NASA Technical Memorandum 83542

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(NASA-TM-83542) FIBEECETICS FCE FECPULSION CCNTEOL SYSTEM (NASA) 15 p HC A02/MF A01 CSCL 20F

N84-14111

Unclas

G3/01 42815

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Prepared for the
Twenty-ninth Annual International Gas Turbine Conference
sponsored by the American Society of Mechanical Engineers
Amsterdam, The Netherlands, June 4-7, 1984

NASA

FIBEROPTICS FOR PROPULSION CONTROL SYSTEMS

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E-1913

ABSTRACT

The term "fiberoptics" means the use of dielectric waveguides to transfer information. In aircraft systems with digital controls, fiberoptics has advantages over wire systems because of its inherent immunity to electromagnetic noise (EMI) and electromagnetic pulses (EMP). It also offers a weight benefit when metallic conductors are replaced by optical fibers. To take full advantage of the benefits of optical waveguides, passive optical sensors are also being developed to eliminate the need for electrical power to the sensor. Fiberoptics may also be used for controlling actuators on engine and airframe. In this application the optical fibers, connectors, etc. will be subjected to high temperatures and vibrations.

This paper discusses the use of fiberoptics in aircraft propulsion systems together with the optical sensors and optically controlled actuators being developed to take full advantage of the benefits which fiberoptics offers. The requirements for sensors and actuators in advanced propulsion systems are identified. The benefits of using fiberoptics in place of conventional wire systems are discussed as well as the environmental conditions under which the optical components must operate. Work being done under contract to NASA Lewis on optical and optically activated actuators sensors for propulsion control systems is presented.

INTRODUCTION

Fiberoptics offers potential improvements in reliability over conventional wire systems in aircraft applications. The term fiberoptics as used herein means the use of dielectric waveguides to transfer optical signals from one point to another. The complete optical circuit consists of a light source, photodetector, optical connectors, optical waveguide and a device that either modulates the optical signal or uses it to accomplish some other task such as activation of an actuator.

This paper discusses the requirements of sensors and actuators needed on future propulsion control systems. The requirements for optical components are also included in this discussion. The benefits of using fiberoptics over conventional wire systems are listed and the work sponsored by NASA Lewis Research Center to develop fiberoptics and optical sensors for use in propulsion control systems is discussed.

REQUIREMENTS

Figure 1 illustrates sensors and actuators which might be required for a supersonic propulsion system. In general, the sensor and actuator requirements will depend on the type of propulsion system being considered. For example, commercial propulsion systems will be different than military systems and supersonic operation will result in different requirements than subsonic operation. Parameters that might be measured in the inlet are pressures to determine terminal shock position and position measurements to identify spike position and bypass door position. For the engine, pressures are measured to control engine steady-state operation. Speed measurements and rate of change of engine speed are needed to control engine acceleration. Speed and turbine inlet temperatures are measured to guard against overspeed and overtemperature. Inlet conditions at the compressor are required measurements to optimize engine geometry. Position measurements are required to monitor and control the variable geometry of the compressor and turbines in order to insure optimum engine operation. Also in some instances, tip clearance measurements and control may be required to improve engine operating efficiency.

The following discussion describes current design practice for electronic control systems. Pressure sensors are usually located in the electronics box to minimize the temperature effects on the pressure measurements. Pressure from the engine is brought to these sensors via pneumatic tubes. Temperature sensors are usually thermocouples located on the engine. Electrical wires connect the sensors to the computer module. Position measurements are made with linear variable displacement transducers which require electrical excitation at the transducers. Electrical signals are received from these position sensors and processed in the computer module. Speed measurements are usually made with a magnetic pickup and the resultant frequency signals are transmitted to the control via electrical conductors. The actuators are driven by two stage electrohydraulic servovalves. The first stage of the servovalve is a torque motor which receives electrical energy from the computer. The torque motor drives a higher power hydraulic stage which in turn operates the actuator.

Current configurations use FET switches located in the electronic control to control current to actuator torque motors. As the number of servovalve interfaces increase on future engines, heat dissipation in the electronic control poses a potential problem. Moving the drive switches outside the electronic box reduces the heat dissipation requirements. To withstand the high temperatures gallium arsenide is used as the active material in the switch circuit components.

The use of fiberoptics in place of electrical components offers potential improvement in reliability because of optics' inherent immunity to EMI, EMP and lightning. Fiberoptics eliminates the threat of fires on aircraft because of electrical insulation failures as well as the threat of short circuits which can cause inadvertent actuation of critical control components. Two additional advantages of fiberoptics are weight reduction, when fiberoptics replaces metallic conductors, and easily implementable redundant circuits.

Since future aircraft materials are likely to be mostly composite, rather than metallic, isolation of the electronic computer from lightning effects and other EMI sources will depend on the type of cables used to transfer signals between the computer, sensors and actuators. With conventional wire systems, electrical transmission lines must be well shielded and surge quenching circuits must be provided to protect the computer from the effects of lightning. Electrical insulation deteriorates due to weather extremes and contact with fuel, cleaning solvents and in certain cases salt spray. The insulation cracks, frays and is embrittled. This breakdown of the insulation can cause fires and short circuits. Fiberoptic cables can eliminate these problems.

