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DESIGN, FABRICATION, AND DEMONSTRATION OF A MINIATURIZED TIP CLEARANCE MEASURING DEVICE

M. J. Ford, et al

Pratt and Whitney Aircraft

Prepared for:

Army Air Mobility Research and Development Laboratory

September 1974

EUSTIS DIRECTORATE POSITION STATEMENT

The work reported herein represents a significant advancement in small gas turbine engine and component test cell instrumentation.

It is expected that the instrumentation concept described herein will be used to measure tip clearance in future efforts to improve turbine tip clearance control.

Appropriate technical personnel of this Directorate have reviewed this report and concur with the conclusions and recommendations contained herein.

Mr. David B. Cale of the Technology Applications Division served as project engineer for this effort.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the design, fabrication, and demonstration of a miniaturized turbine blade tip clearance measurement system for use with small gas turbine engines during engine operation.

This system was originated by Pratt & Whitney Aircraft (P&WA™) and uses laser light that is focused on the blade tips. The light reflected from the blade tips is imaged onto an output device. The relationship between the change in tip clearance and the change in position of the output light spot provides a direct indication of tip clearance.

A P&WA engine in the 3 to 5 lb/sec airflow range was selected as the potential application to determine system design criteria.

The system was fabricated and laboratory tested to demonstrate that the design criteria were met. Satisfactory system operation was demonstrated with respect to range, accuracy, response rate, sensitivity, temperature tolerance, power requirements, and life. The cost of a typical system has been defined.

PREFACE

The work described in this report was accomplished for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, under Contract DAAJ02-73-C-0084. The 10-month technical program covered the period July 1973 through April 1974, and was divided into two tasks:

1. Preliminary design of a miniaturized tip clearance measurement system.

2. Final design, fabrication, and demonstration testing of the clearance measurement system.

This program was conducted by two elements of the United Aircraft Corporation: The Florida Research and Development Center (FRDC) of P&WA and the Connecticut Operations of P&WA. FRDC was the prime contractor for the program, with Connecticut Operations contributing engineering assistance in optical systems design.

Mr. David B. Cale of the Eustis Directorate was the contract technical monitor.

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INTRODUCTION

Blade tip clearance is a critical parameter affecting gas turbine engine performance. The clearance between blades and case presents a leakage path that permits a portion of the engine gas flow to bypass the rotor without doing work. In small engines the blade clearance constitutes a greater percentage of the overall flow path than in large engines and is thus particularly critical. The importance of blade tip clearance in small engine operation has made development of a miniaturized tip clearance measurement device (MTCMD) desirable.

This report describes a 10-month technical program by P&WA to design, fabricate, and demonstrate such a device. A small gas generator in the 3 to 5 lb/sec airflow range was used as the basis for determining system operational, environmental, and mechanical requirements.

Technology gained by P&WA during development of larger tip clearance measuring systems for the JT9D, F100/F401, and ATEGG engines was used during this development program.

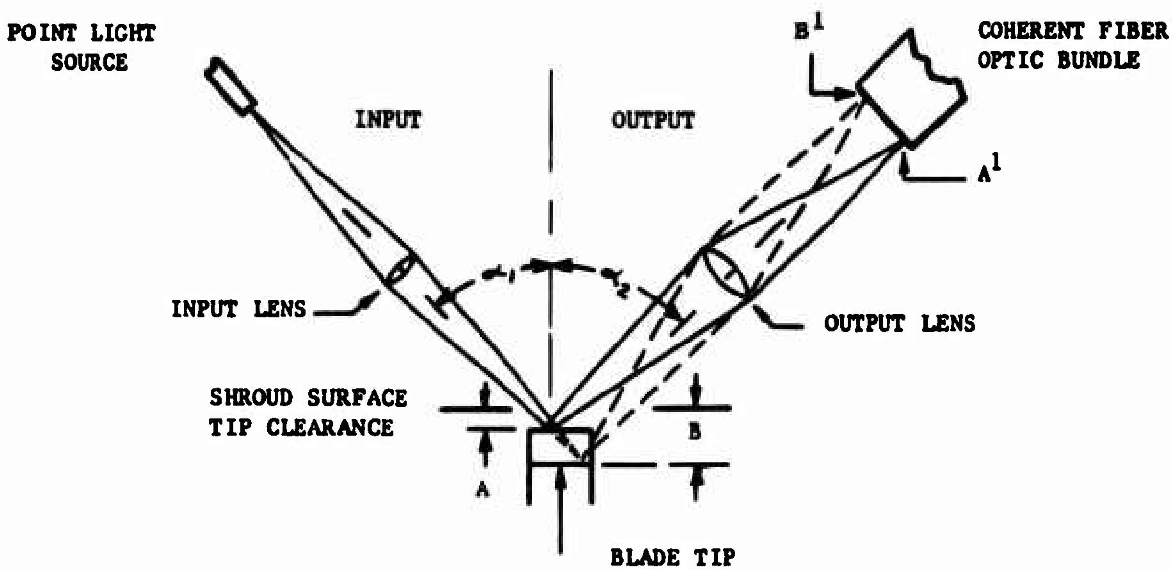
This program was sponsored by Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, under Contract DAAJ02-73-C-0084.

