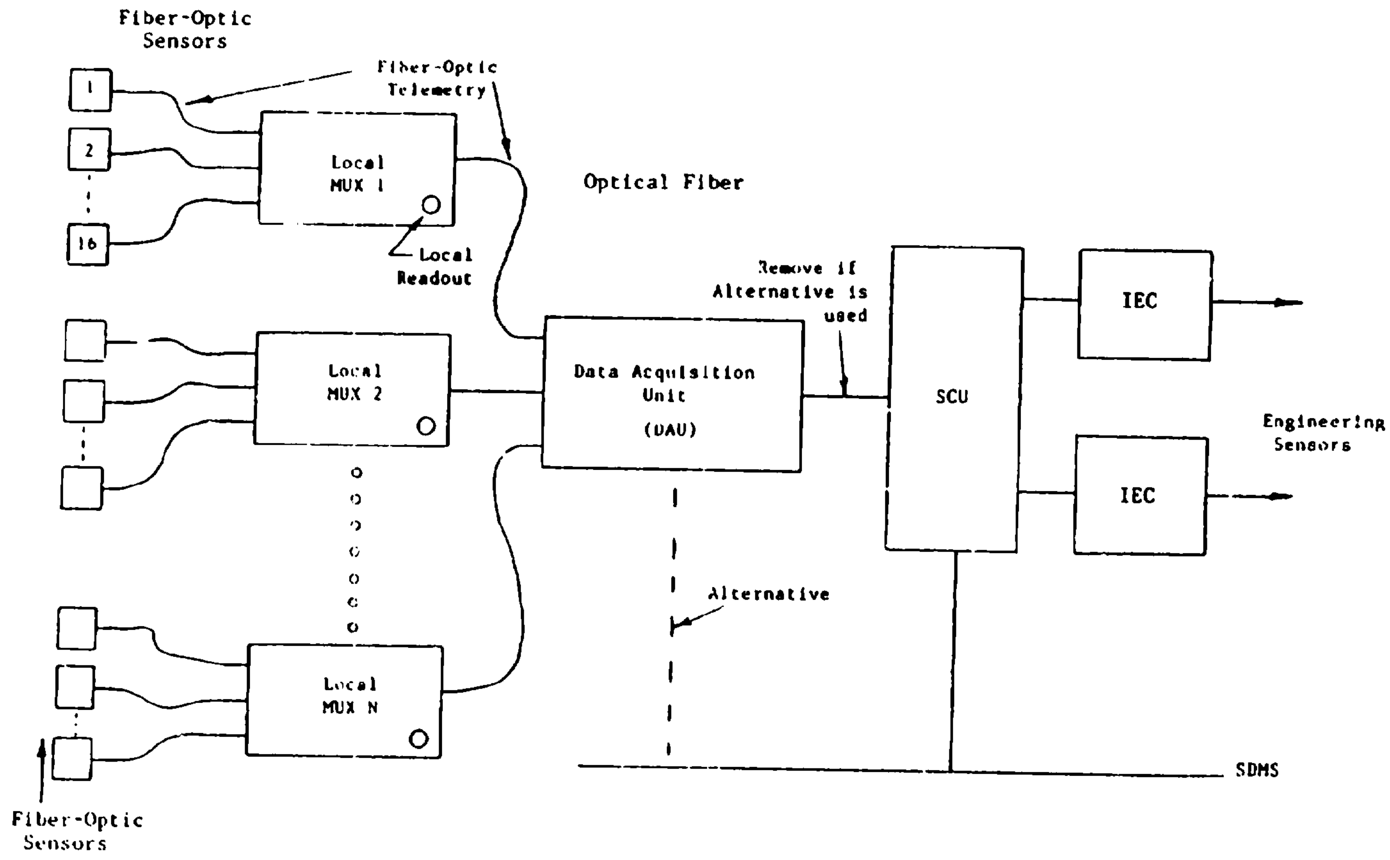


Figure 1.1-1. Fiber-Optic Sensor and Telemetry System

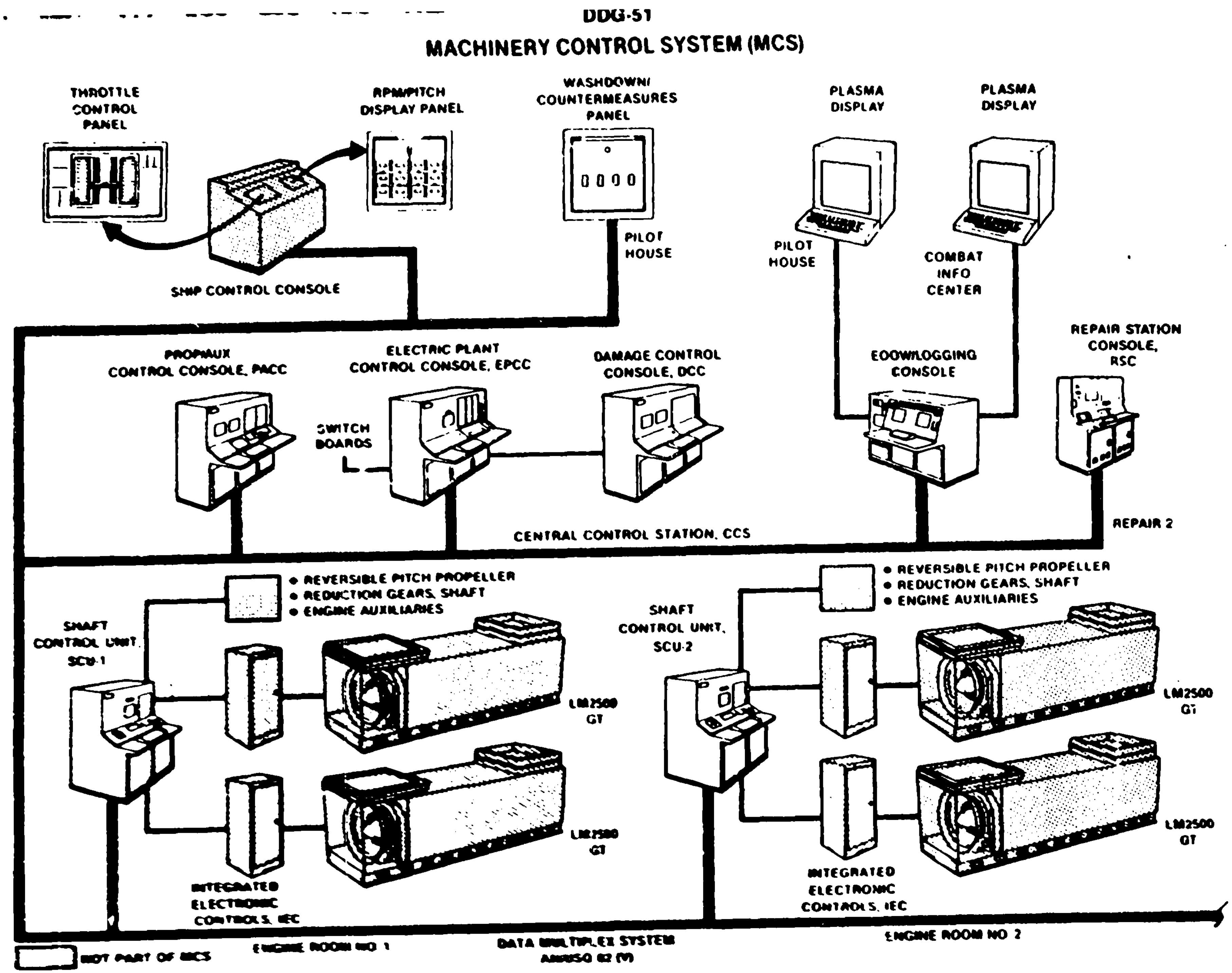


Figure 1.4-1. DDG-51 Machinery Control System

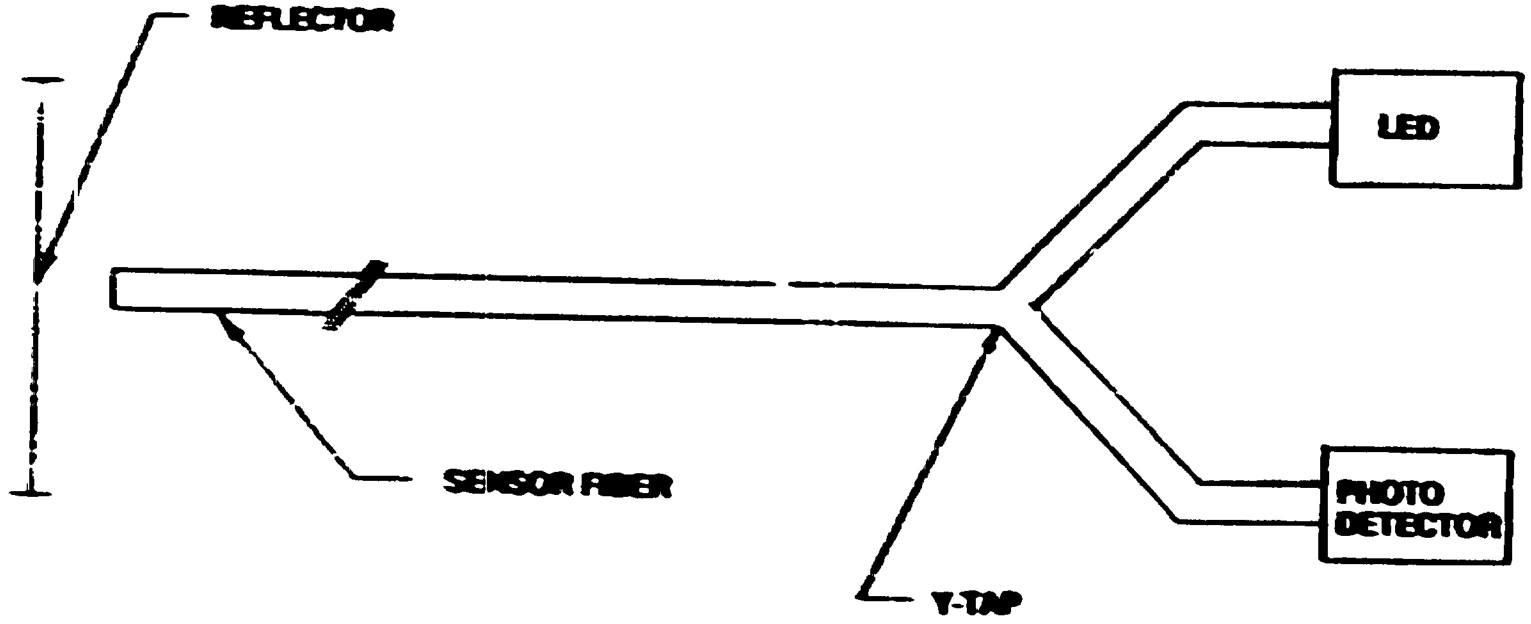


Figure 3.3-1. Reflection Sensor Concept

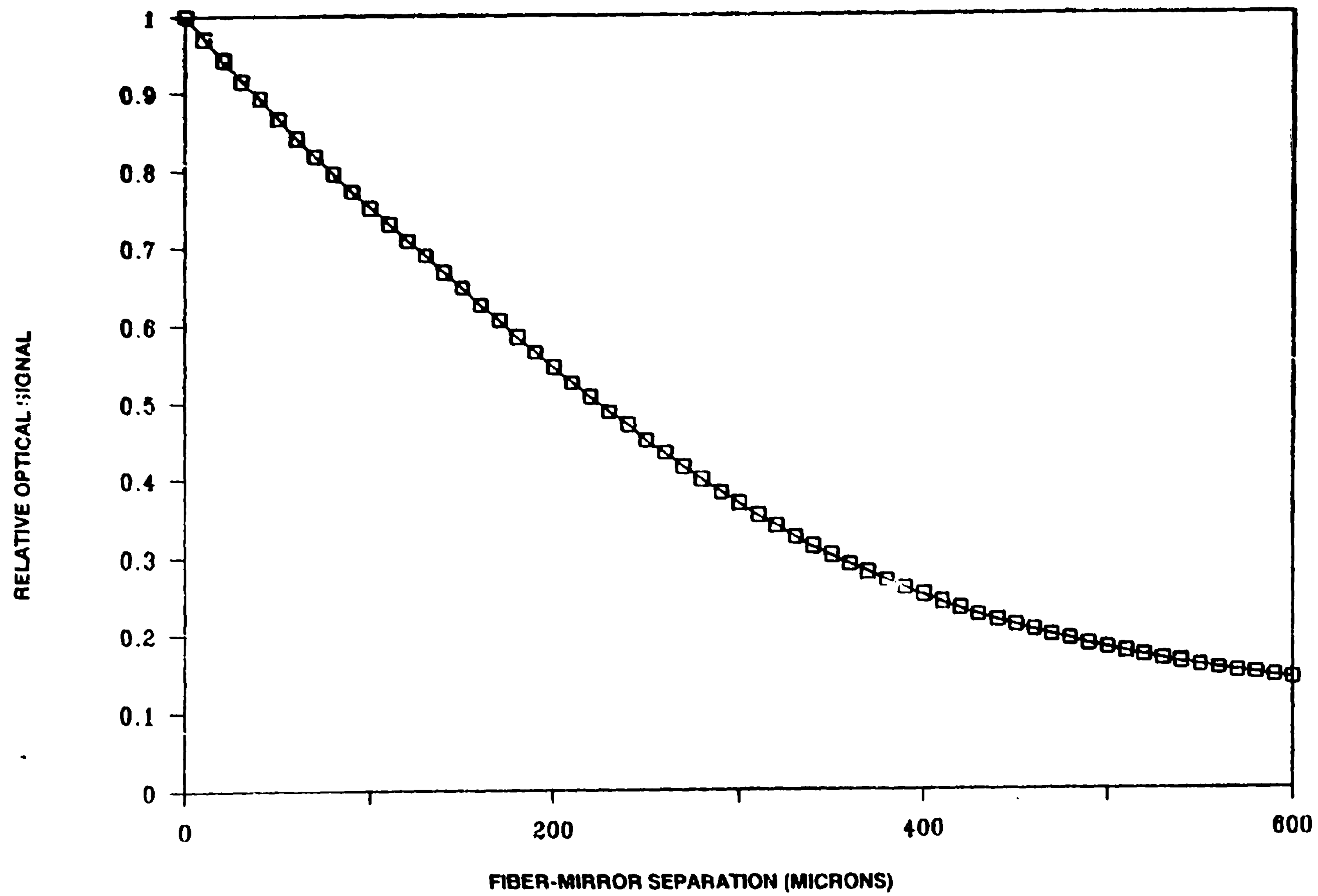


Figure 3.3-2. Typical Reflection Sensor Data

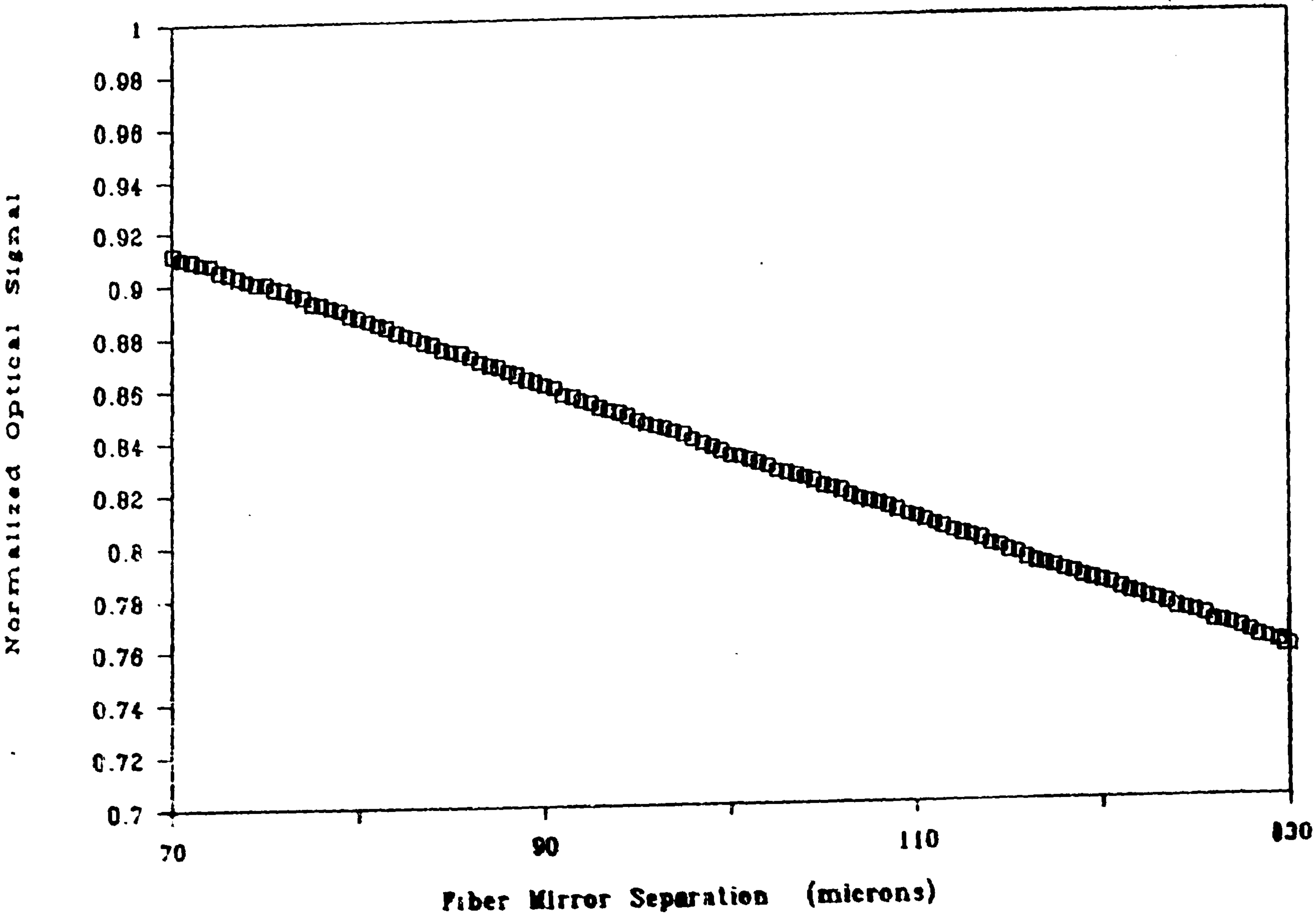


Figure 3.3-3. Typical Reflection Sensor Data

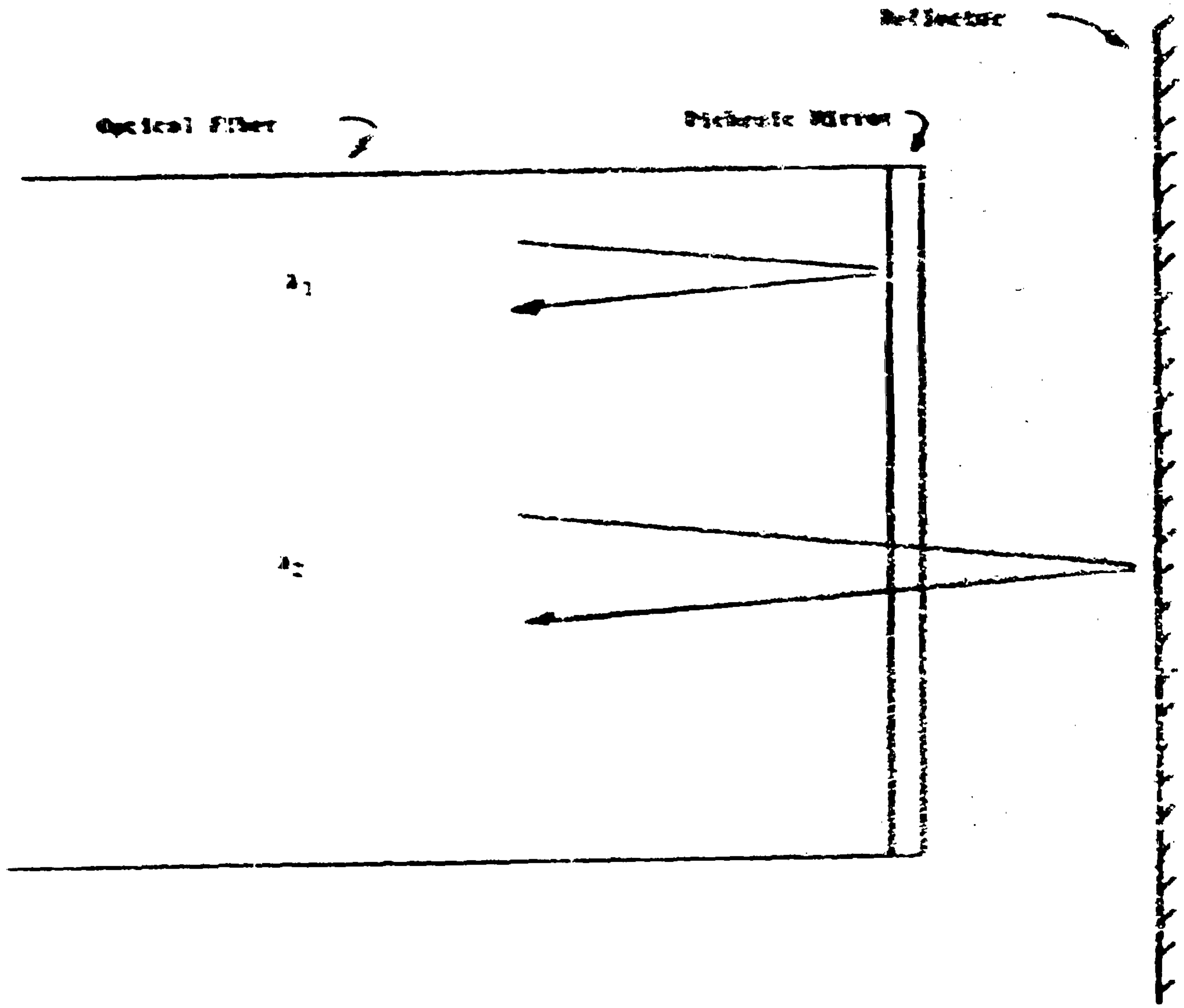


Figure 3.3-4. Dual Wavelength Technique for Attenuation Compensation

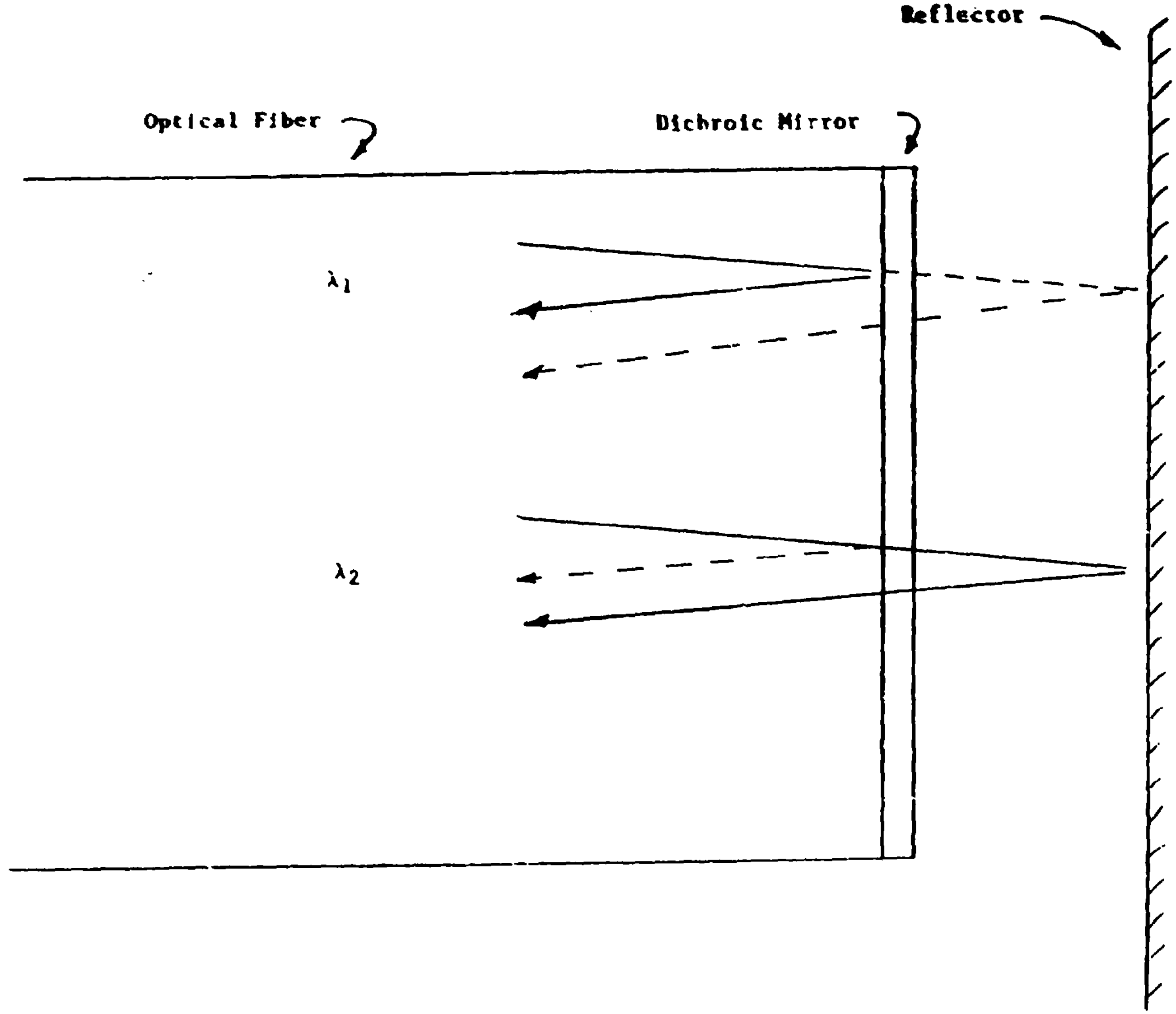