Figure 2 illustrates the different optical circuits that could be used in aircraft applications. Fiberoptic waveguides can link the computer of the airframe and propulsion system with their respective optical sensors and actuators which are to be controlled with optical signals. For integrated control of airframe and propulsion system the two computers can be linked via fiberoptics.

Since most initial applications involving fiberoptics were for land communication lines operational reliability in severe engine environments was not of concern. More work is required to ruggedize both sources and detectors to operate in a higher temperature environment. Temperatures in the electronics box are usually maintained at 100° C or less. Rugged optical connectors that can be disconnected and reconnected repeatedly need to be developed and evaluated.

SENSORS

The number of concepts for measuring physical parameters, such as pressure, temperature, and vibration using optics has increased dramatically in the past few years because of advances made by the communication industry in the area of fiberoptics, integrated optical circuits, sources and detectors. Optical parameters such as phase, intensity, wavelength and polarization are used to measure physical parameters such as pressure, temperature, position, magnetic fields and electrical current. Many concepts have been demonstrated in the laboratory and some prototypes have been built and tested. Optical sensors to measure acoustic pressure and magnetic fields using phase modulation are well documented as are amplitude modulating sensors for measuring temperature. Various schemes are compared in Refs. 1 and 2.

The technology of optical encoders and tachometers is a mature technology compared to the other type of optical sensors although significant developments are needed to integrate these components into engine control systems. A passive optical encoder and optical tachometer were the first sensors built for Lewis and tested on an engine in an altitude facility. These sensors were not packaged for mounting on a flight engine but rather represented prototypes which demonstrated remote operation of these sensors.[3]

When compressor and turbine blade tip clearances are excessive component performance and efficiency are adversely affected. To decrease this loss closed-loop or open-loop tip clearance control can be used. Tip clearance measurements are required for closed-loop control or for monitoring purposes.

An optical sensing scheme for measuring tip clearances, shown in Fig. 3, was built and tested in the laboratory by General Electric under contract to NASA Lewis. Fiberoptic bundles direct light to the sensor and carry the modulated signal to the detectors. Light from the input bundle is directed across the gap between the engine case and blade tips and is imaged onto a coherent output bundle which transmits the signal to the detector array. As the blade intercepts part of the light beam directed between the source and detector fibers, light that normally would fall on the detector bundle is blocked. Blade clearance is determined by the position of the boundary between light and dark areas on the detector array. The laboratory tests on the tip clearance sensor were conducted with a compressor rotor stage driven by an electric motor.[4]

One concept for measuring engine gas temperature using optical techniques is the Fabry-Perot interferometer. The Fabry-Perot sensor produces spectral amplitude modulation using multiple interference of a broad band input spectrum. The modulation is related to the resonator thickness which in turn is a function of temperature. A temperature sensitive cylinder controls the spacing between two parallel mirrored surfaces whose faces are partially transmitting and partially reflecting as shown in Fig. 4. The Fabry-Perot principle provides for multiple reflections between mirrored surfaces. The maximum transmitted intensities occur at wavelengths for which the resonator gap ($g = N\lambda/2$) where N is the order of interference.

Figure 5 is a photograph of the Fabry-Perot sensing element. The pedestal is constructed of ultra low expansion silca material. The temperature sensitive expansion element is made of silica as is the end cap. In this prototype model the Fabry-Perot element is held in the sensor holder by a spring. The input and output fibers are shown installed in the Fabry-Perot element. Ceramic cement is used to hold the fibers in the sensing element. The assembled sensor is shown in Fig. 6.

Figure 7 shows the electro optics box. The electronics are located on the bottom side of the box. Shown in the figure are the light source (on left) and the receiver fiber on the right side. In the current prototype model an incandescent bulb (similar to one used in medical applications) is used to produce a broad band light source. The modulated signal returns on the right hand fiber, is collimated by the first lens and directed through a prism where the wavelengths are spread out and focused on the CCD element by the second lens. The dispersed spectrum is focused on the face of a 128-element linear CCD array. The output from the CCD array is converted to 128 8-bit digital words and fed into a microprocessor. Algorithms are then used to determine the maximum intensity wavelengths, which are then correlated to resonator gap thickness and hence temperature. This sensor was built by OPCOA, Inc. (Anaheim, CA) under contract to NASA Lewis. This sensor has been tested up to 1000° C.

Another sensor measures temperature by measuring the change in light intensity as it passes through a rare-earth material. This sensor was developed by United Technologies Research Center under contract to NASA Lewis. Rare-earth materials were chosen for the sensor because they have numerous absorption lines in the visible and near IR spectrum. Absorption lines result from optical transitions originating in the electronic ground state of the ion and from low lying excited states. The population distribution of ions is a function of temperature. The strength of the absorption is proportional to the populations of ions in the state from which the absorbing transition originates.