To assist the reader in understanding this report, a glossary is included that defines the optical terms used.

DISCUSSION

SYSTEM CONCEPT

The Miniaturized Tip Clearance Measuring Device (MTCMD) is a laser optic system that operates using a basic light beam triangulation method, as illustrated in Figure 1. Input light from a point source is focused through a lens onto the blade tips at an angle α_1, with a line normal to the tip surface. The light reflected from the blade tips is imaged through the output lens in direction α_2 and is focused onto a coherent fiber optic bundle. The figure shows two different blade tip positions, corresponding to a change in tip clearance. With the smaller blade clearance, the input light impinges on the blade tip at point A, and the reflected light is imaged onto the output bundle at point A^1. Assuming an increase in blade clearance, the location of input light impingement would move to point B, and the reflected light would be imaged onto the coherent bundle at point B^1. The position of the output light spot is, therefore, a measure of tip clearance.



INPUT LIGHT IS FOCUSED THROUGH INPUT LENS ONTO THE BLADE TIP. LIGHT REFLECTED FROM THE BLADE TIP IS FOCUSED THROUGH THE OUTPUT LENS AND IS INCIDENT ON THE COHERENT FIBER OPTIC BUNDLE. AS THE BLADE TIP MOVES FROM POSITION A TO POSITION B (REPRESENTING AN INCREAS IN TIP CLEARANCE), THE FOCUSED OUTPUT BEAM MOVES FROM POSITION A^1 TO POSITION B^1. THIS CHANGE IS THEN RECORDED AS REPRESENTING THE CHANGE IN TIP CLEARANCE.

Figure 1. Basic Triangulation System.

SYSTEM CONFIGURATION

Figure 2 illustrates the MTCMD system configuration. The system consists of:

- A probe containing the basic triangulation system
- An input light source
- A detection system
- A data recording and display system