Figure 3.3-5. Dual Wavelength Technique for Attenuation Compensation

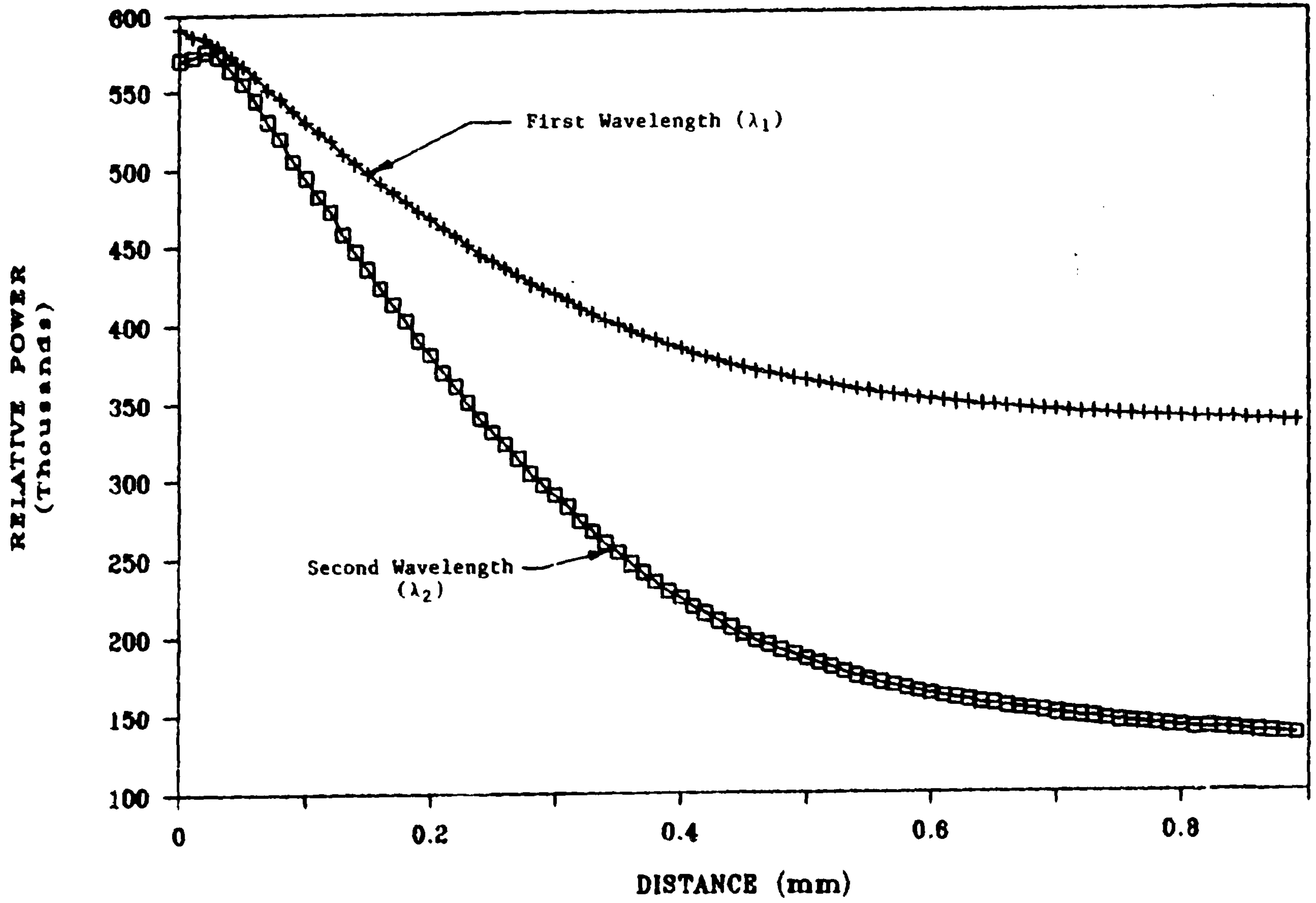


Figure 3.3- 6. Dual Wavelength Reflection Data

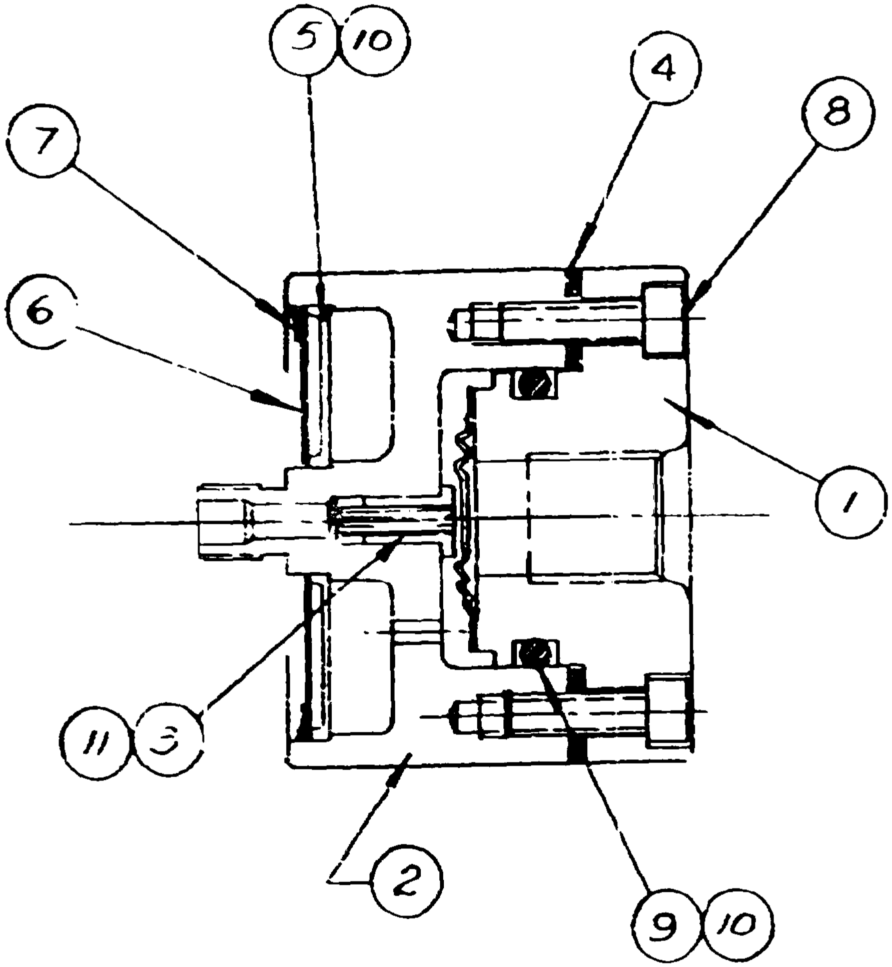


Figure 3.4-1. Reflection Type Pressure Sensor

ITEM	DESCRIPTION	PART Nº	REQ'D
1	INPUT BODY		1
2	OUTPUT BODY		1
3	GRIN·ROD ASSY		1
4	SHIM		AR.
5	MEMBRANE		1
6	MEMBRANE RET.		1
7	RETAINING RING	TRUARC #5005-150 PLATED OR ST. STEEL	1
8	SCREW SOCKET HEAD	#6-32 NC x .5 LONG STAINLESS STEEL	4
9	O-RING	PARKER 2-117 BUNA N	1
10	SILICONE GREASE		AR
11	LOCK TITE		AR