Figure 8 shows some of the energy levels of europium. Absorption peaks arise from the transition from the low lying states to the 5_{d0} and 5_{d1} states. The expected distribution of ions in the lower states as a function of temperature is shown in Fig. 9. The population of the ground state N_0 decreases with temperature. The 7_{F2} state (N_2) shows a population that increases with temperature. Absorption lines that originate in this state would increase in strength as temperature increases. The physical configuration of this rare-earth sensor is shown in Fig. 10. This configuration uses alumino-silicate glass doped with neodymium as the sensing element. A sensor using this configuration has been designed for testing in a turboshaft engine between the gas generator turbine and power turbine. To separate the temperature dependent absorption from cable and connector losses, a second wavelength at which the change in intensity is temperature independent is used to factor out the losses in the cable/connectors. The sensor to be installed in the engine is shown in Fig. 11 undergoing acceptance tests in the laboratory. The optical cable is enclosed in a braided metal tube to protect it during engine installation.

Pressure sensing using fiberoptics is also being investigated. Concepts that are being considered for use in measuring pressure are microbending and photo elastic effect. Both of these sensors are intensity measuring sensors. These sensors must be relatively temperature insensitive. A material study is also being conducted to minimize temperature effects on the force transmitting member of the pressure sensor.

ACTUATORS

Actuators will be connected to the computer by fiberoptic cable for purposes of electrically isolating the computer. Optical signals generated by the computer control the flow of electric power to the servovalve. Two types of servovalves are considered (fig. 12). One type (fig. 12(a)) is a two stage servovalve which has a low power torque motor (60 mw) which drives a higher power spool valve. The spool valve controls the flow of hydraulic power to the actuator. The second type (fig. 12(b)) is a direct drive valve which has no low power stage. The spool valve is driven directly by a torque motor. This configuration requires much more power (50 W) to operate than does the two stage valve. The direct drive valve eliminates the low power stage with its potential for plugging because of contaminants in the fluid. There were two configurations considered for the optical circuit in a program done at UTRC for NASA Lewis (fig. 13). In one, an optical link would be used to control the flow of electrical energy to the torque motor. The electrical power supply is connected to the torque motor through a JFET power transistor. The gate of the power JFET is connected to the circuit containing the phototransistor. When an optical signal is applied to the phototransistor the JFET turns on, allowing current to flow to the torque motor. This concept can be applied to either the two stage or direct drive servovalve. The configuration illustrated in Fig. 13(a) was built and tested over the temperature range -55° to 260° C. The switch was designed to switch 100 ma with an off state voltage of +20 V. For the direct drive valve the switched current would be considerably higher (1 amp). In either case the electrical energy is developed locally, at the point of use. Various schemes to generate this electrical power have been proposed. Included in these concepts are the use of piezolectric stacks, photovoltaic cells, photomechanical techniques and hydraulically driven electric driven generators. The hydraulic electric generator contains a small hydraulic motor which can be operated from the aircraft hydraulic power supply. This latter concept can develop relatively large amounts of electrical power, enough to operate the direct drive valve.

The second configuration is illustrated in Fig. 13(b) and is called power-by-light because whatever power is required to operate the torque motor is converted directly from optical power. This scheme does not require locally generated power. The power conversion can be accomplished a number of ways. One scheme uses photovoltaic cells to convert the optical energy directly to electrical energy. Since the power requirements are considerably larger for the direct drive valve the power by light system was considered only for use with the two stage servovalve. If system efficiency is to be optimized for the photovoltaic case an active impedance matching device between the torque-motor load and photovoltaic cells must be provided which will compensate for temperature induced impedance changes. The system would be too complex and the impedance matching technique wasn't pursued any further. The alternative to impedance matching over the range of operating temperatures (-55° C to 260° C) is to consider impedance matching of the torque motor and photovoltaic cell only at one temperature. In this approach the impedance match is set for the highest temperature since the power output of the photovoltaic cells is lowest at the high temperature. Because of the high temperature requirement a number of photovoltaic cells are required for impedance matching. If the highest temperature is reduced to approximately 150° C instead of 260° C the number of photovoltaic cells needed for an impedance match are reduced by a factor of 1/2. However, the overall system efficiencies for the photovoltaic system are extremely poor with today's technology.

CABLE AND CONNECTORS

The development of rugged, reliable optical cables and connectors for aircraft installation is needed before fiberoptics can be considered as a replacement for electrical wires. An optical cable made of glass core and cladding usually has a buffer material applied to the cladding to protect the optical fiber. The buffer material commonly used breaks down at temperatures above 125° C. To accommodate temperatures that will be encountered in an aircraft environment the buffer material will have to operate over -55° C to 260°. Current research on buffer material indicates that polyimides or silcone with teflon jackets have potential for a durable buffer coating on cables.

DISCUSSION

Fiberoptics in aircraft systems has potential for improving the reliability of the overall electronic control system because of its immunity to EMI, EMP and lightning effects. In addition, fiberoptic waveguides eliminate the potential of fire and short circuits caused by corrosion of the electrical insulation.

To fully utilize the benefits of fiberoptics, research into passive optical sensors and optically activated actuators was initiated by NASA Lewis. This would completely eliminate the need for electrical wires and thereby divorce the engine control computer from any sources of disturbances due to EMI, EMP or lightning.