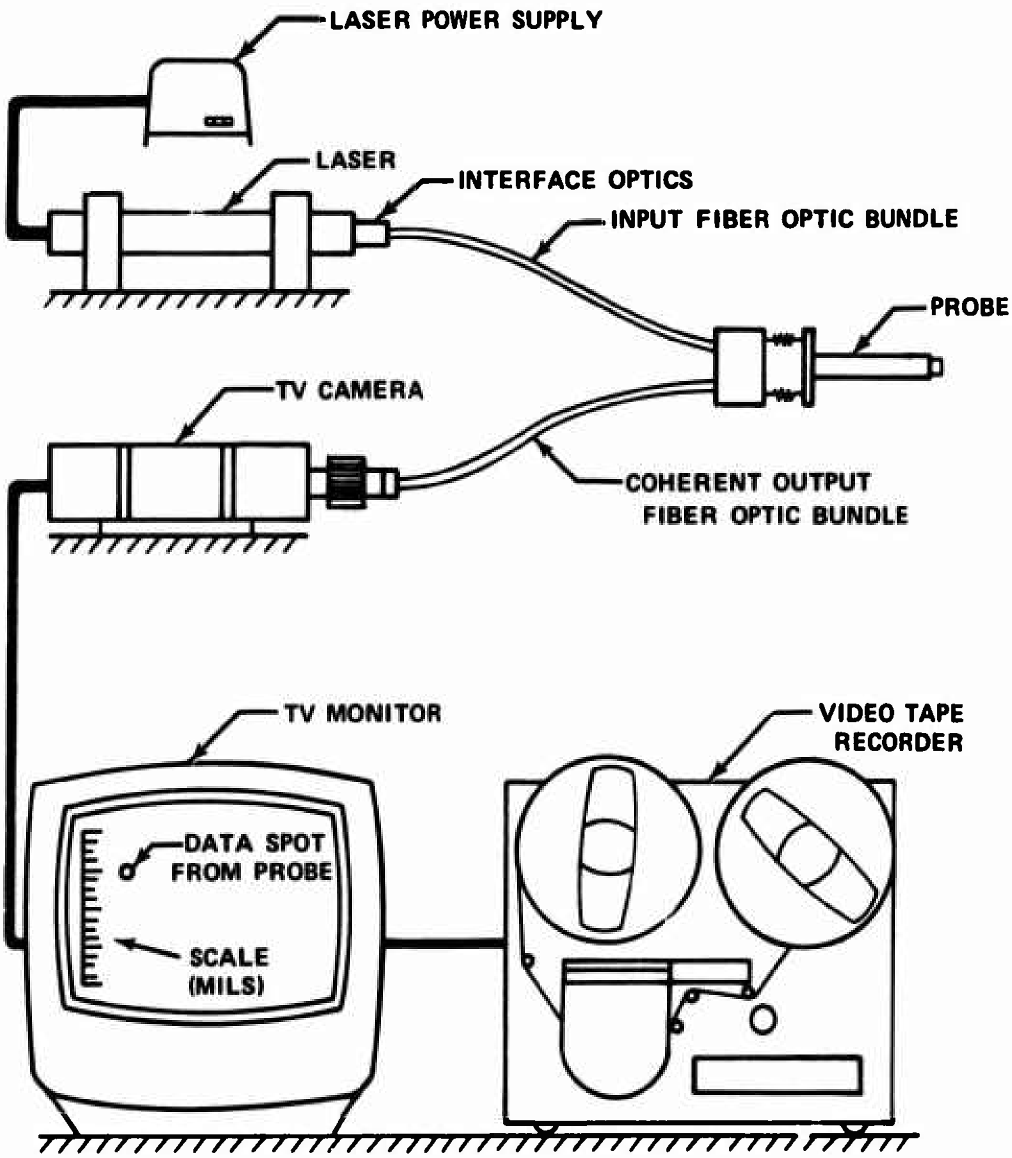


Figure 2. MTCMD - System Configuration.

Probe

Application of the tip clearance measurement system to operating engines requires the basic triangulation system to be fitted into a compact envelope. A prism is used to "fold" the triangulation system (Figure 3). The prism is located at the end of the probe tip and allows the two lenses of the triangulation system to be replaced by a single lens located in the center of the probe. The resulting compact envelope allows the basic triangulation system to fit into a tubular probe housing requiring a single access port of minimum size in the engine case.

Input Light Source

A 10-milliwatt helium-neon (He-Ne) laser is used as the system light source. The laser beam is focused through a microscope objective onto a single fiber of a noncoherent fiber optic bundle. This light is transmitted through the fiber optic bundle to the MTCMD probe. Use of the flexible fiber optic bundle allows the laser to be located away from the adverse temperature and vibration environment of the engine.

A laser is used as the light source in this application because:

- The narrow laser beam can be focused to a small area.
- The laser light is monochromatic; thus system chromatic aberration is avoided.
- The laser is capable of operating several thousand hours without replacement.

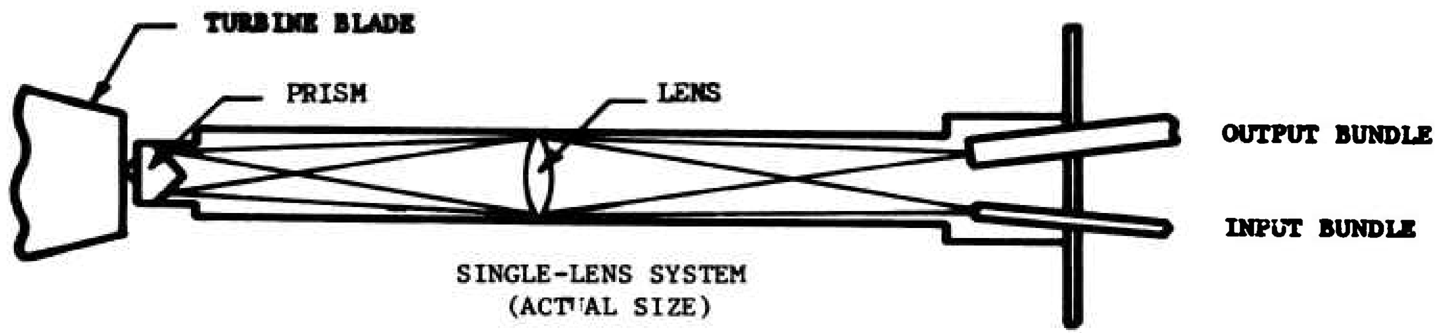
Detection System

A television camera is used to detect the position of the returning light spot reflected from the blade tips. The television camera is equipped with a silicon vidicon tube. This vidicon tube can withstand the high laser light intensities without damage.