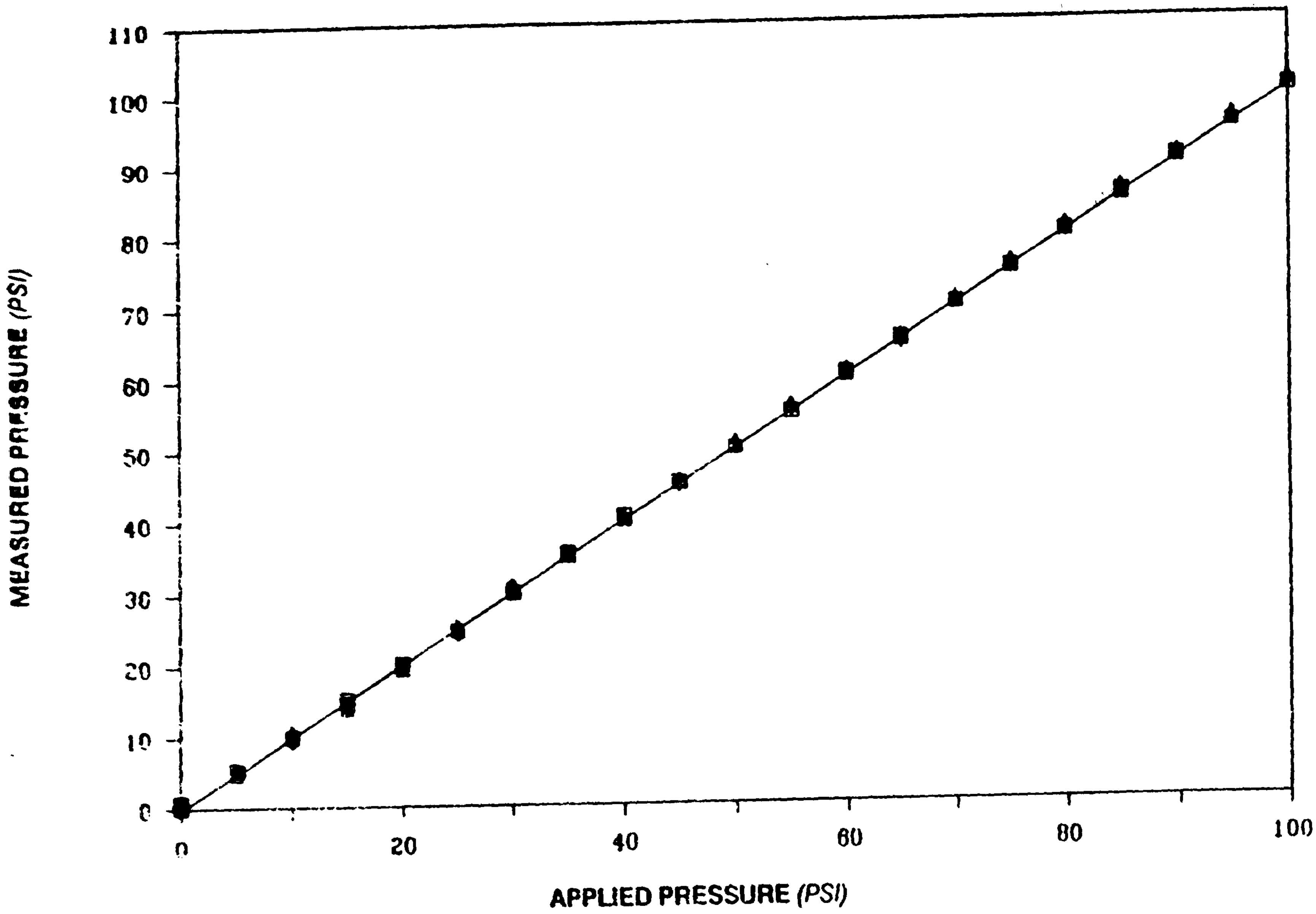


Figure 3.4-2. Reflection Type Pressure Sensor Performance Data

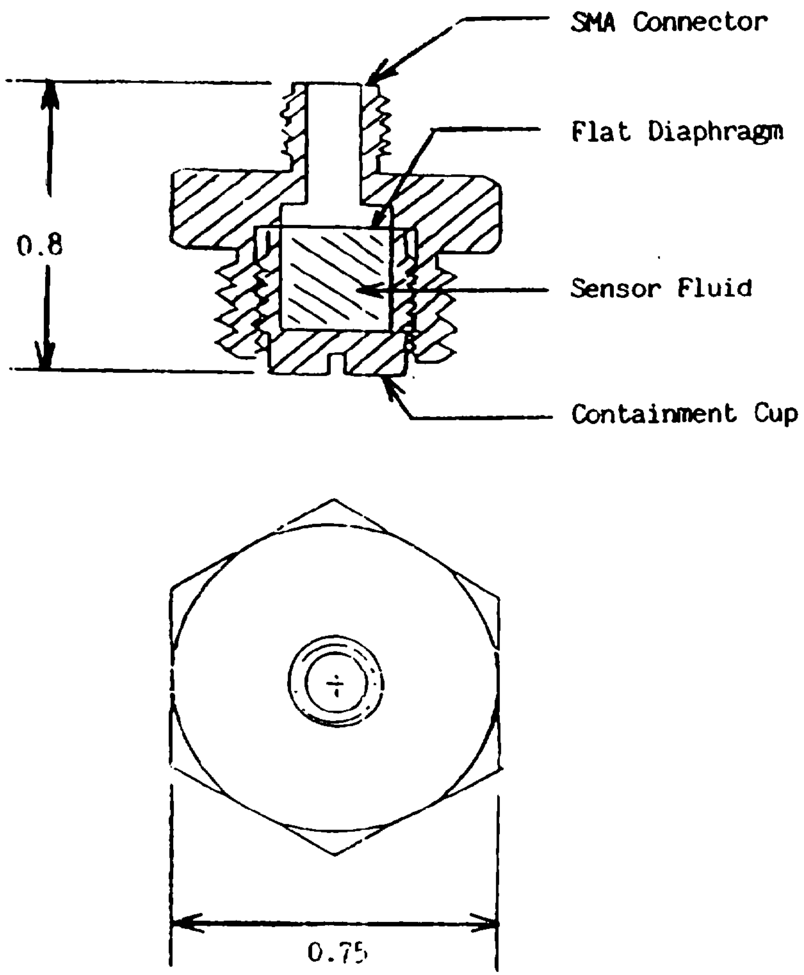


Figure 3.5-1. Current Reflection Temperature Transducer Design

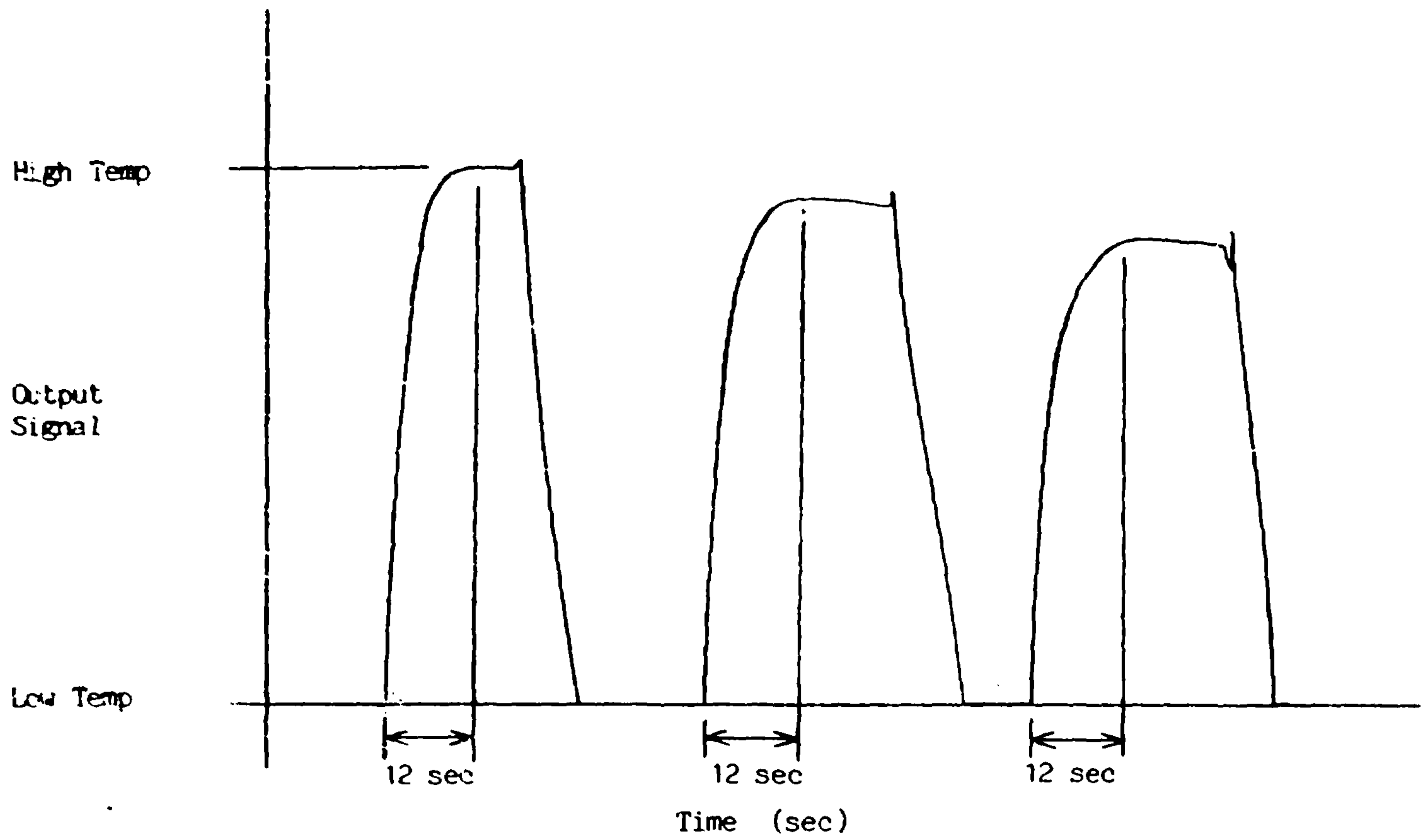


Figure 3.5-2. Response of Temperature Transducer to Step Increase In Temperature

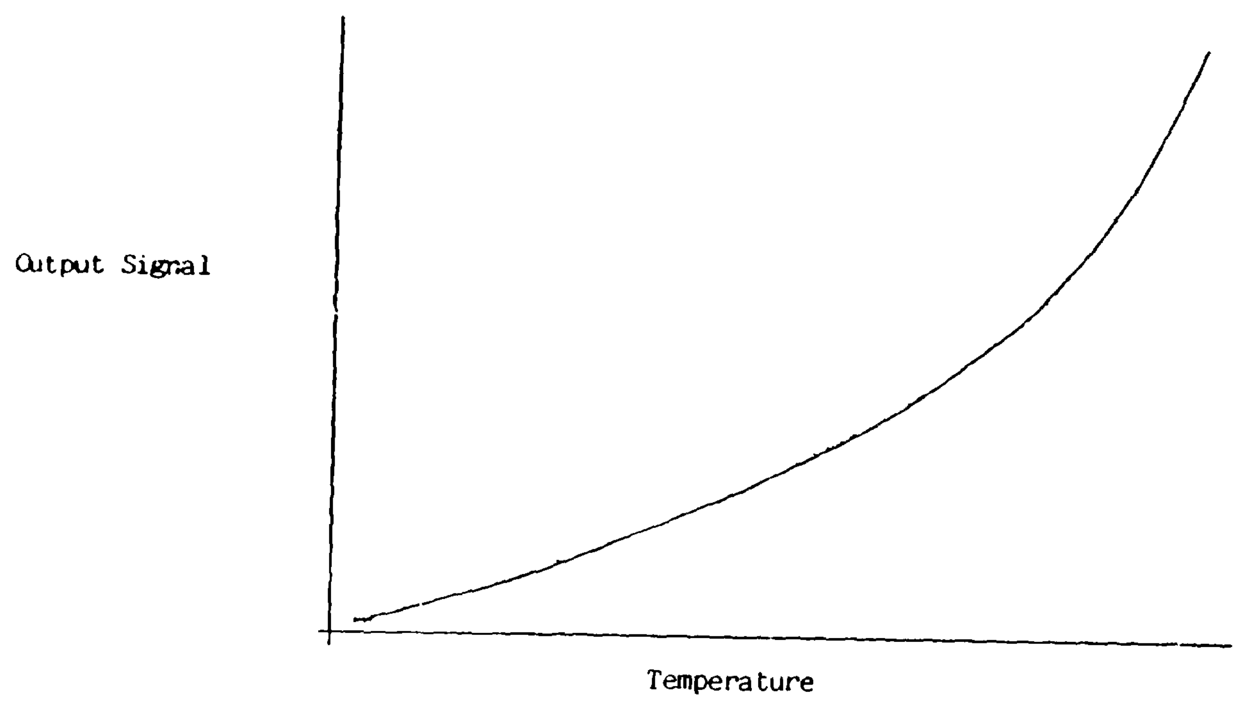


Figure 3.5-3. Characteristic Curve of Flat Diaphragm Temperature Transducer

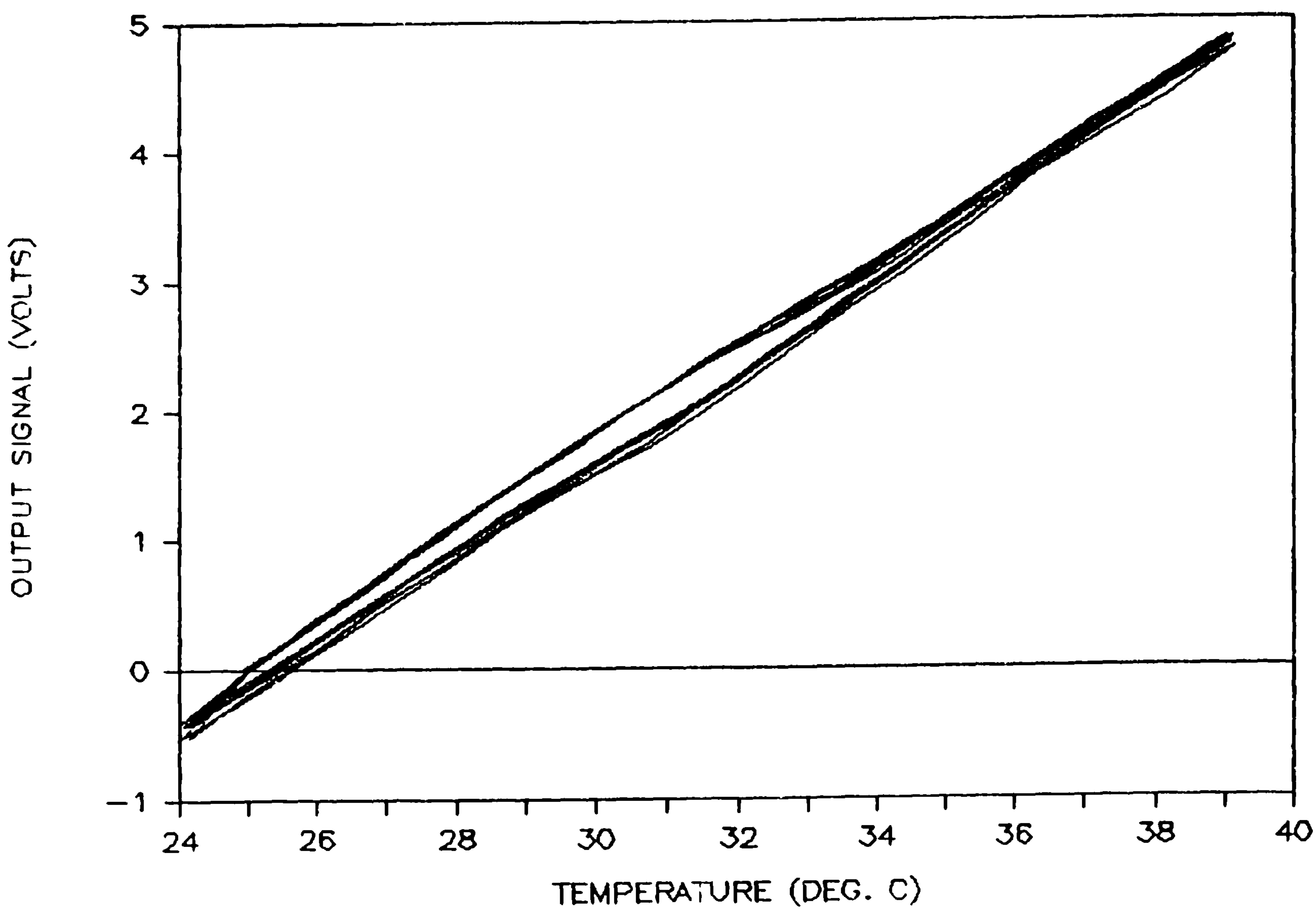


Figure 3.5-4. Typical Temperature Sensor Data

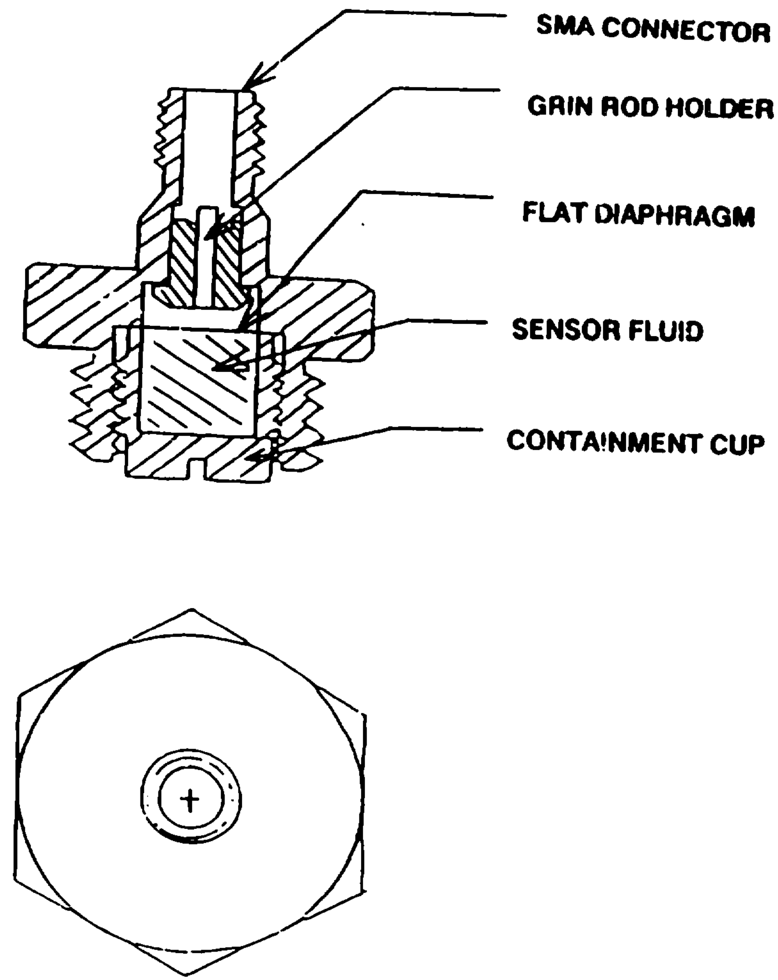
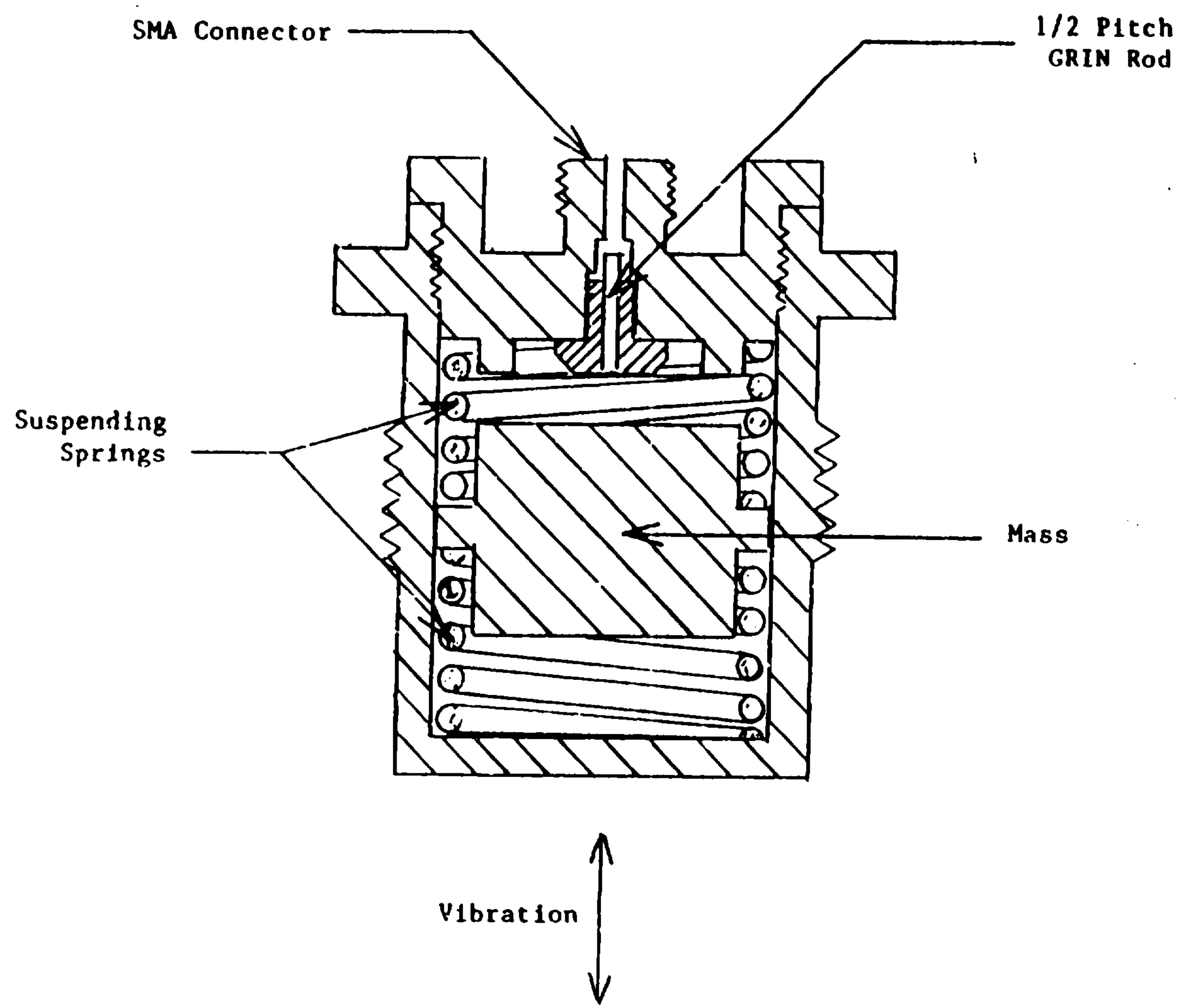