Before fiberoptics can fully replace wire systems in aircraft, reliability of all components from light sources and detectors to optical connectors and fiberoptic wave guides must be assured. The optical cables and connectors will have to operate reliability over a -55° C to 260° C temperature range. In addition engine test experience must be obtained and optical system integration, including packaging, must be fully addressed.

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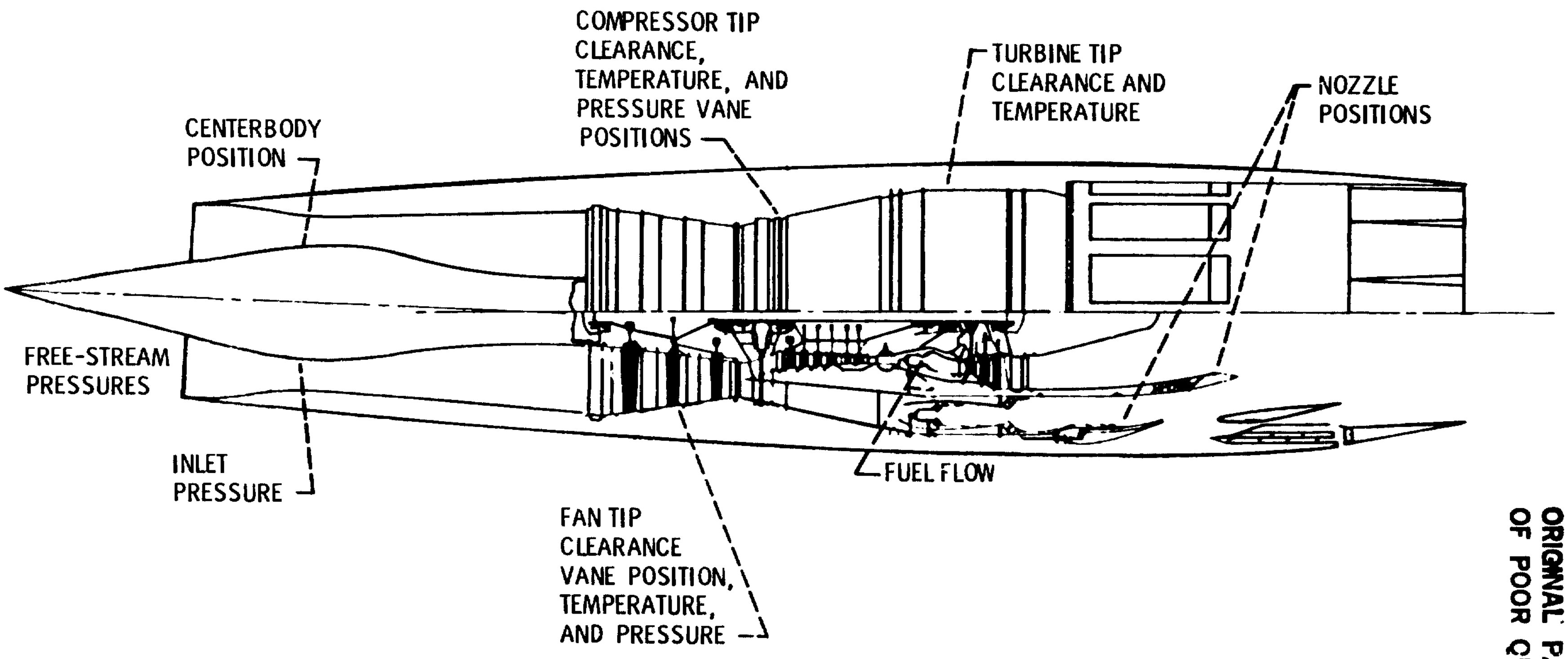

Figure 1. - Inlet/engine measurements for control and monitoring.

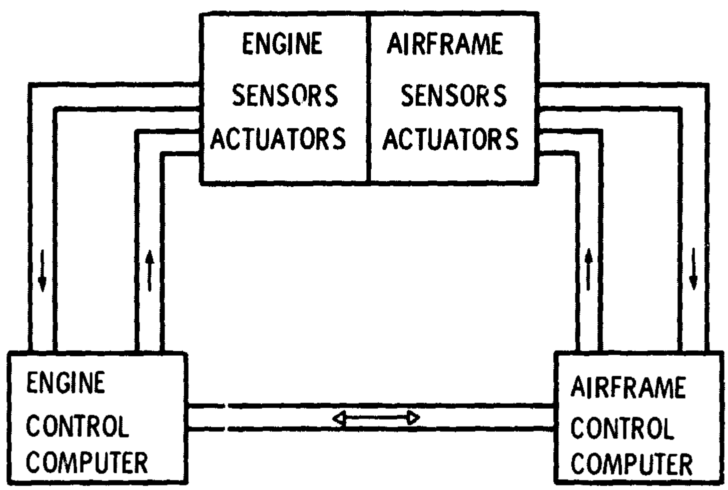

Figure 2. - Optical circuits in aircraft systems.