The reflected spot returning through the probe is focused on the end of a coherent fiber optic bundle. This bundle transmits the spot image to the television camera. A focusing arrangement interfaces the camera with the coherent fiber optic bundle. The coherent fiber optic bundle allows the television camera to be located away from the adverse temperature and vibration environment of the engine.

Recording and Display System

The television camera output is displayed on a television monitor located in an area remote from the test cell. A video tape recorder can be used to permanently record engine test data.



THE PRISM "FOLDS" THE BASIC TRIANGULATION SYSTEM. THE SINGLE LENS PERFORMS THE FUNCTIONS OF THE SEPARATE LENSES OF THE BASIC TRIANGULATION SYSTEM.

Figure 3. MTCMD Probe Configuration.

DEFINITION OF SYSTEM DESIGN CRITERIA

A P&WA small gas turbine engine in the 3 to 5 lb/sec airflow class was chosen as the potential application for the clearance measurement system.

Because of the small engine size, the proximity probe purge flow and physical dimensions represent the most stringent system design requirements expected for engines in this class. The first turbine stage was selected as the blade tip clearance measuring application for the engine. The first turbine blade clearance is considered the most difficult measurement location due to the limited accessibility of the blades and the high-temperature environment.

The MTCMD design criteria are defined with respect to:

- Mechanical requirements
- Environmental requirements
- Operational requirements
- Cost
- Life

These criteria are summarized in Table 1.

TABLE 1. MTCMD DESIGN CRITERIA

Requirement	Parameter	MTCMD Part	Design Criteria
Mechanical	Available Space	Probe Body	See Figure 4
Environmental	Temperature	Probe Tip	1900°F
		Probe Body	1000°F
		Probe Head	500°F
		Laser/Television Camera	150°F
	Pressure	Probe Body	10 Atmospheres
	Vibration	Probe Assembly	±1G from 50-250 Hz
			±2.5 G's from 250-500 Hz
			±10G's from 500 Hz - 1K Hz
			±20G's from 1-2.5K Hz
Operational	Range	System	0.065 in.
	Accuracy	System	±0.001 in.
	Sensitivity	System	±0.0005 in.
	Response Rate	System	0.4 x 10^{-6} sec
	Cooling Flow Rate	Probe Assembly	0.016 lb/sec or less
	Power Consumption	System	280 watts or less
Cost		System	$6,300 or less
Life		System	50 hr or greater

MECHANICAL REQUIREMENTS

The maximum allowable probe envelope established for use in the selected engine is illustrated in Figure 4. Installation of the probe in the engine is illustrated in Figure 5.

The envelope allows the probe to be installed and removed from outside the engine combustor case. The probe is attached at the turbine case by a bayonet-type locking arrangement so that the probe tip remains fixed relative to the shroud inside diameter. The probe tip is slotted to allow the laser light to be emitted from the probe, impinge on the target, and be reflected back into the probe. The probe housing contains a bellows section to accommodate differential thermal growth of the probe and engine case and to provide a seal against leakage of compressor air to the atmosphere.

ENVIRONMENTAL REQUIREMENTS

Environmental requirements for components of the MTCMD subjected to severe operation conditions are defined with respect to:

- Temperature
- Pressure
- Vibration

Temperature

Temperature requirements are specified for the MTCMD:

- Probe tip
- Probe body
- Probe head
- Laser and television camera

Temperatures are based on expected engine and test stand conditions. Requirements are not specified for the television monitor and video recorder since this equipment is normally installed in a controlled environment.

Probe Tip

The probe tip is required to withstand 1900°F continuous operation. This requirement is based on the maximum turbine case inner wall temperature of the engine.

Probe Body

The probe body is required to withstand 1000°F average surrounding air temperatures. The requirement is based on the temperature of the compressor air surrounding the probe body.

Probe Head

The probe head is the part of the probe containing the fiber optic bundles and cooling purge connector and is located outside the engine case. The head temperature expected will not exceed 500°F.