Figure 3.5-5. Second Generation Design for Reflection Temperature Transducer



3.6-1. Fiber-Optic Vibration Sensor

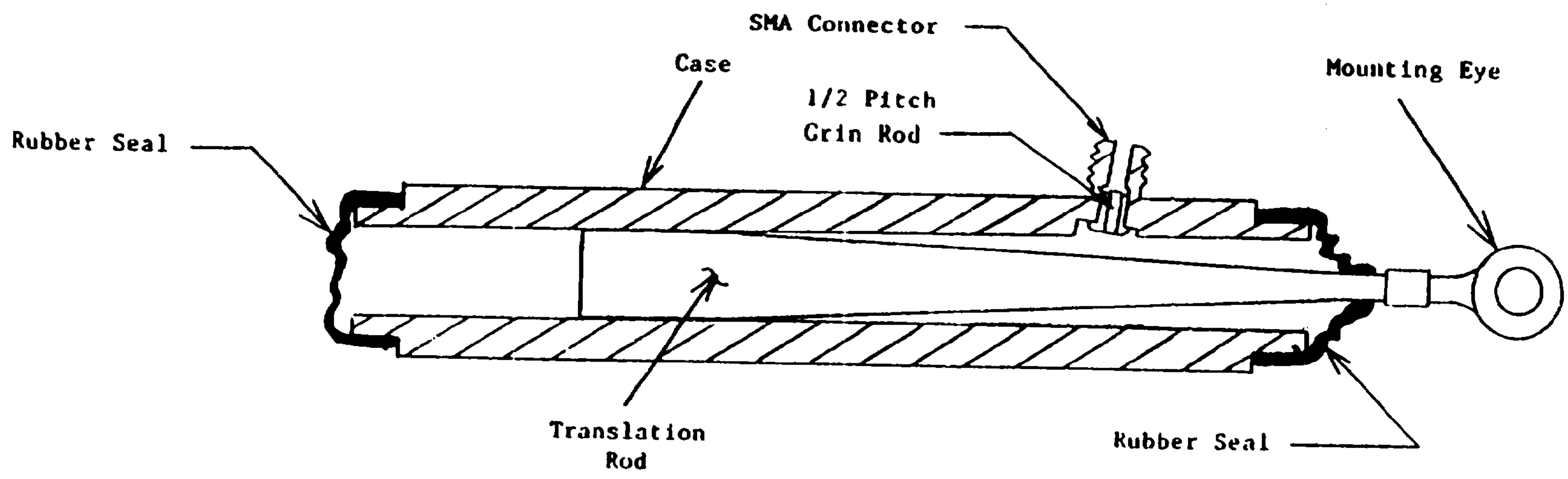


Figure 3.7-1. Linear Displacement Sensor

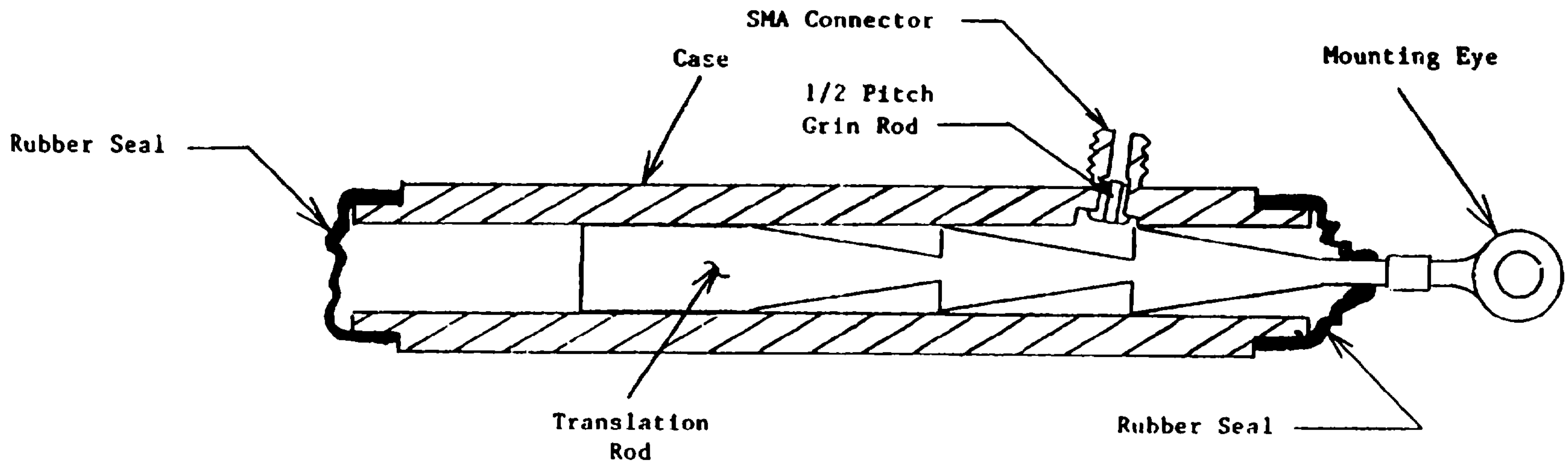


Figure 3.7-2. High Resolution Linear Displacement Sensor

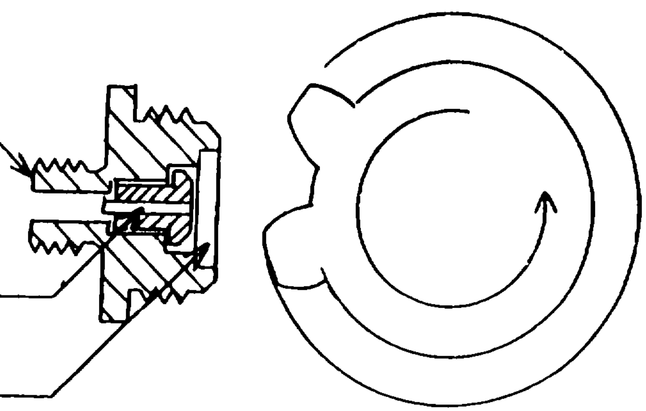


Figure 3.8-1. RPM Sensor

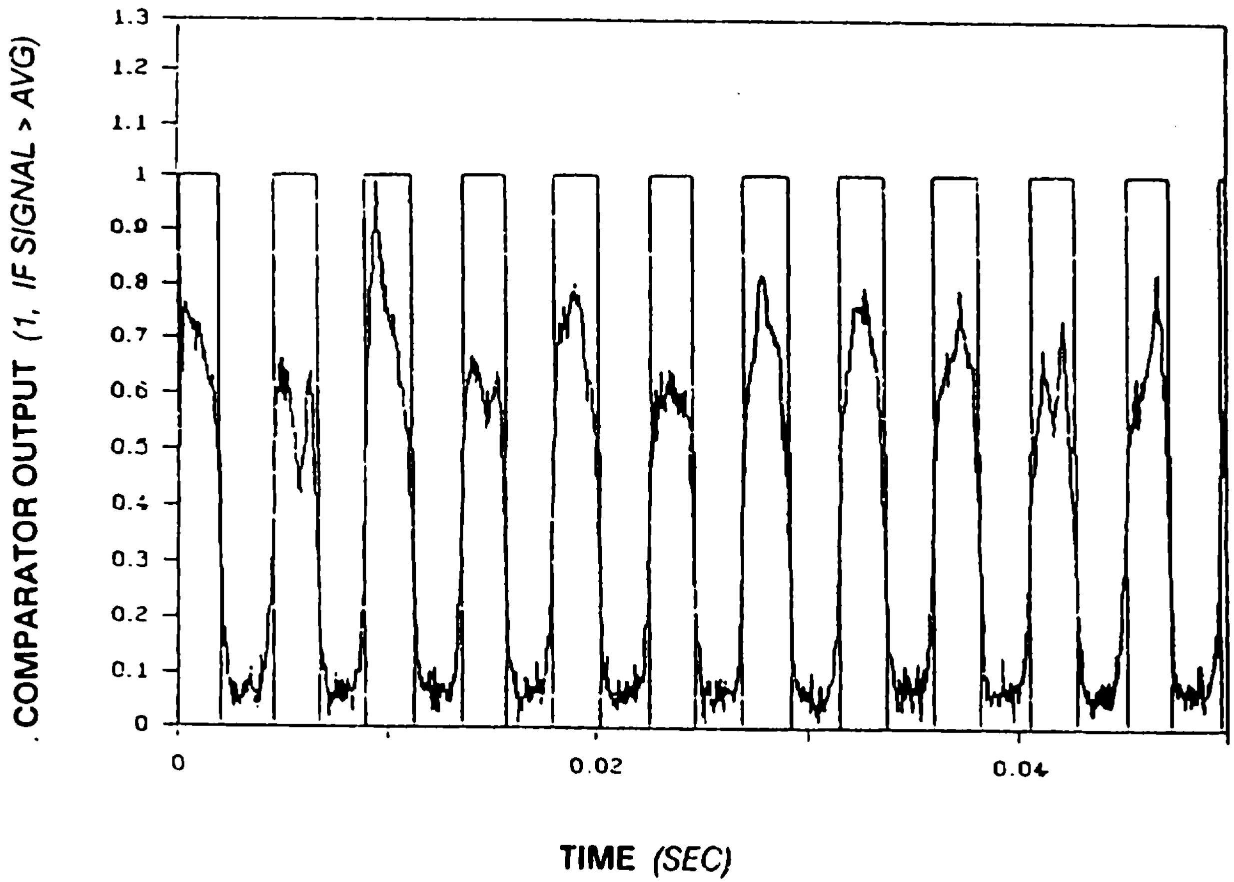


Figure 3.8-2. Typical RPM Sensor Data

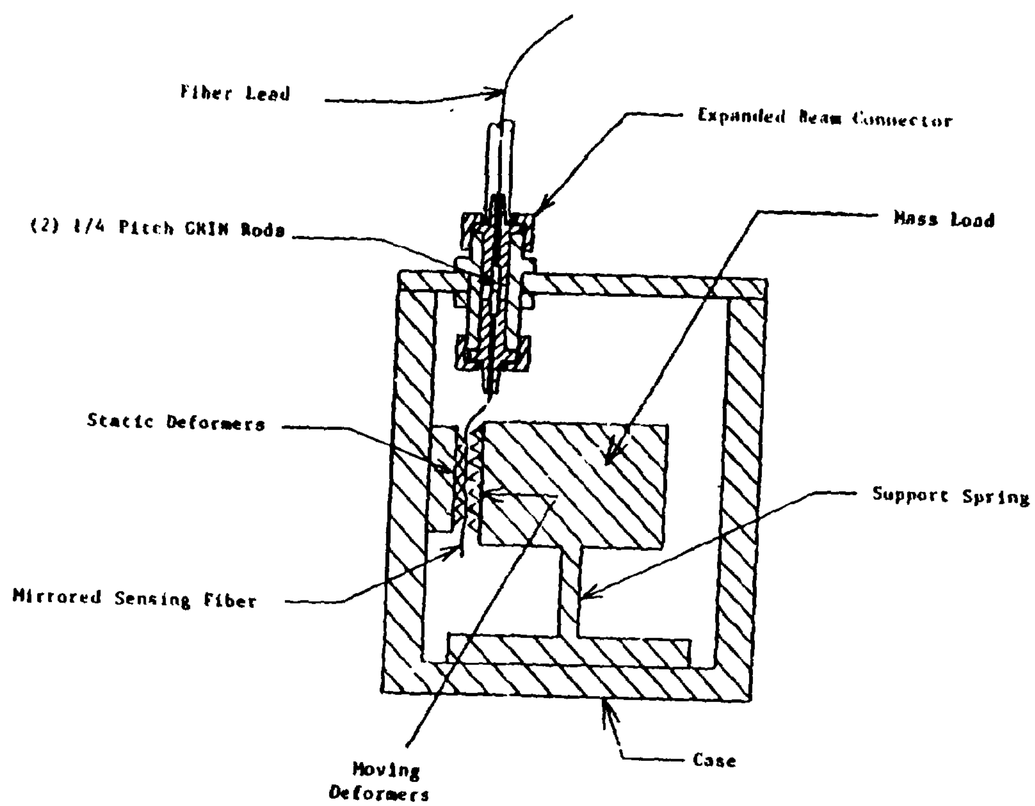


Figure 3.9-1. Microbend Accelerometer

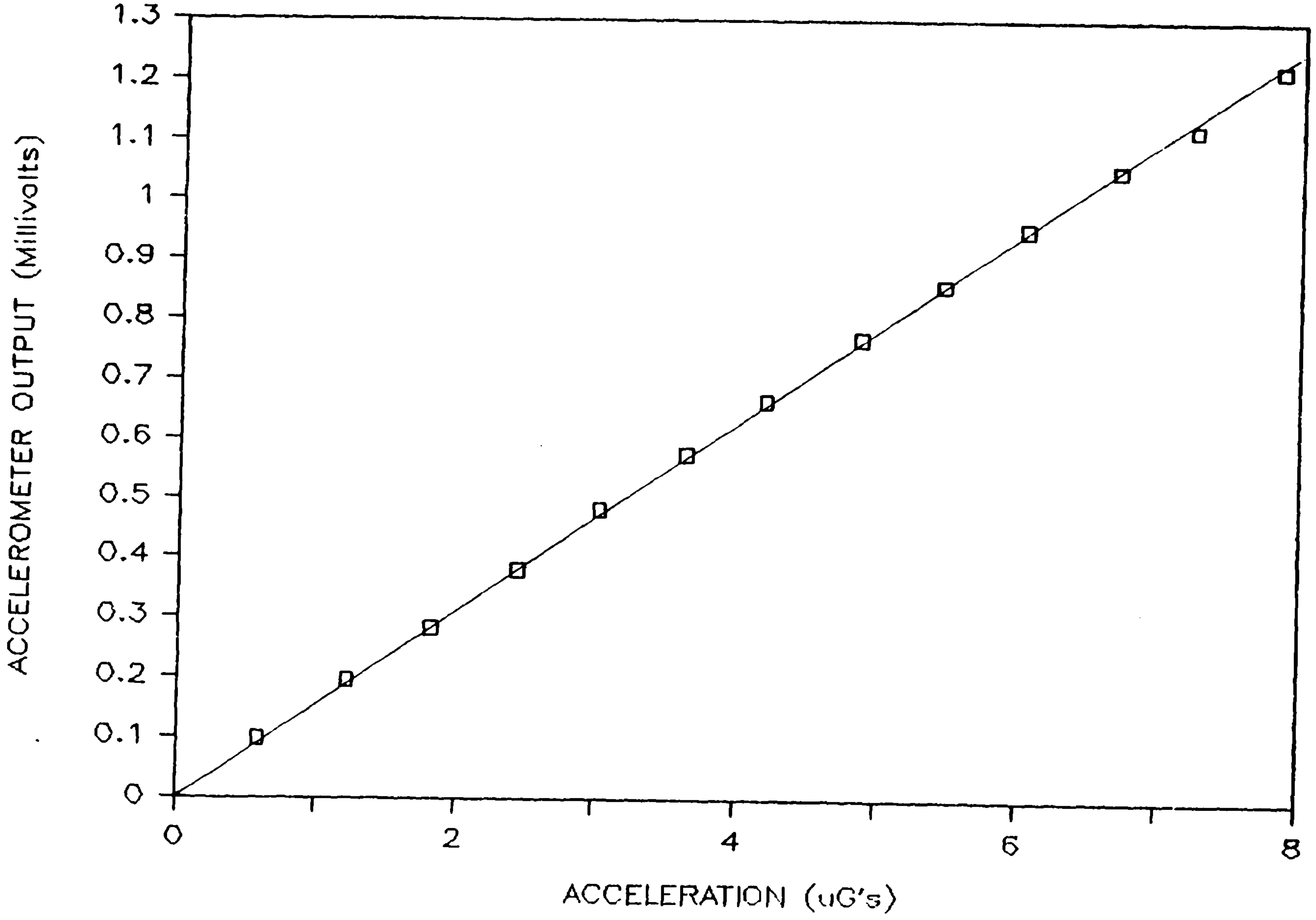


Figure 3.9-2. Typical Microbend Accelerometer Data