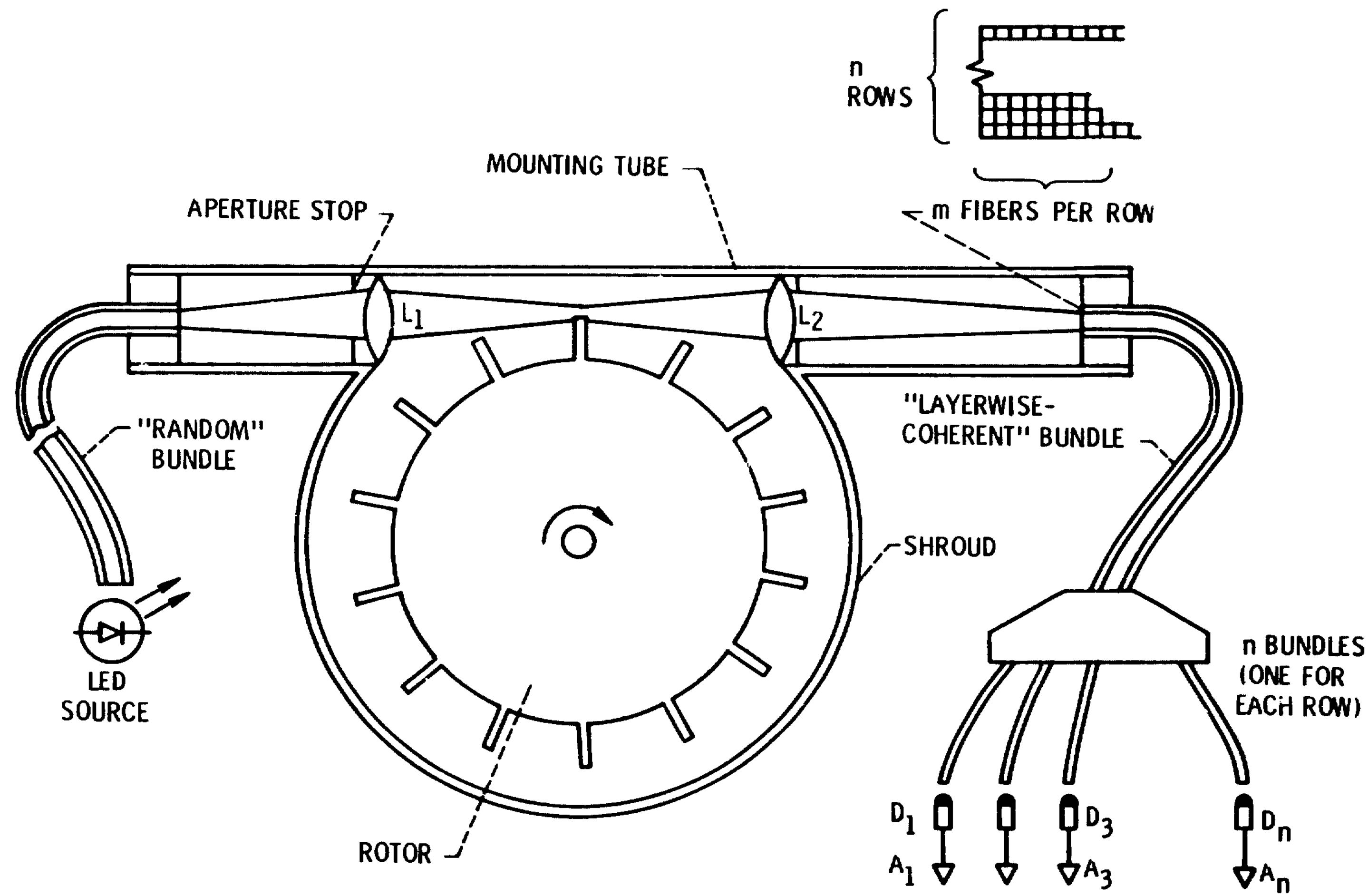

Figure 3. - Optical tip clearance sensor.

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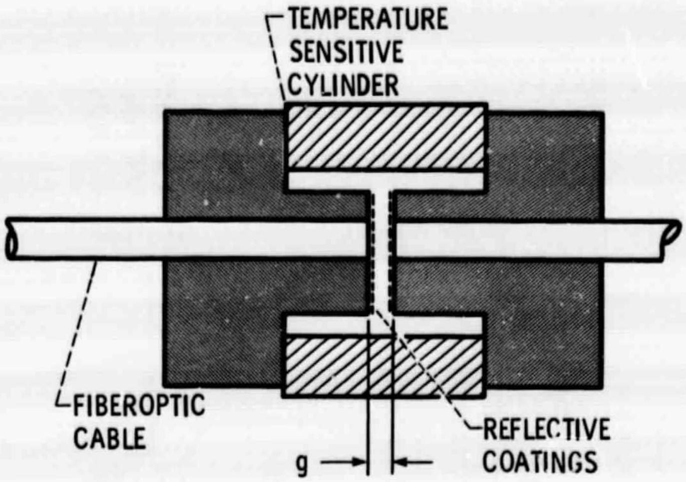


Figure 4. - Temperature sensitive gap for use in Fabry-Perot temperature sensor.