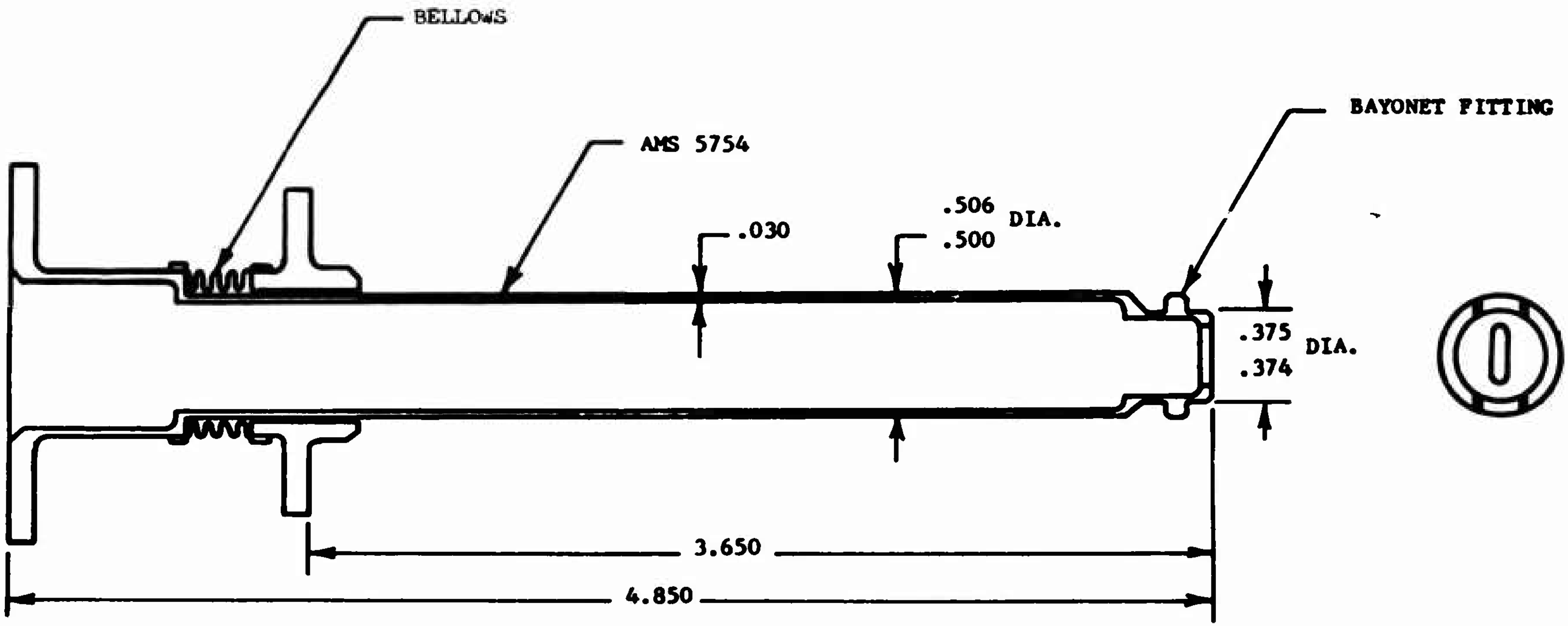


Figure 4. Probe Housing Envelope.