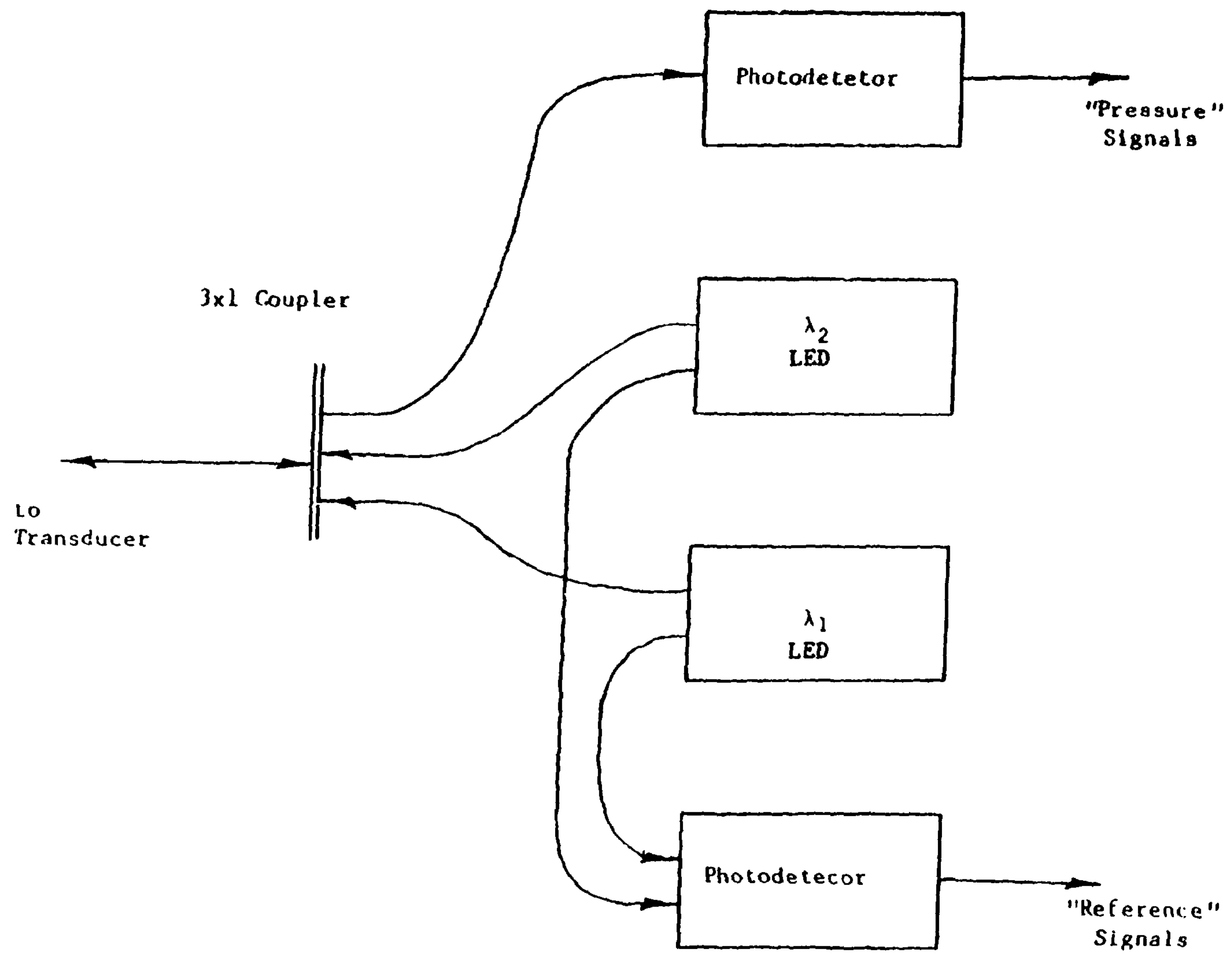


Figure 4.3-1. Amplitude Type Sensor Optical Interface

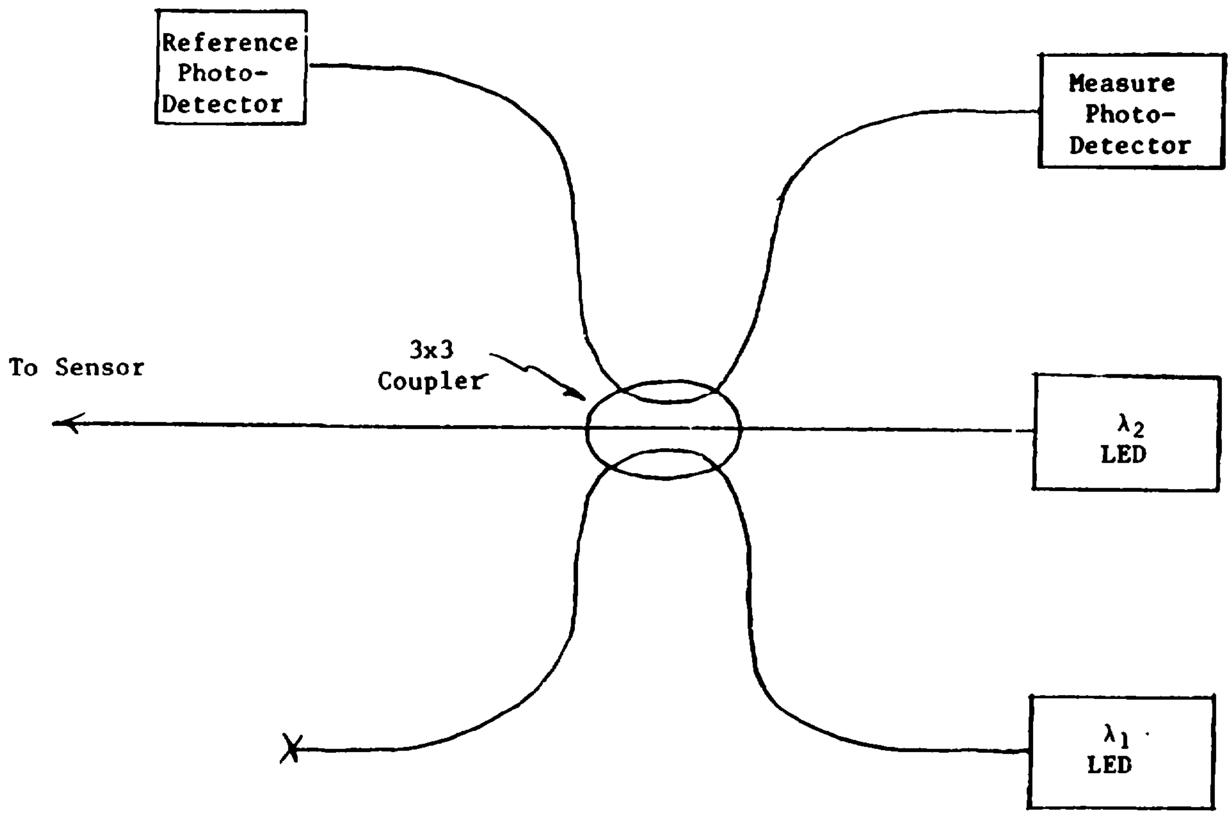


Figure 4.5-1. Alternate Optical Module Design

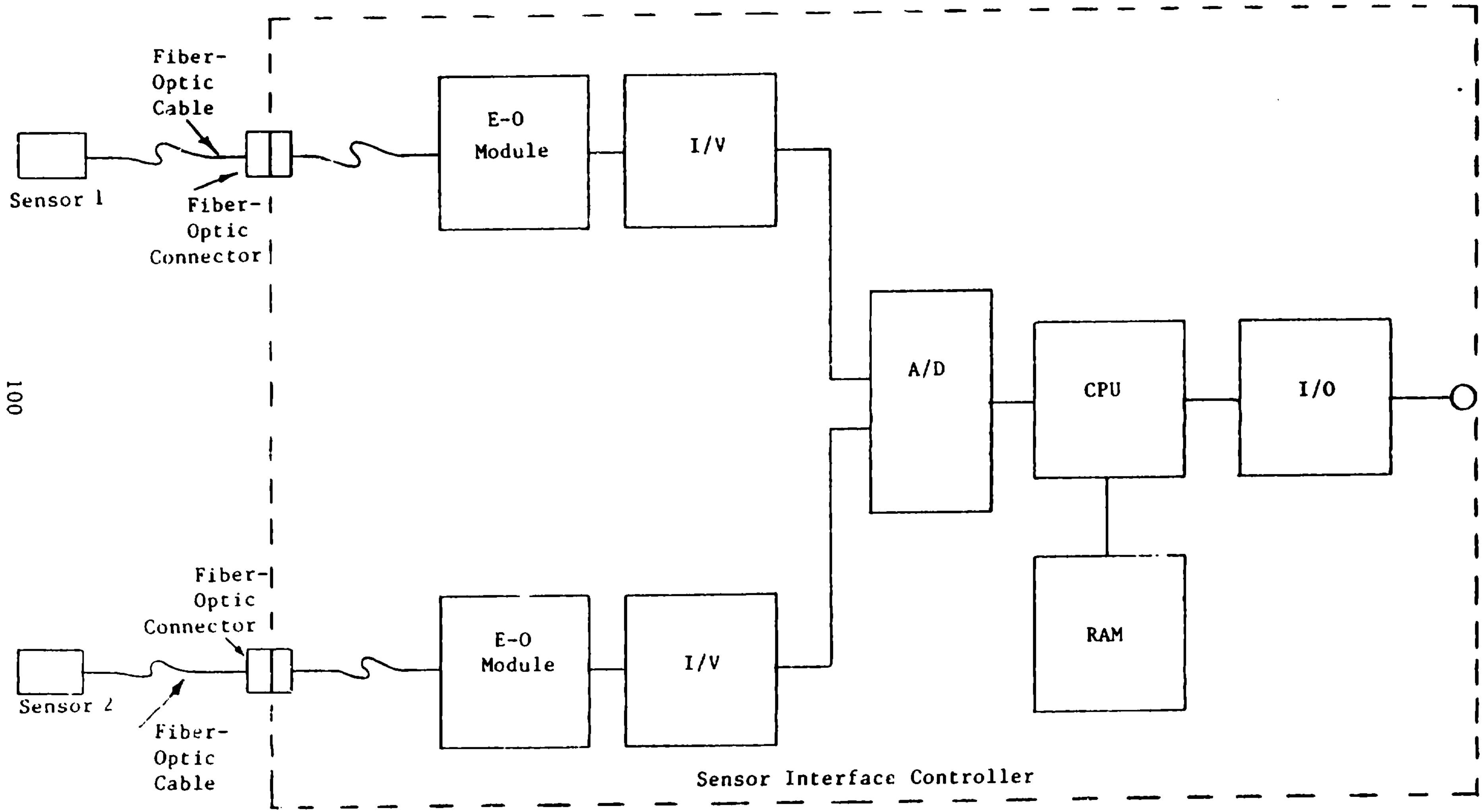


Figure 5.4-1. Sensor Interface Controller Block Diagram

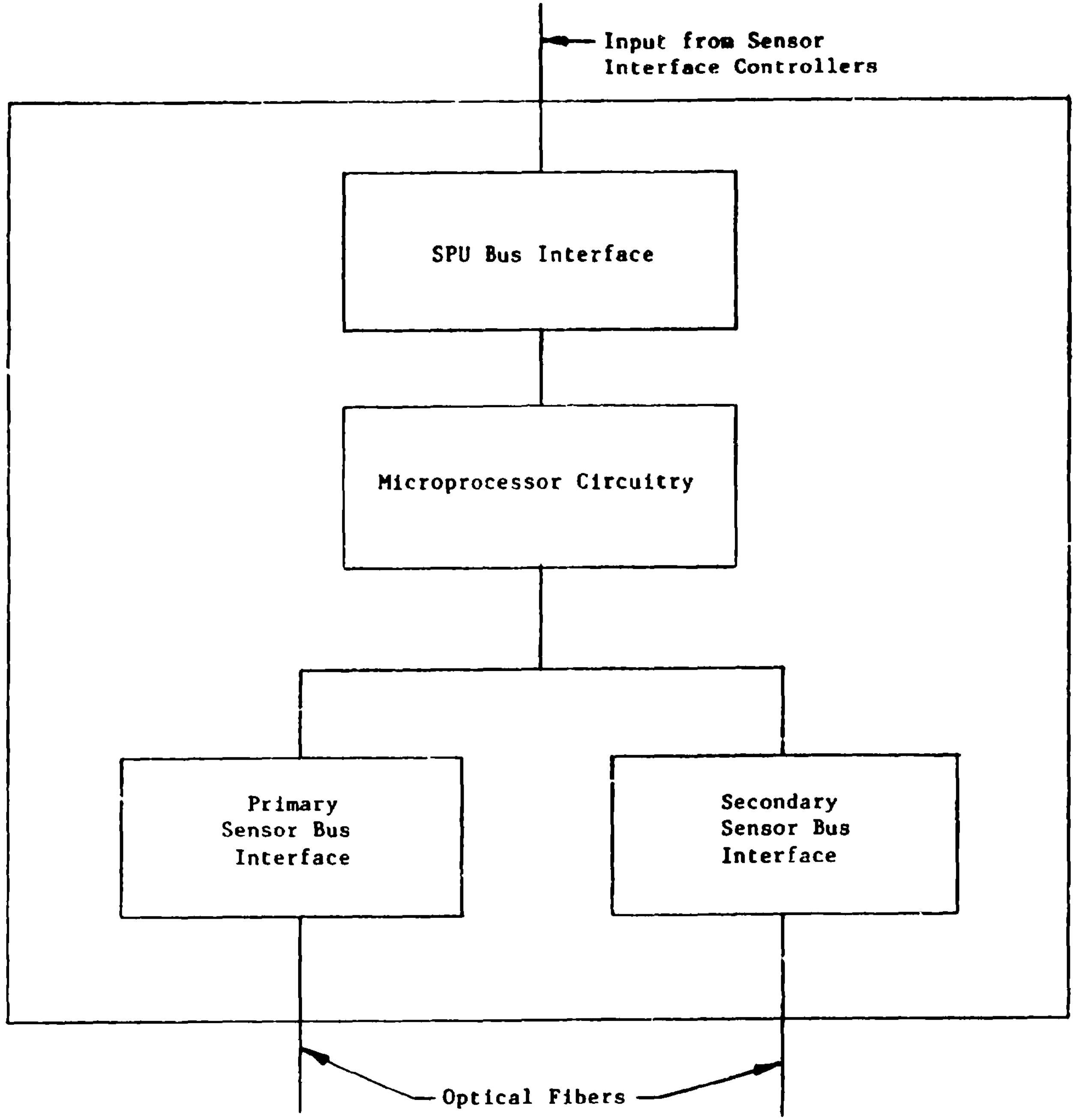


Figure 5.5-1. Sensor Management Controller

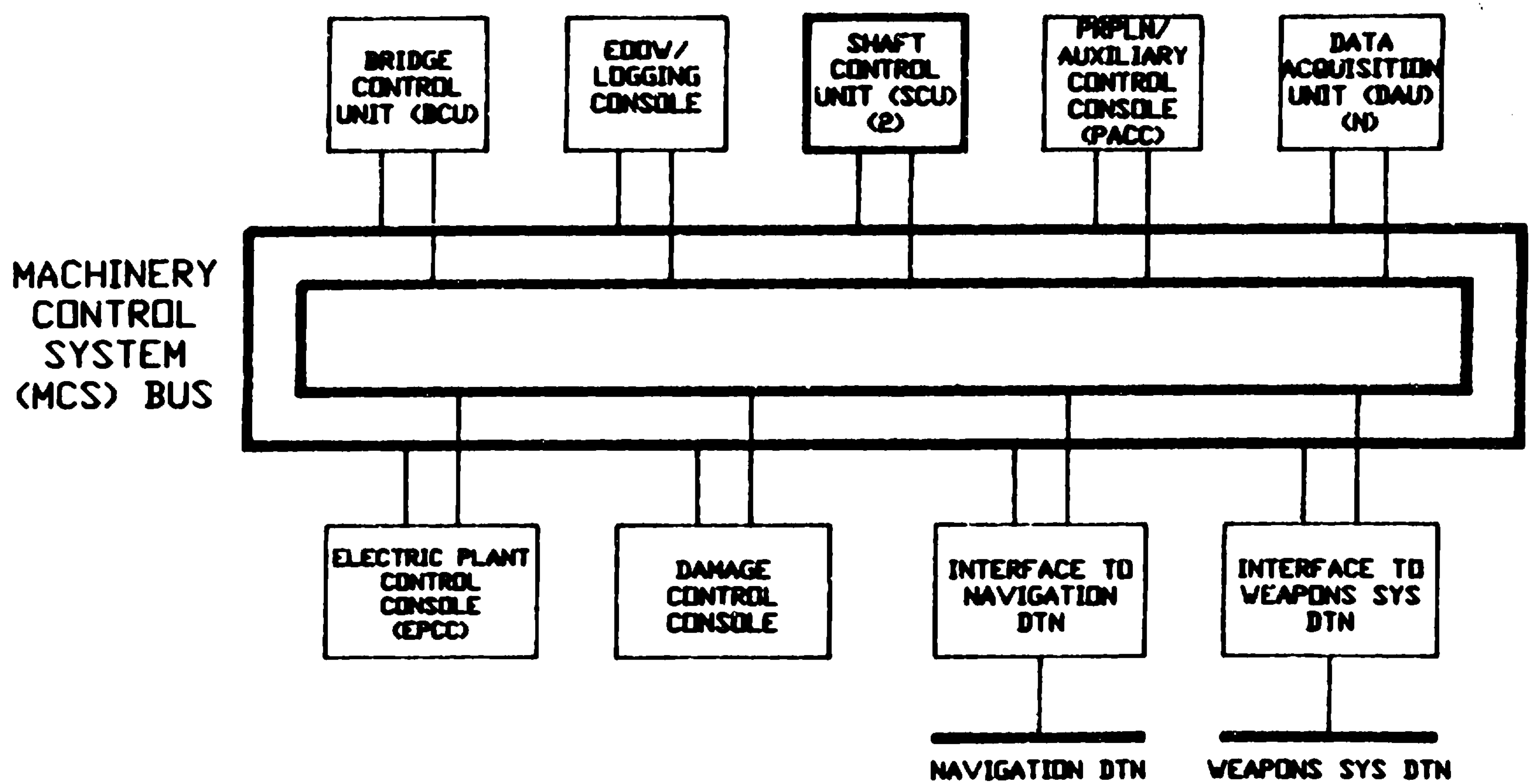


Figure 6.3-1. Shipboard Data Transfer Network

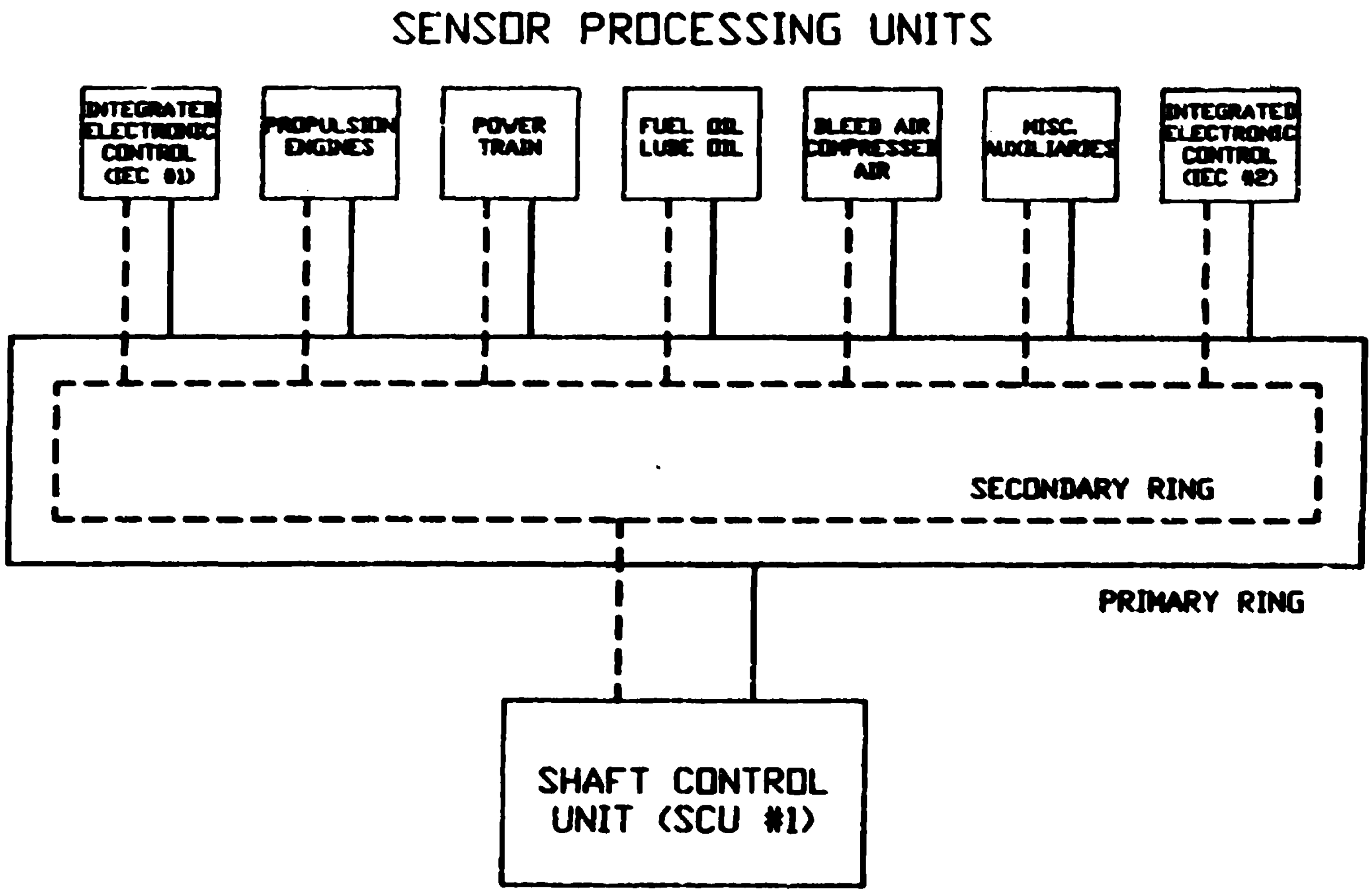


Figure 6.3-2. Shaft Control Unit Bus Implementation

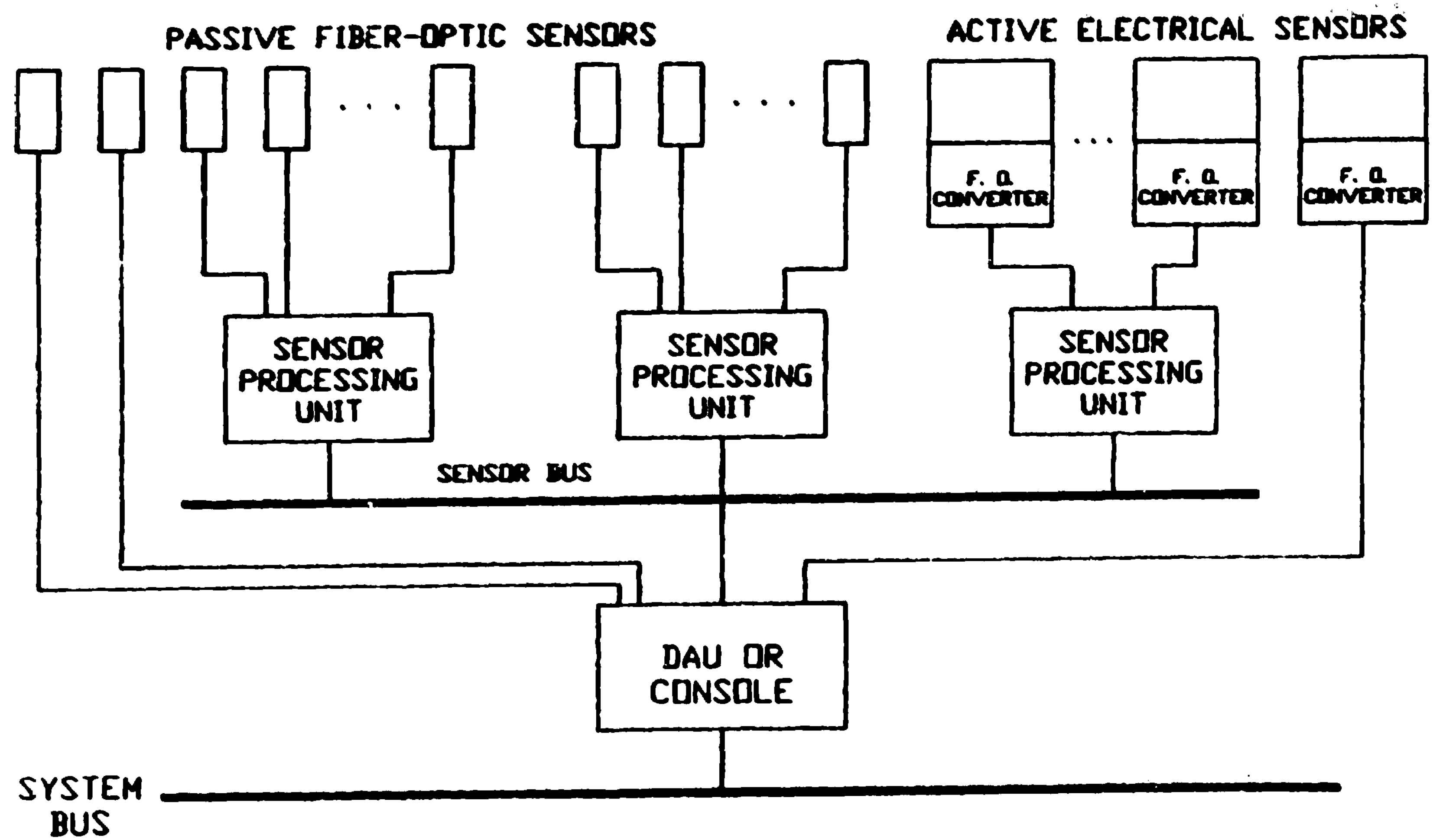


Figure 6.3-3. Sensor Telemetry Subsystem