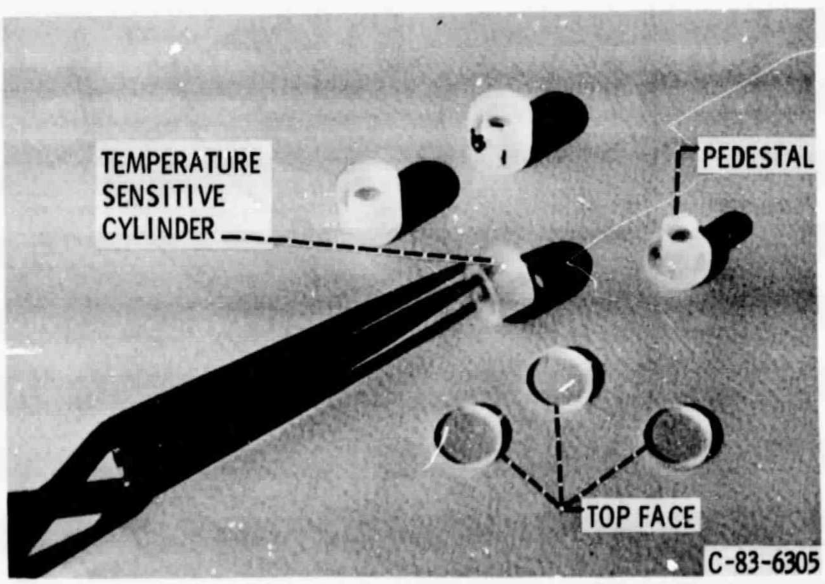


Figure 5. - Temperature sensitive Fabry Perot sensor.

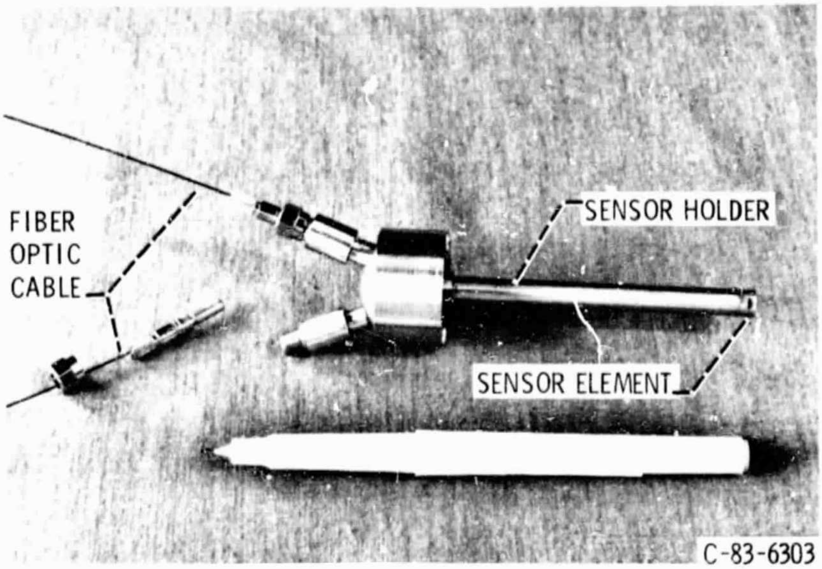


Figure 6. - Assembled Fabry Perot temperature sensor.

Figure 7. - Electro-optics for Fabry Perot.

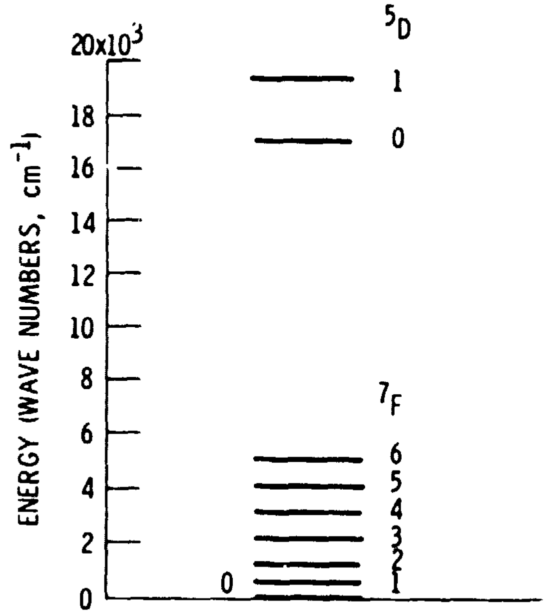


Figure 8. - Energy level diagram for europium in glass.