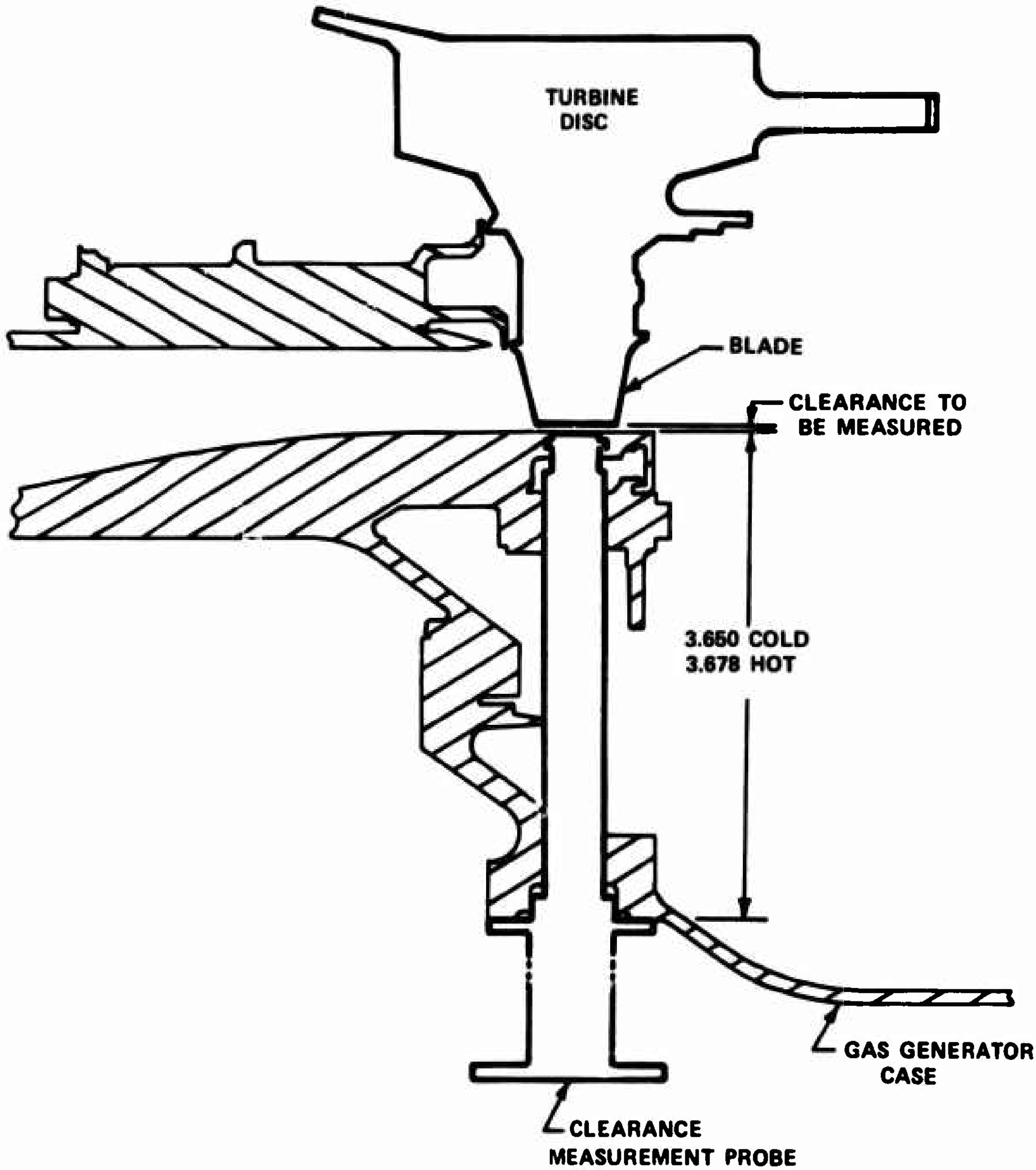


Figure 5. Probe Installation in Engine.

Laser and Television Camera

The laser and television camera are required to operate continuously in a 150°F environment. The laser and camera are mounted several feet from the engine outer case and are subjected only to heat radiated from the engine case.

Pressure

The MTCMD probe body is required to withstand a pressure environment of 10 atmospheres. The requirement is based on engine compressor air pressures. No other components of the MTCMD system are subjected to pressure environments other than normal atmospheric pressure.

Vibration

The MTCMD probe is required to withstand the following vibration levels:

- ± 1 G from 50-250 Hz
- ± 2.5 G's from 250-500 Hz
- ± 10 G's from 500 Hz-1 KHz
- ± 20 G's from 1-2.5 KHz

No other system components are mounted on the engine, and thus none will experience unusual vibrational levels.

OPERATIONAL REQUIREMENTS

The MTCMD operational requirements are defined with respect to:

- Range
- Accuracy
- Response rate
- Sensitivity
- Cooling flow rate
- Power requirements

Range

The MTCMD is required to have a 0.065-in. sensing range measured from the probe tip. This range is based on the greatest possible blade tip-to-inner wall clearance for the selected engine application.

Accuracy

A clearance measurement accuracy of ±0.001 in. is required to make the MTCMD useful as a diagnostic tool. This accuracy will enable engine designers to evaluate effects of blade tip clearance on engine performance.

Sensitivity

The system must be capable of resolving a tip clearance change of ±0.0005 in. This sensitivity is required to discern small engine geometry changes and ensure that the accuracy requirement is met.

Response Rate

The MTCMD is required to have a response rate of 0.4×10^{-6} sec or better. This response rate will enable the MTCMD to detect the clearance of blade squealer tips in the selected engine. The response rate does not mean the system can detect a tip clearance change that occurs within this time.

Cooling Flow Rate

A gaseous nitrogen cooling flow rate of 0.016 lb/sec is allowed to cool the probe internal parts. This flow rate was established as the maximum that could be introduced into the engine gas path without significantly affecting engine performance. The cooling flow enters the probe at the probe head and exits the probe at the probe tip. The coolant is discharged into the engine flow path.

Power Consumption

The system power consumption is restricted to not more than 280 watts.

COST

The total system hardware cost is restricted to $6,300. The cost includes the probe head, input and output fiber optics, laser, television camera, television monitor, and video recorder. This does not include the cost of probe fabrication or assembly.