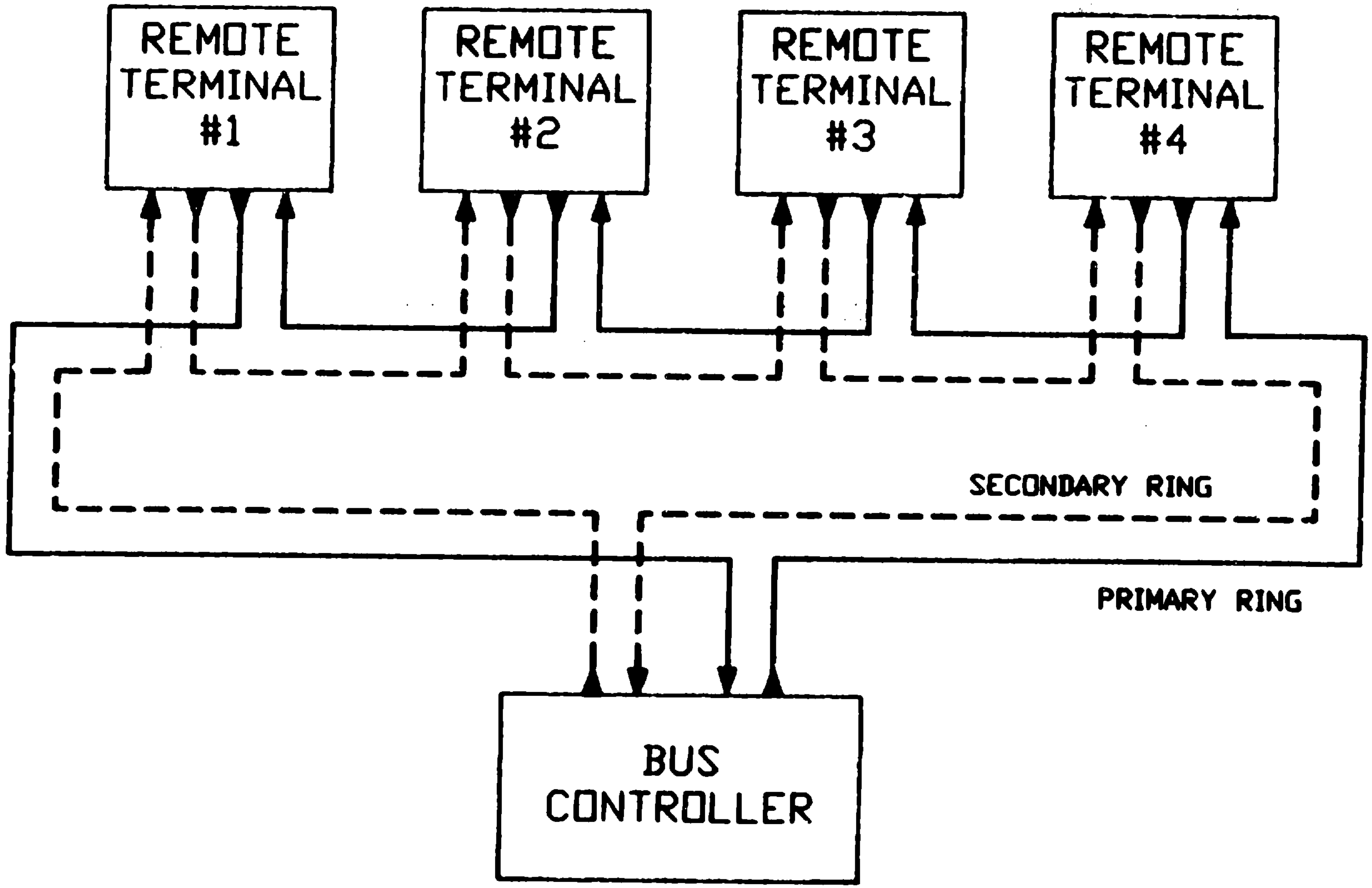


Figure 6.6-1. Counter-Rotating Ring Bus

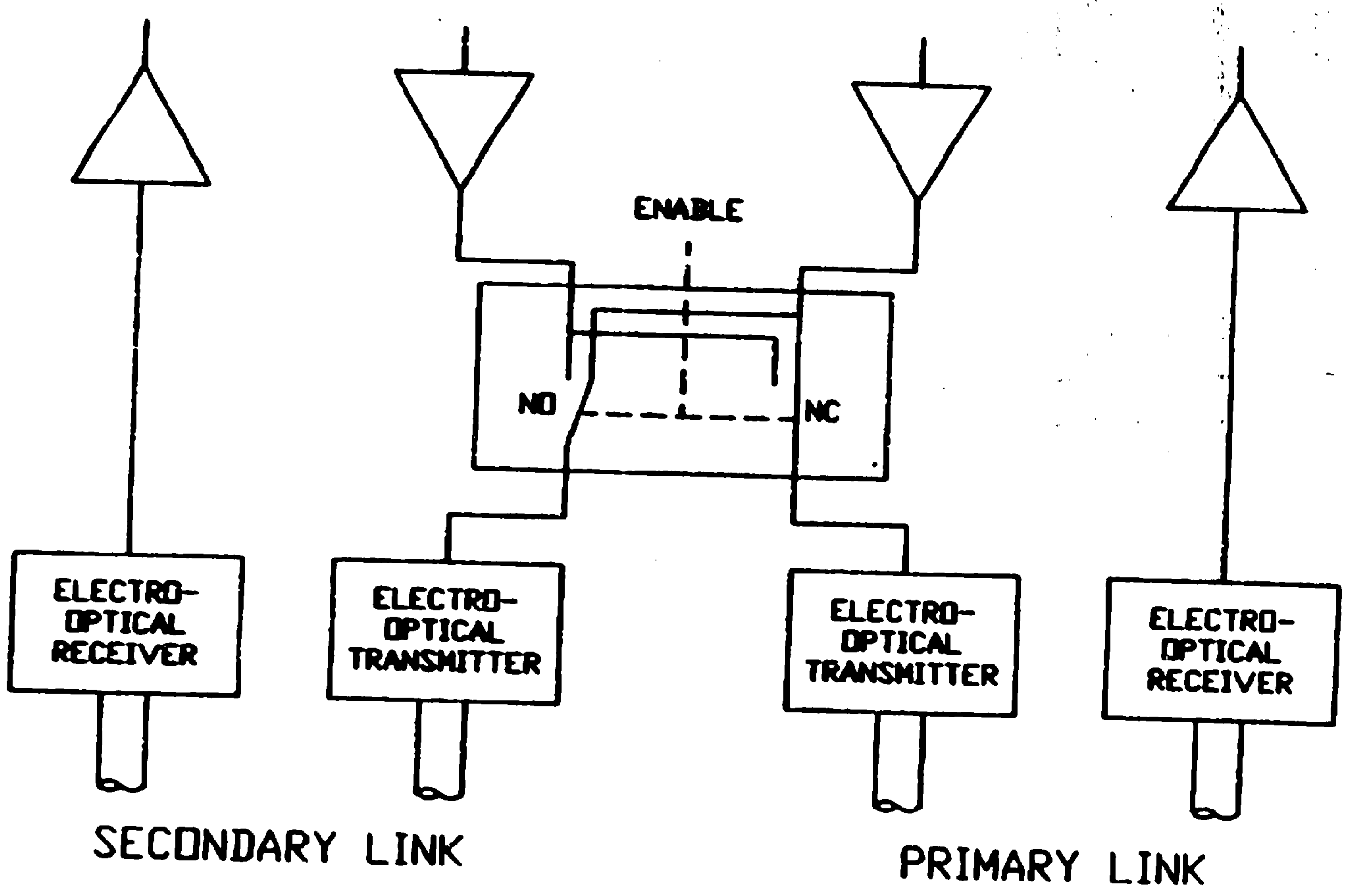


Figure 6.6-2. Ring Bus Switching Scheme

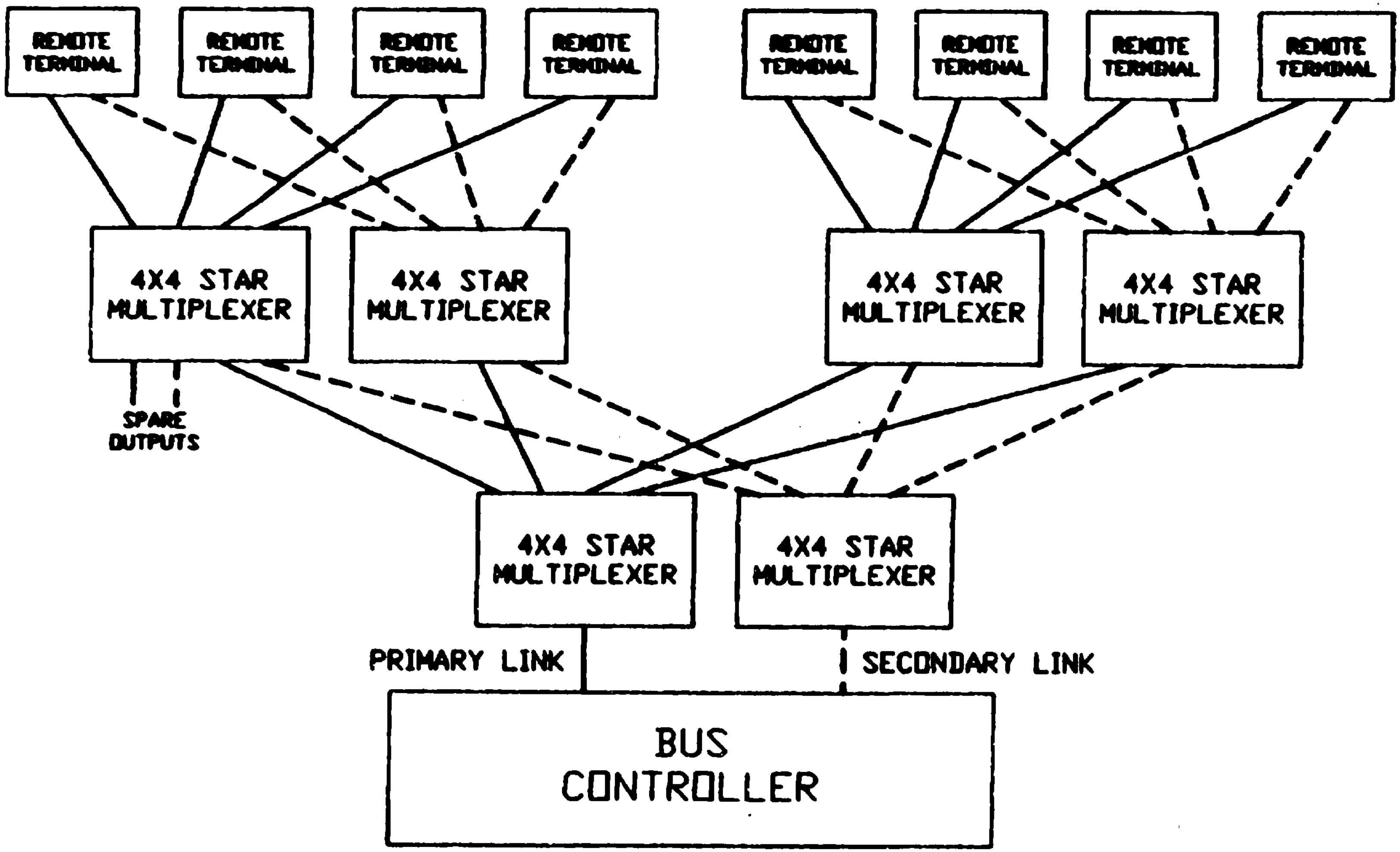


Figure 6.6-3. Star Network Using 4x4 Stars

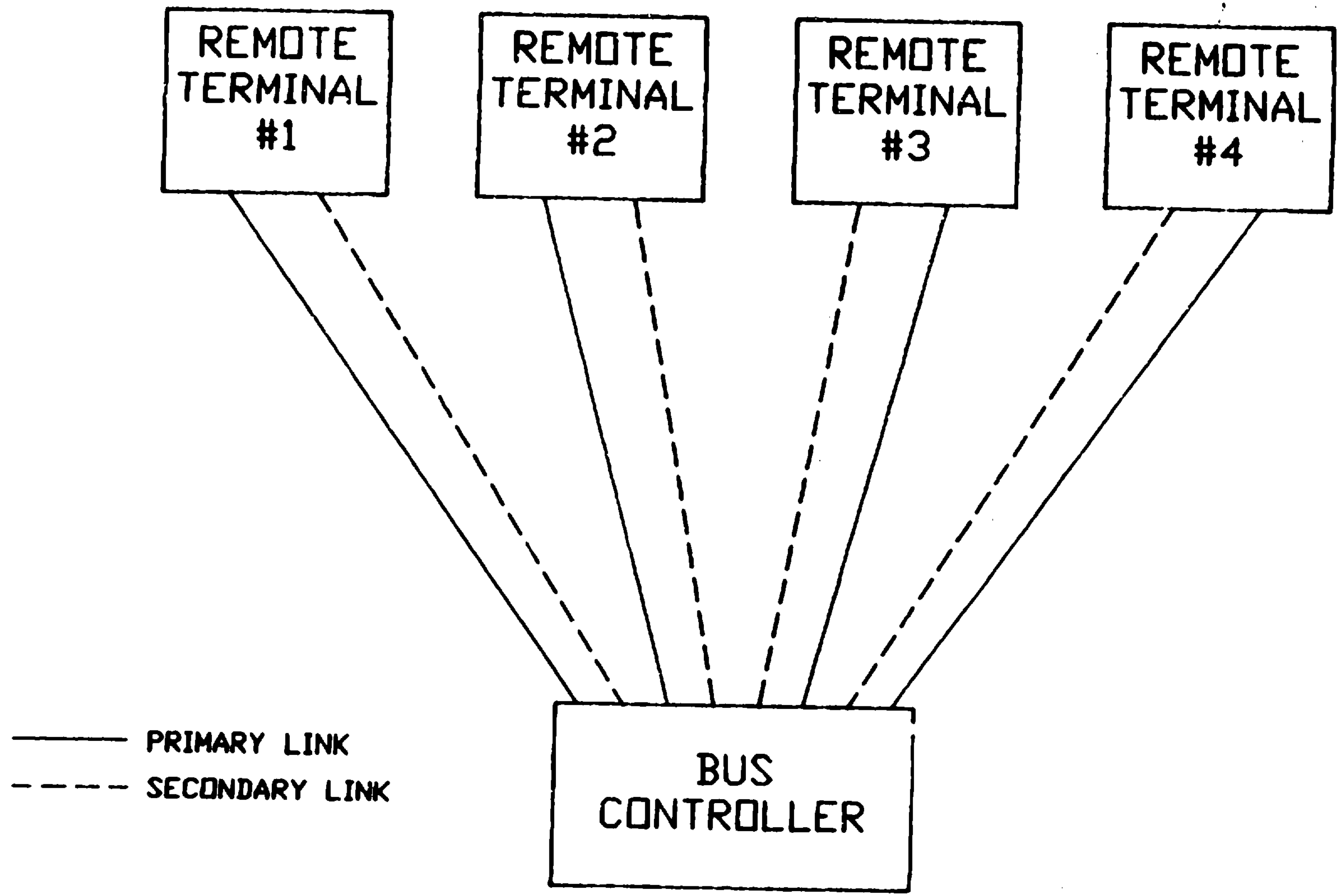


Figure 6.6-4. Point to Point Network

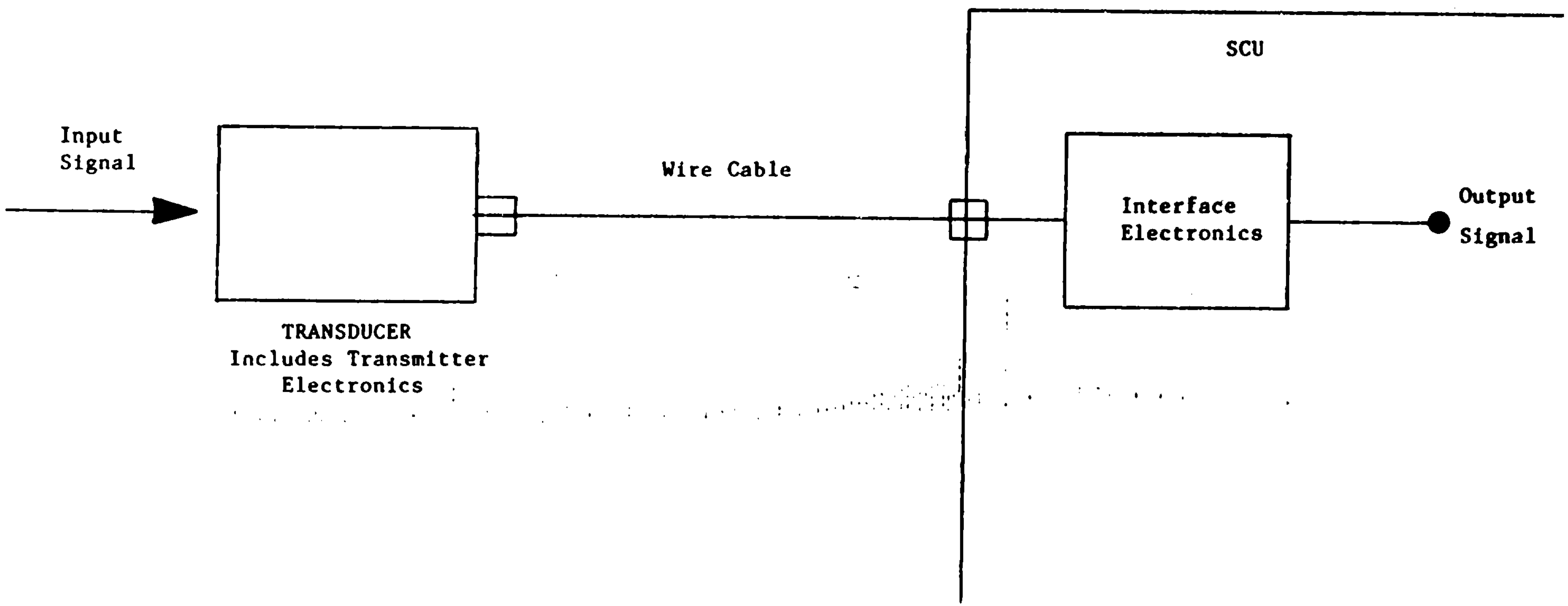


Figure 7.1-1. Cost Model for Conventional Transducer Systems

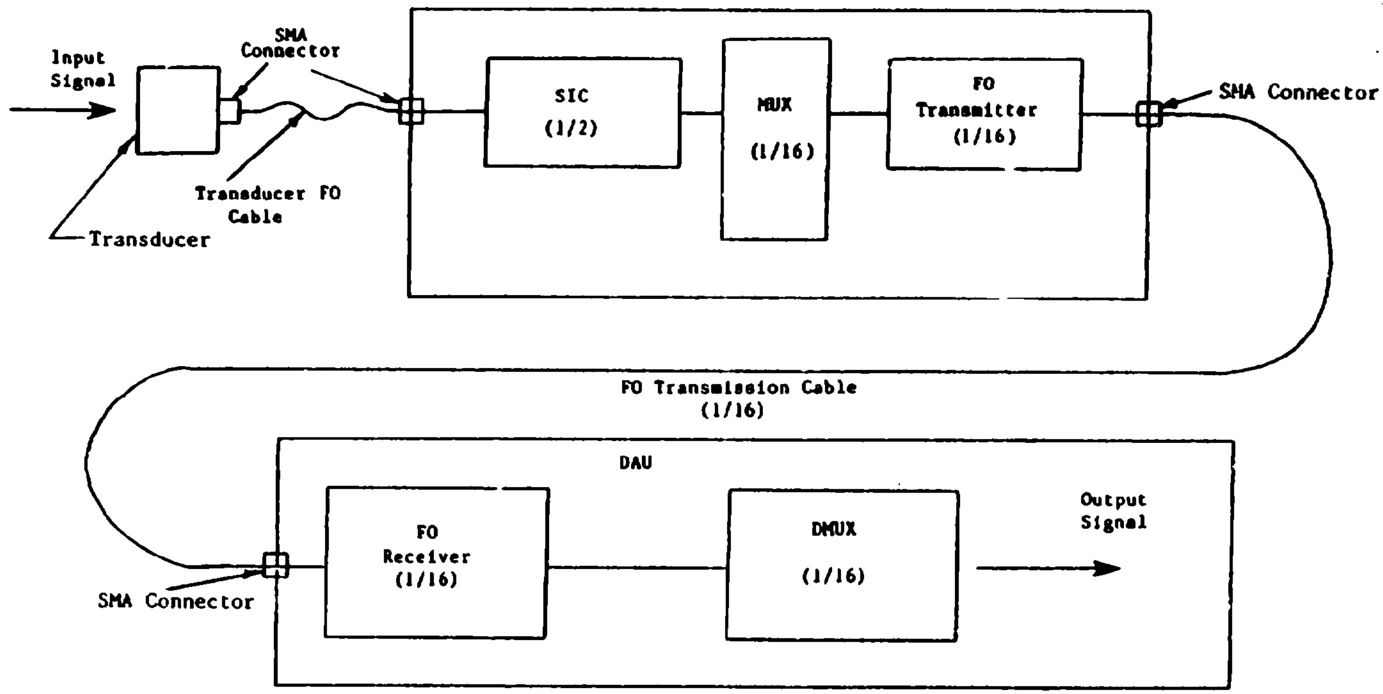


Figure 7.1-2. Cost Model for Fiber-Optic Transducer Systems

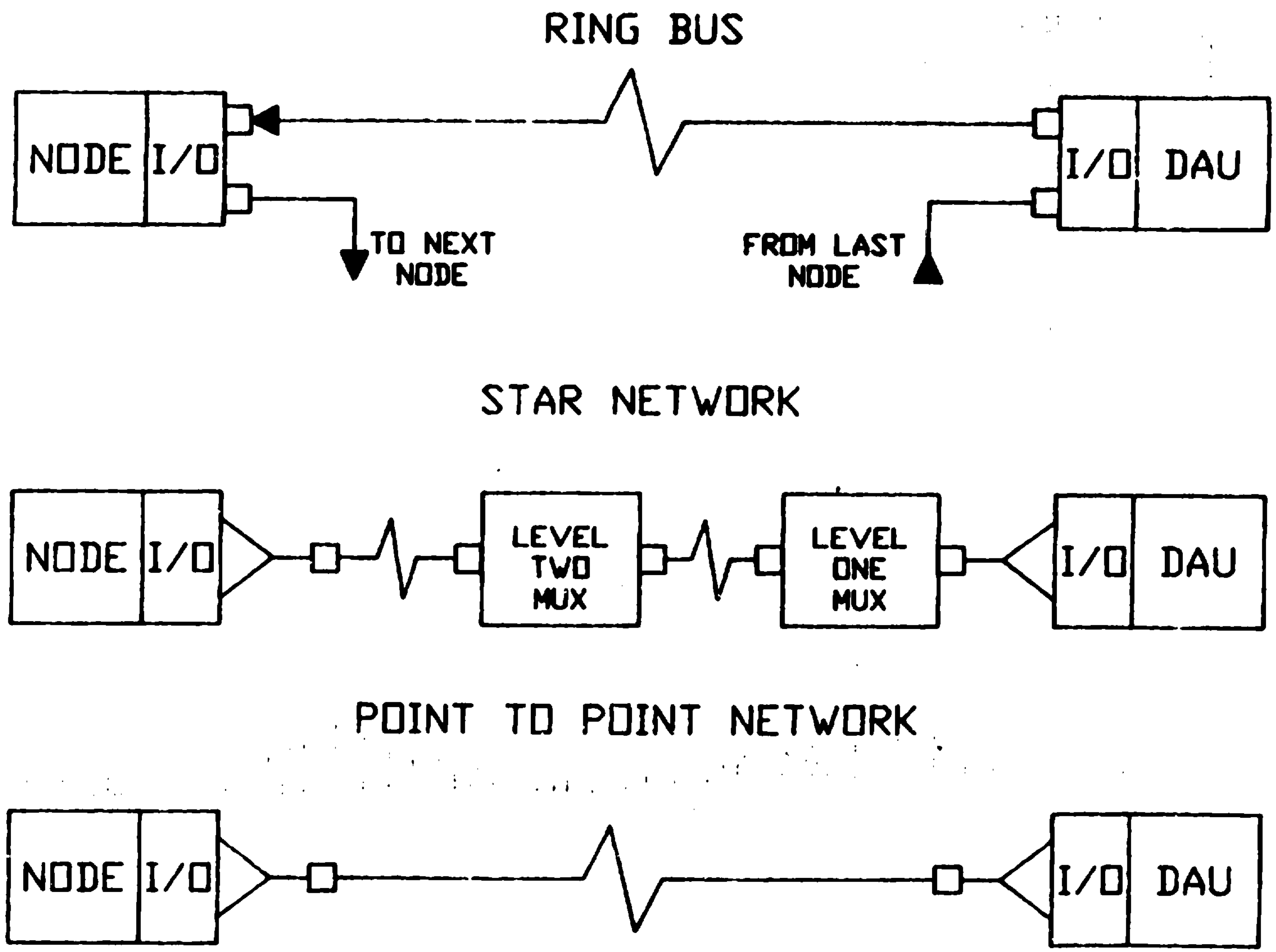


Figure 7.2-1. Telemetry Comparison Cost Models