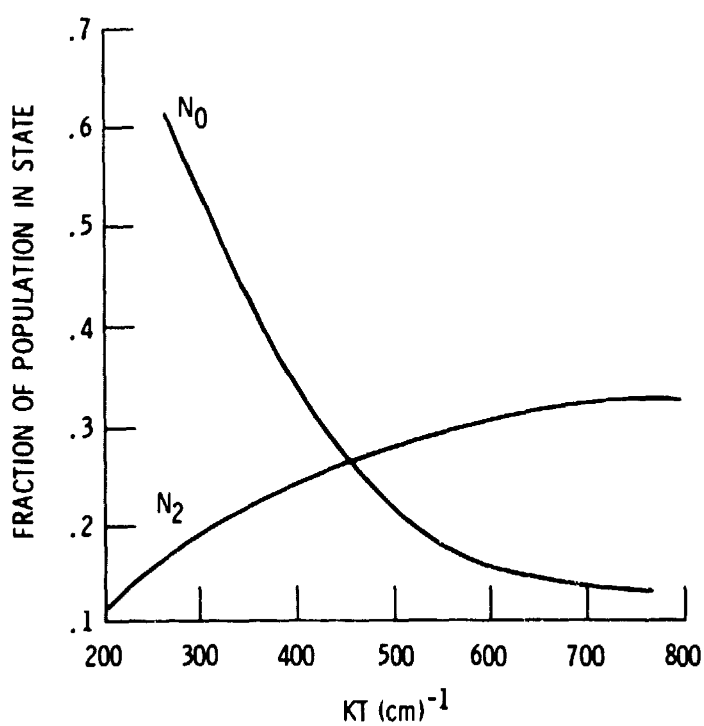


Figure 9. - Population of ground states of EU^{3+}.

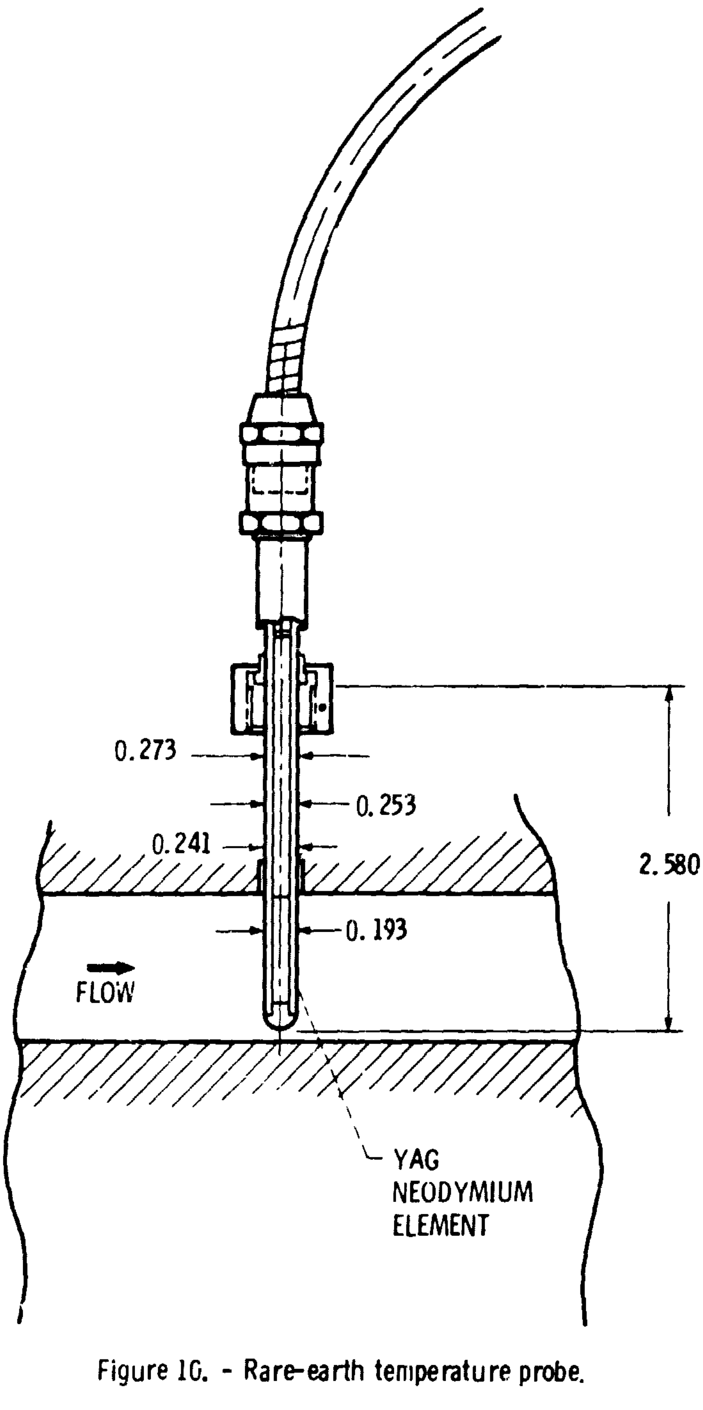


Figure 10. - Rare-earth temperature probe.