LIFE

The required probe head life is 50 hours before refurbishment. Refurbishment requires disassembly and cleaning of the MTCMD optical elements. The laser, television camera, television monitor, and video recorder will be capable of several hundred hours of normal operation before failure. The established probe life will enable the MTCMD to be used during extended test programs.

SYSTEM DESIGN

Preliminary system design concentrated on:

- Designing an optical system to fit the basic triangulation method into the specified probe envelope
- Designing the MTCMD input light system
- Designing the MTCMD television camera interface

OPTICAL SYSTEM

Figures 6 and 7 show the assembled MTCMD probe and the probe internal parts. Figure 8 shows the internal arrangement of the probe parts in the probe.

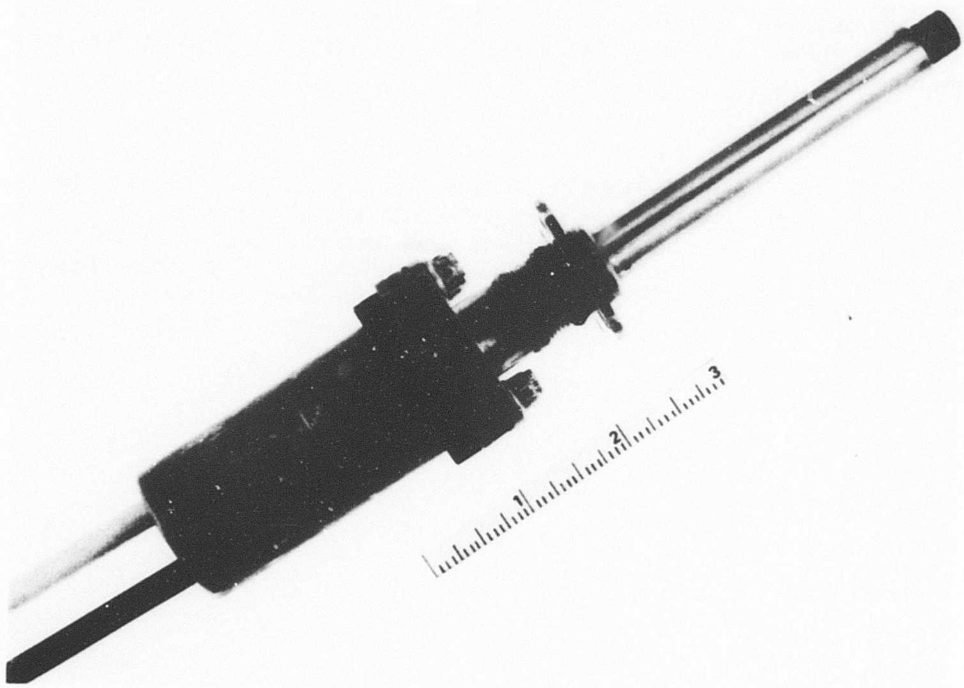


Figure 6. MTCMD Probe.