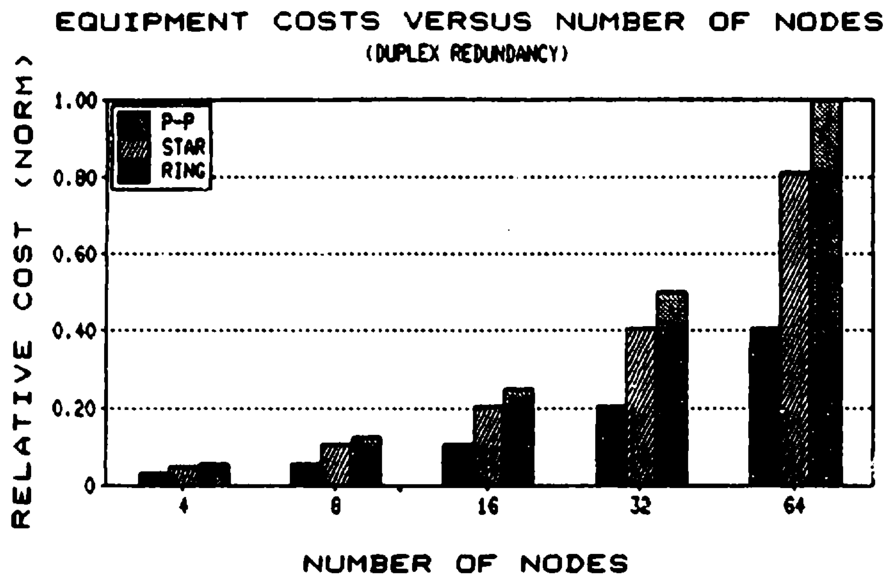


Figure 7.2-2. Normalized Equipment Cost Comparision

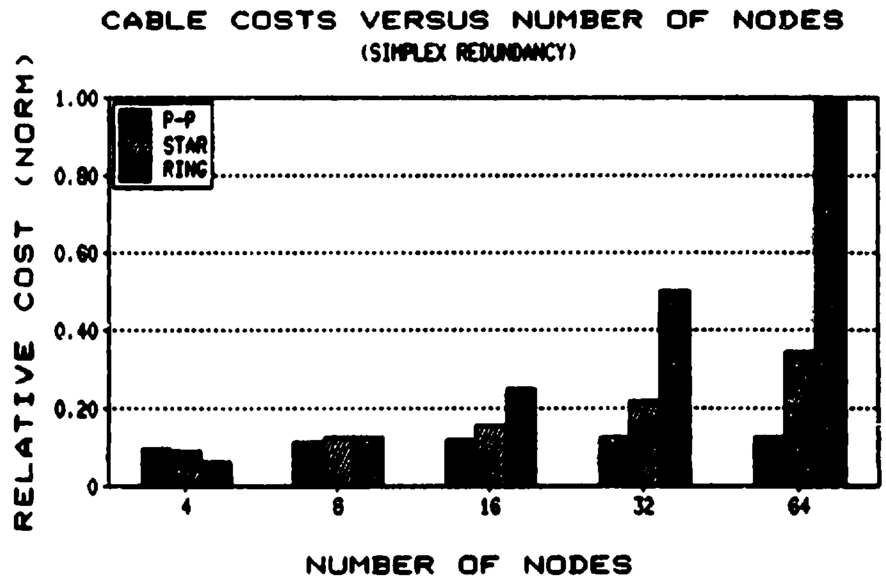


Figure 7.2-4. Normailized Cable Length Comparison

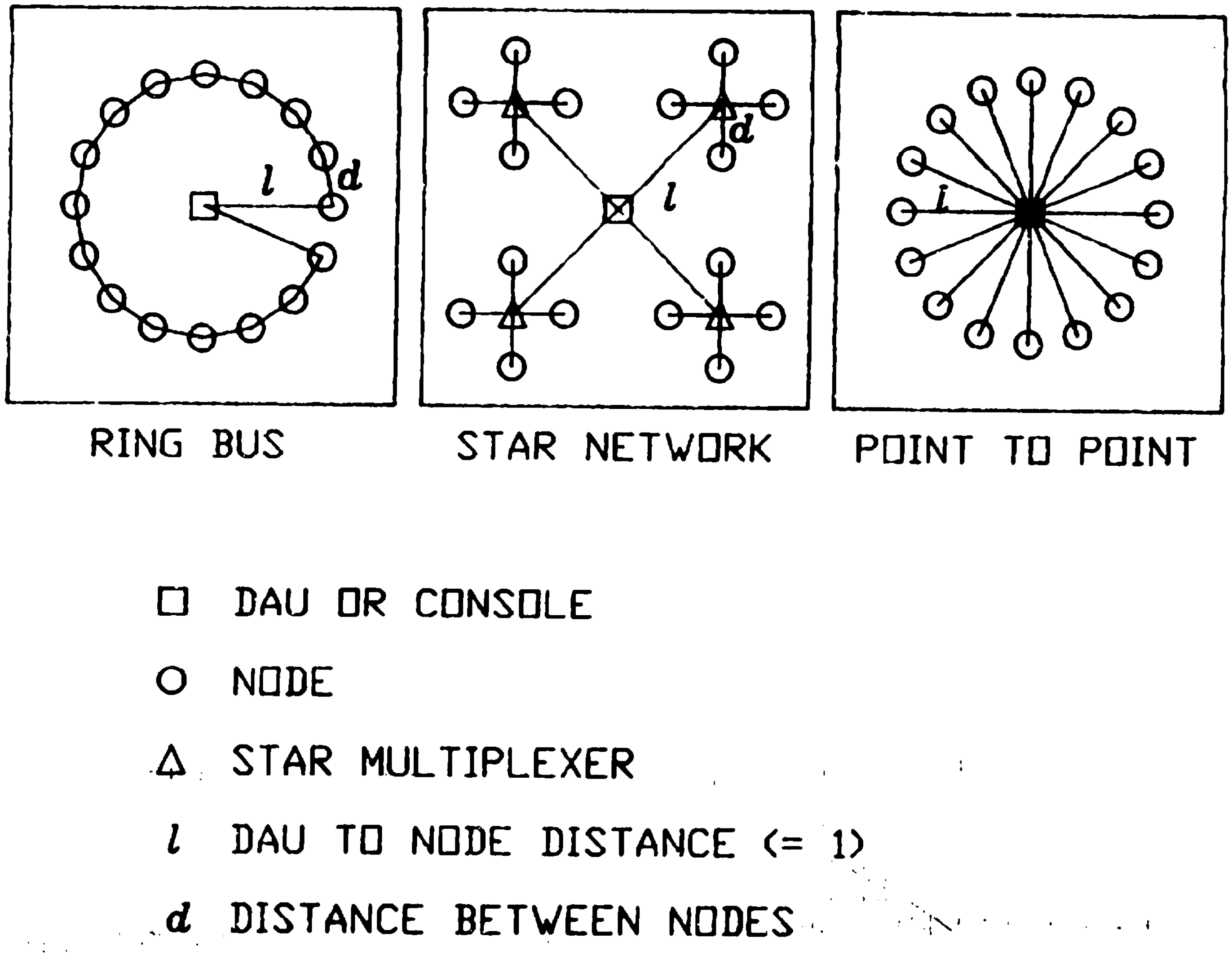


Figure 7.2-3. Node Configuration for Cable Comparisons

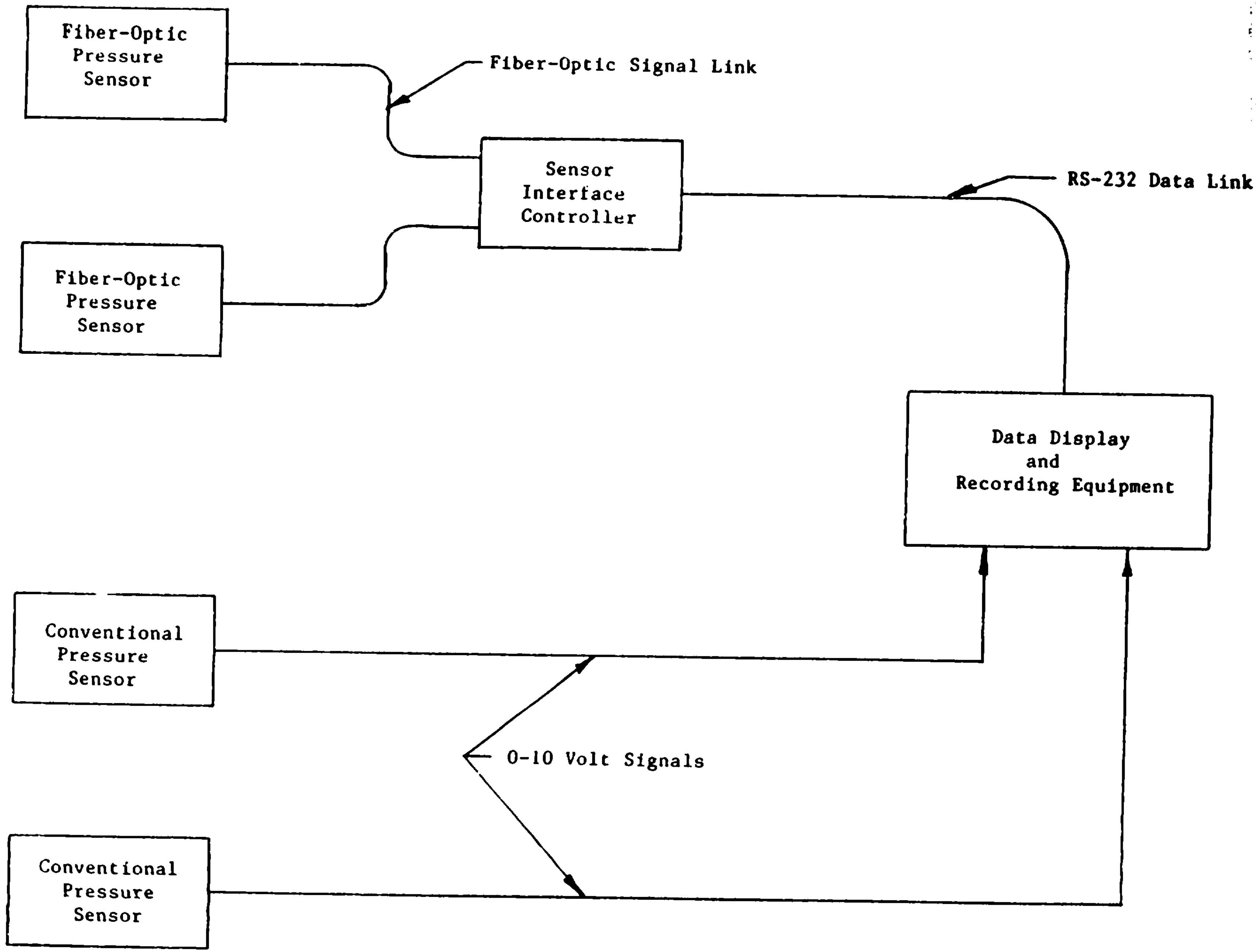


Figure 8.1-1. Laboratory Demonstration Model

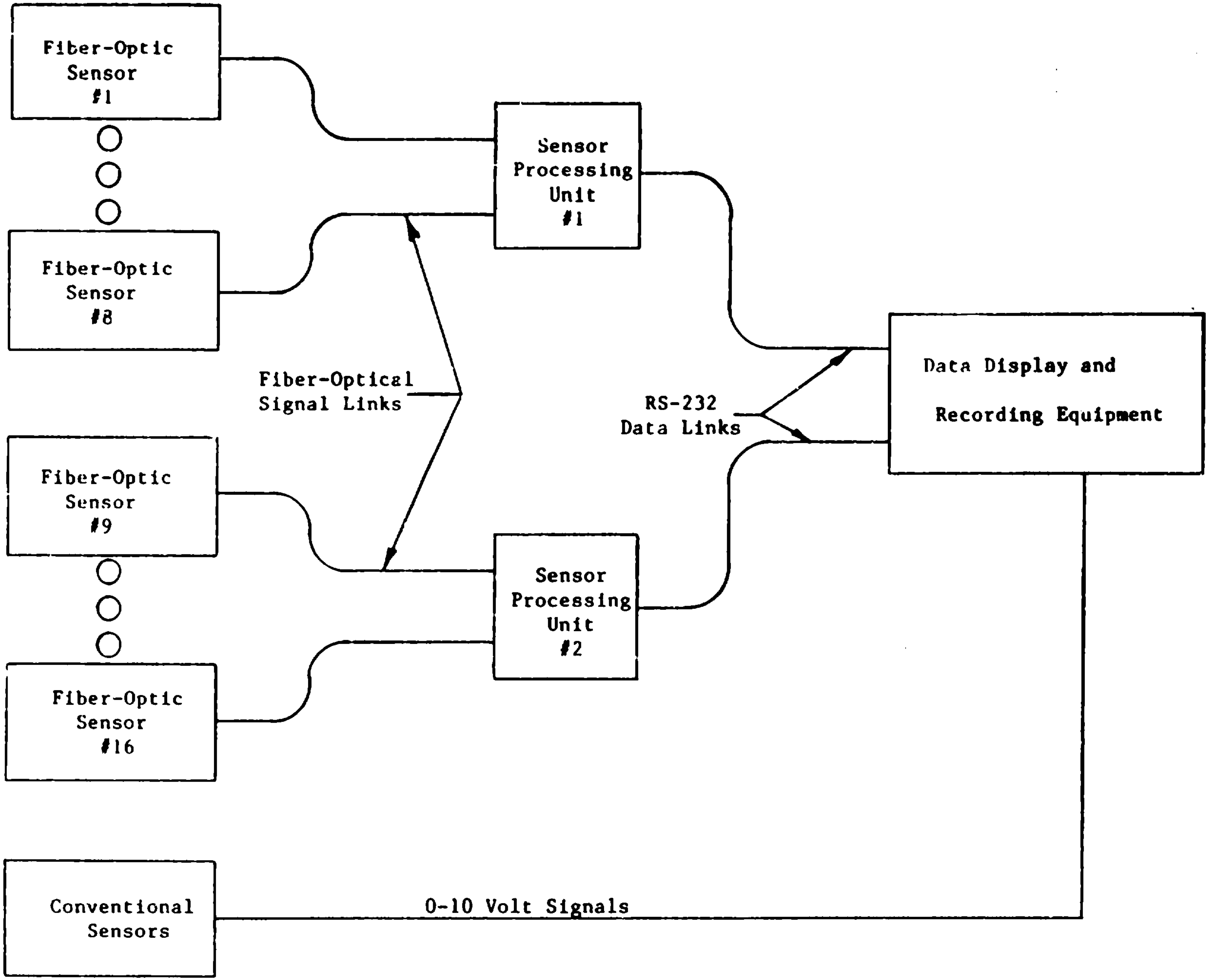


Figure 8.2-2. Advanced Development Model

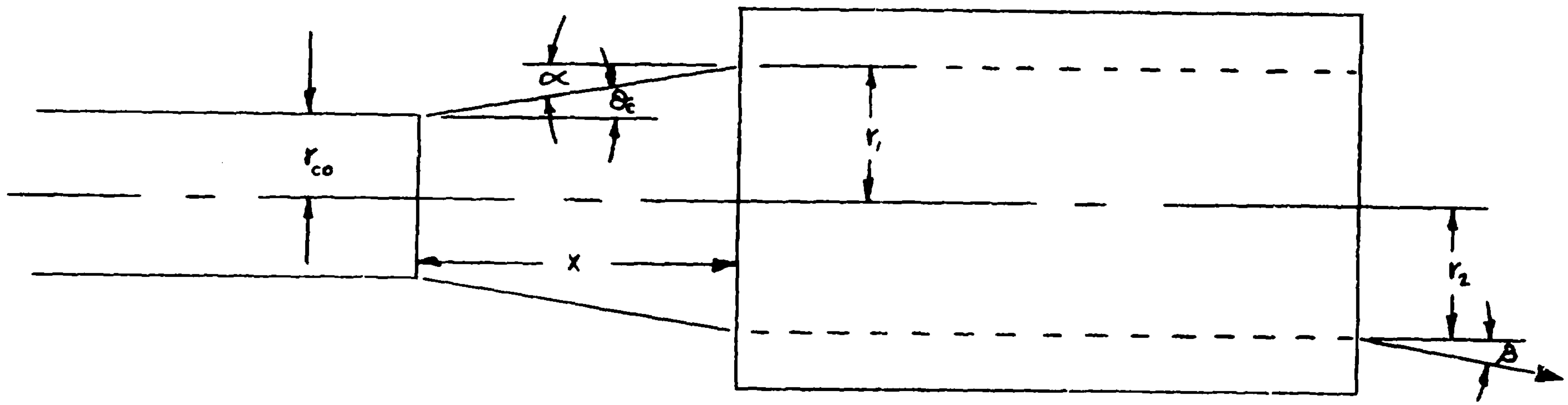


Figure 13.0-1. GRIN Rod Geometry

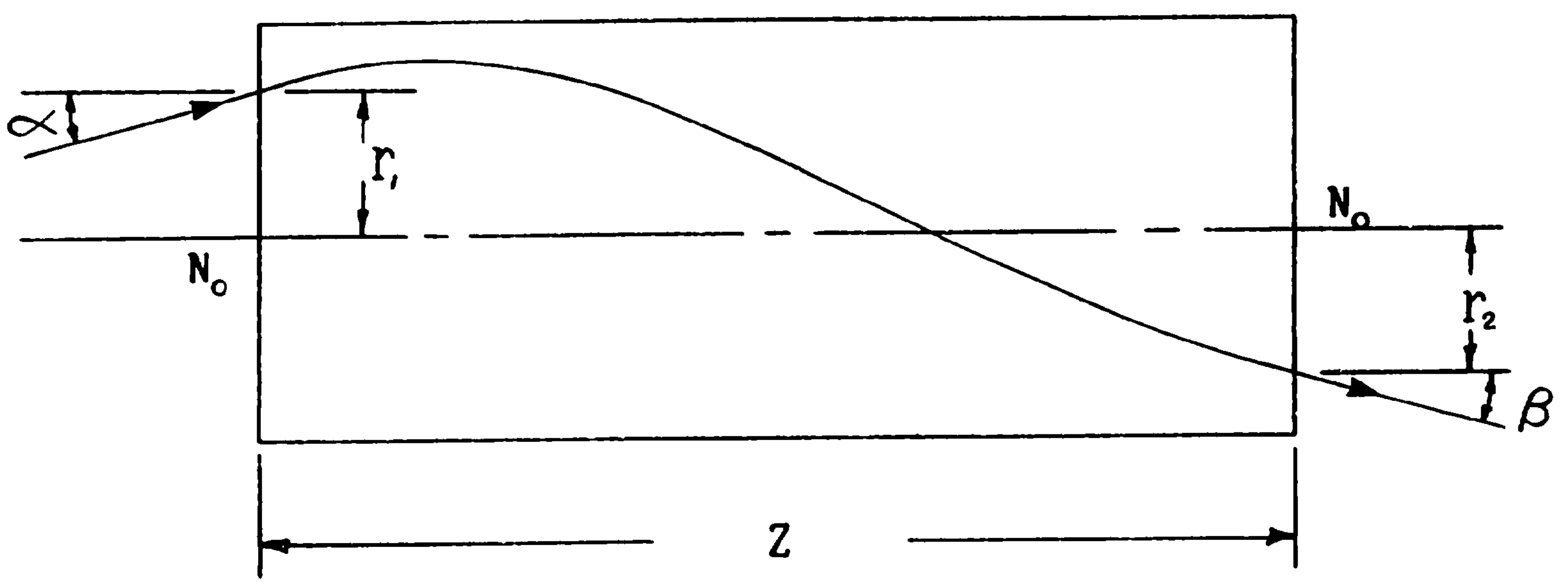


Figure 13.0-2. GRIN Rod Ray Design

NA = 0.20 L= 10 cm Constant Curvature Loss