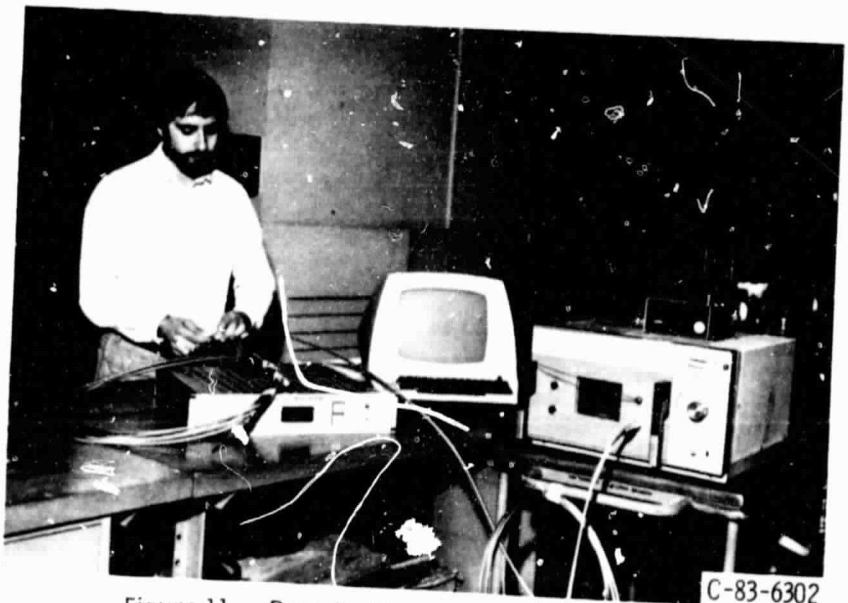
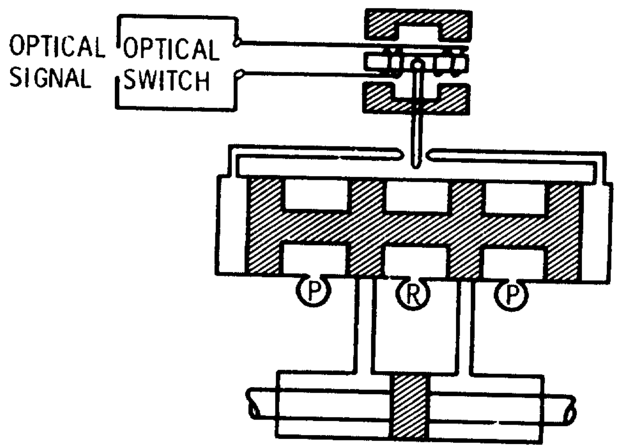
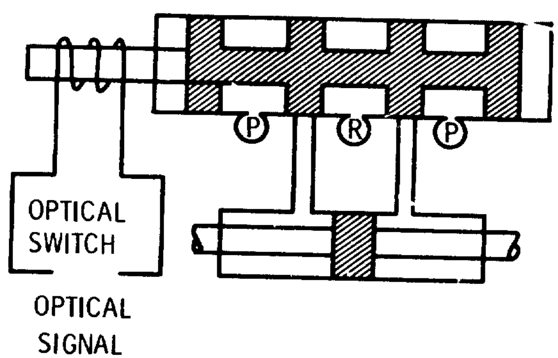


Figure 11. - Rare-Earth sensor acceptance testing.

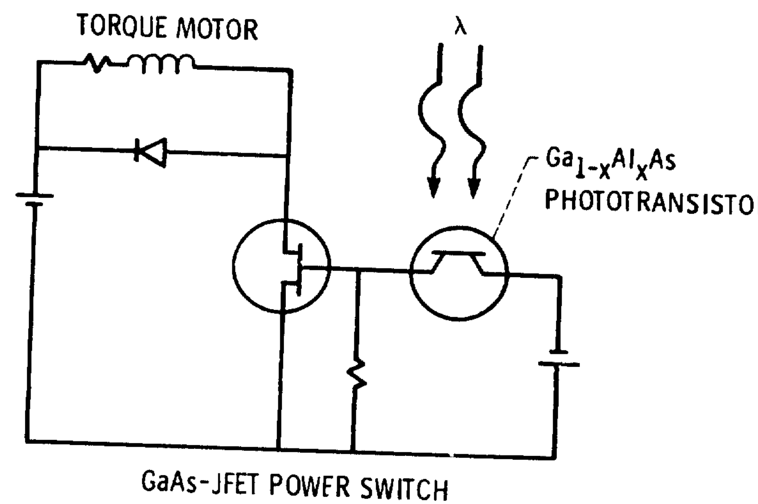


(a) Fly by light two stage servovalve.

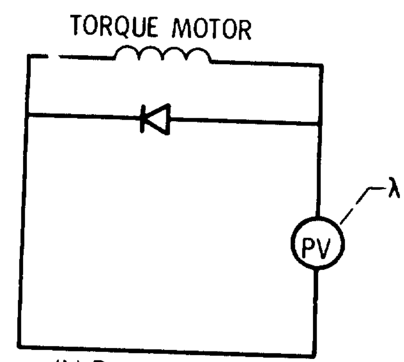


(b) Fly by light direct drive valve.

Figure 12. - Optical actuation of servovalves.



(a) Light on, power switch off.



(b) Power by light.

Figure 13. - Optical circuit configurations for actuators.