n_c = 1.472, n_{cl} = 1.458, n = 1.463, NA = 0.2

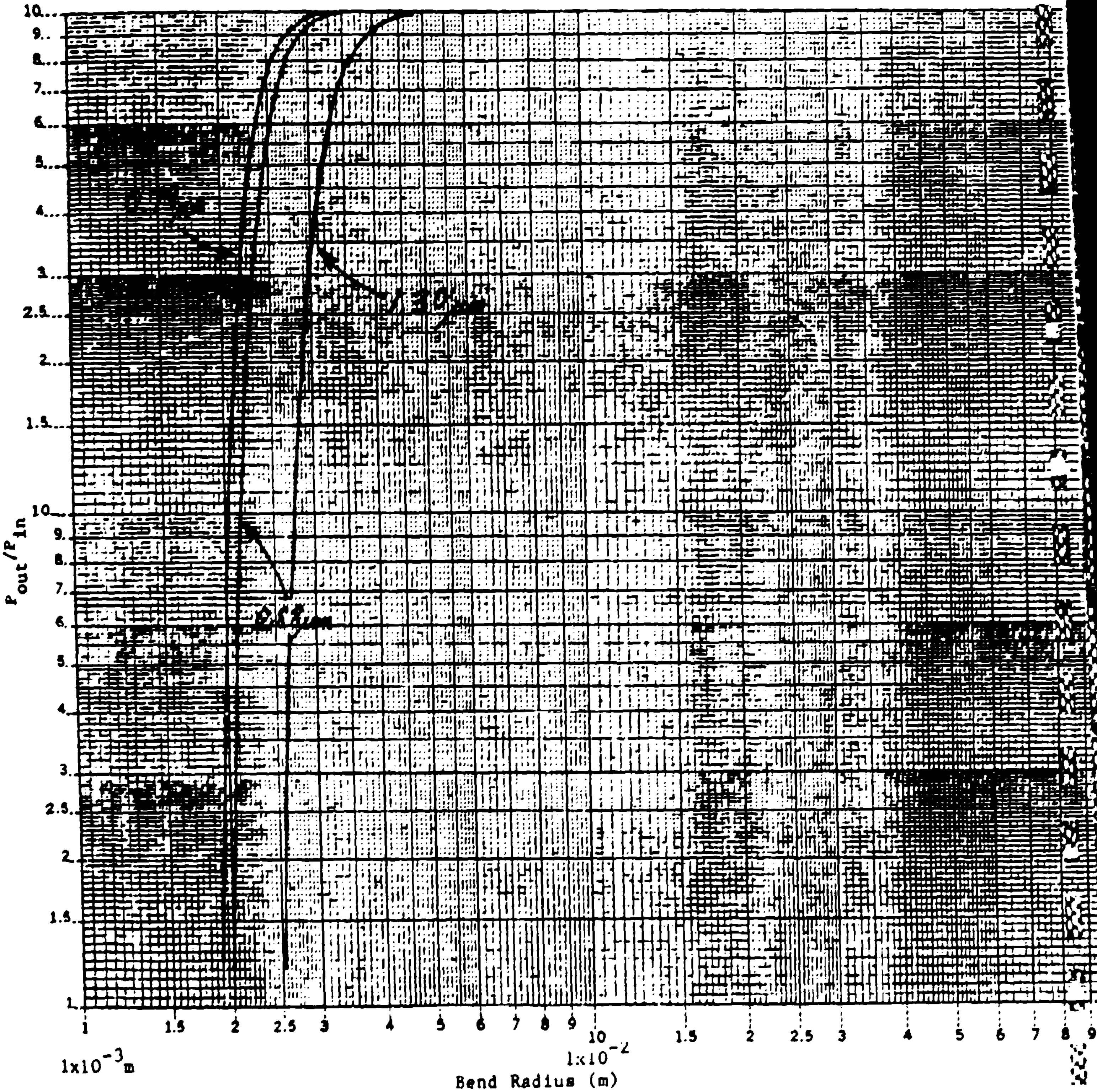


Figure 14.2-1. Attenuation vs. Bend Radius for Constant Curvature Fiber

Transition Loss for a Fiber Where $N_c = 1.463$, $N_{cl} = 1.458$, $a = 2\mu m$, NA = 0.12

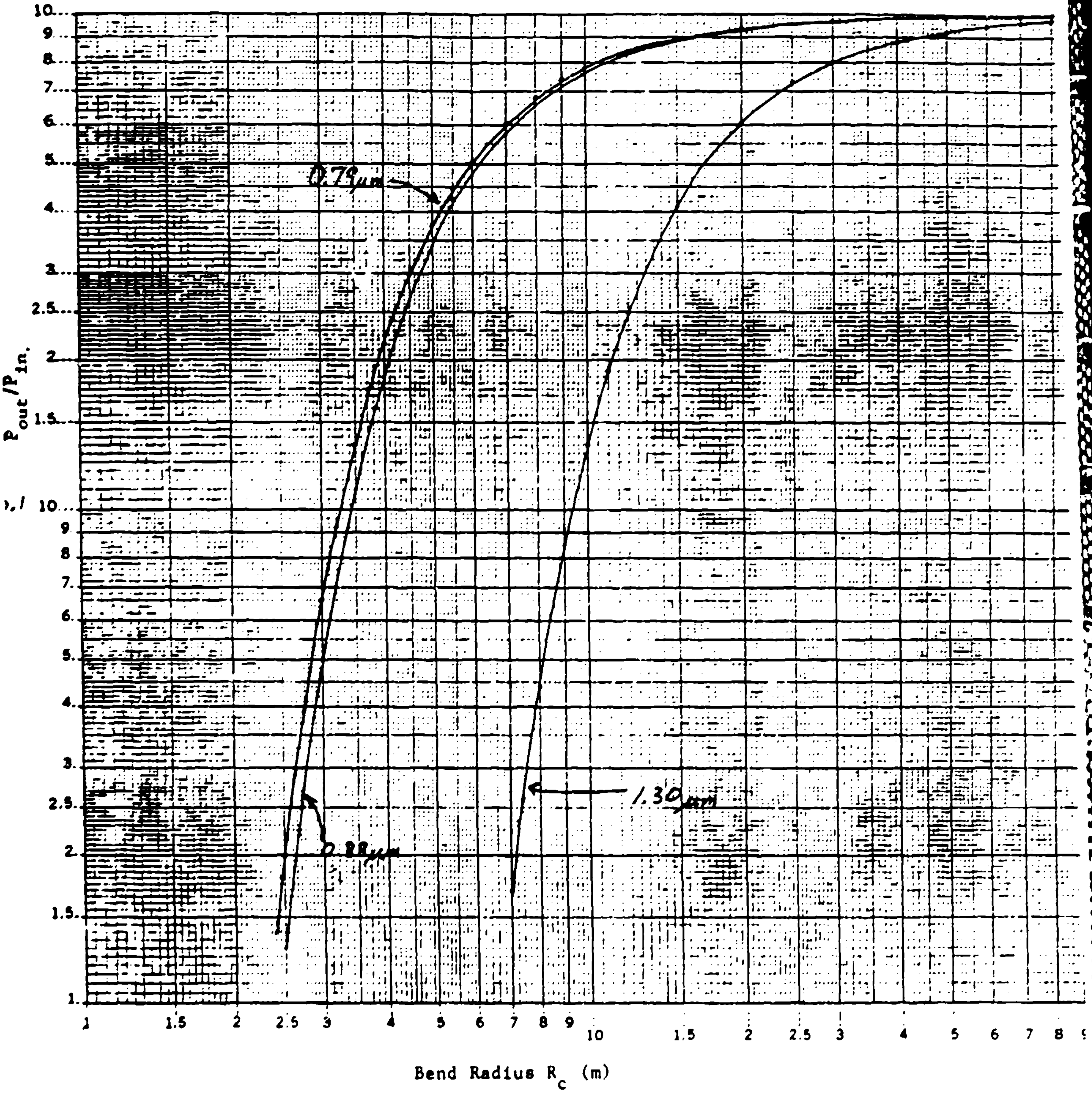


Figure 14.3-1. Attenuation vs. Bend Radius for a Straight-to-Curved Fiber Section

Transition Loss: Two Curved Sections
("S" Curve with R_c = For Both Curves)
1/27/86 N_c = 1.463, N_{cl} = 1.458, a = 2μm, NA = 0.12

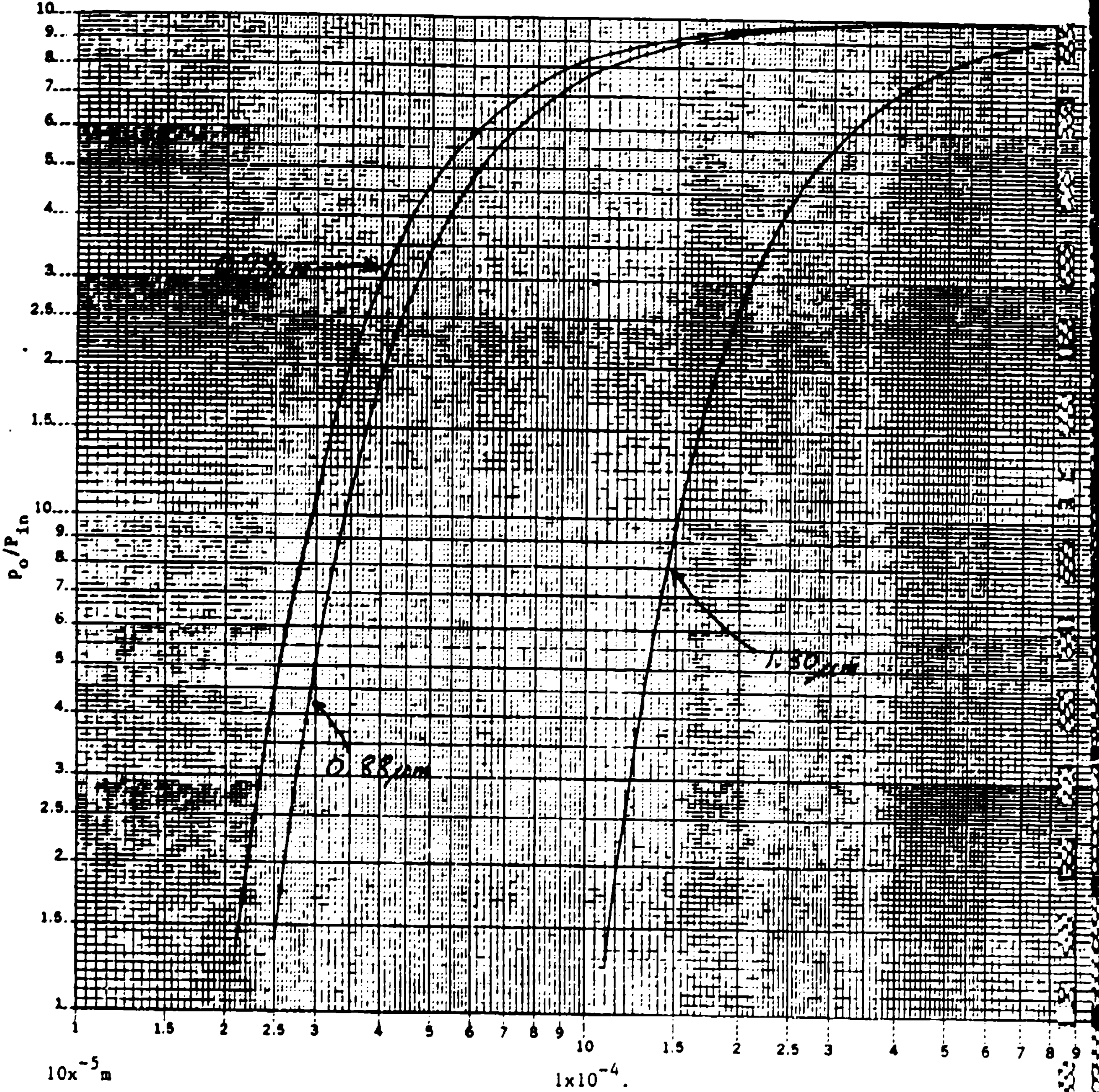


Figure 14.3-2. Attenuation vs. Bend Radius for a Curved-to Curved Section of Fiber