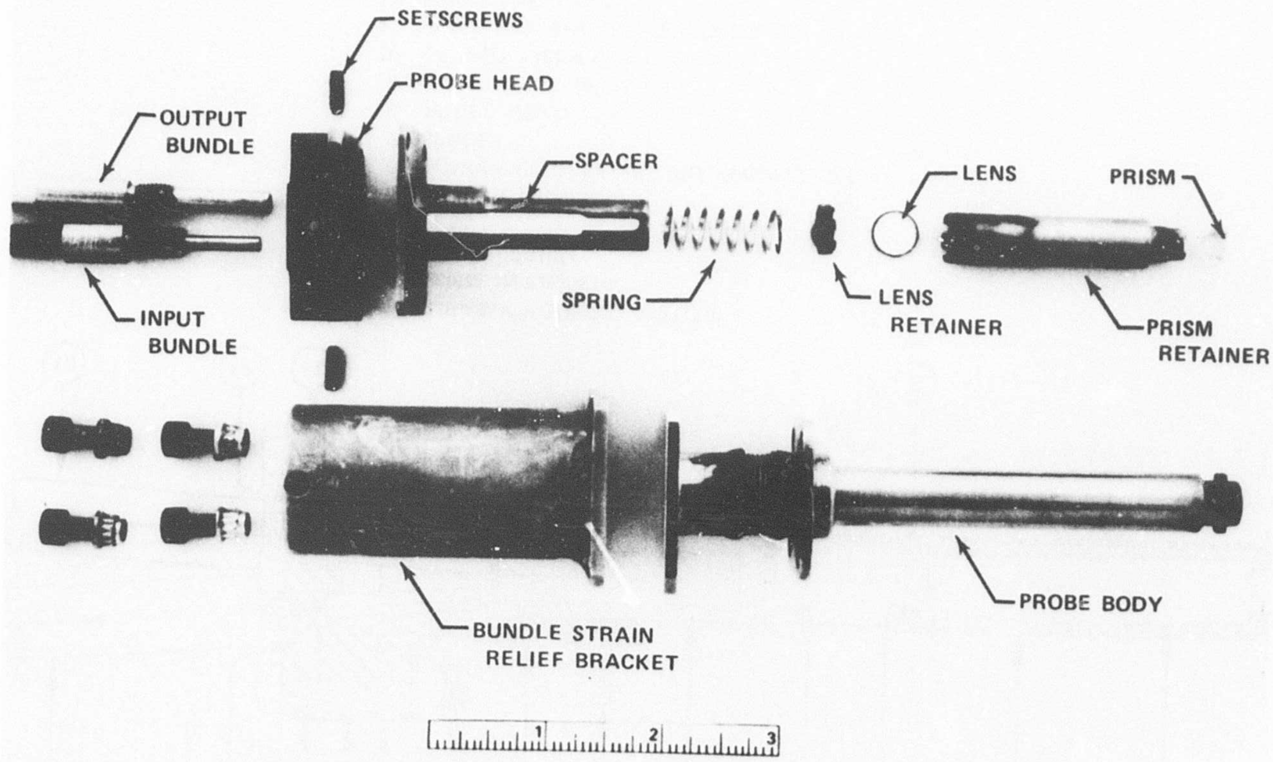
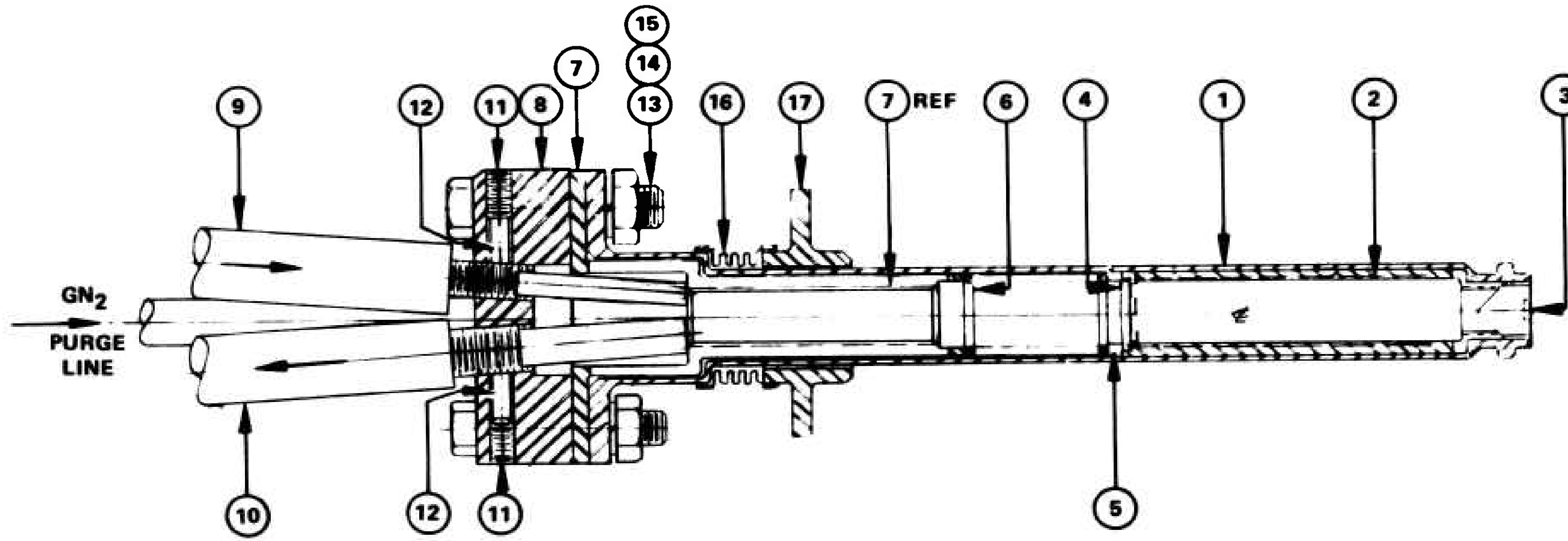


Figure 7. MTCMD Probe Internal Parts.



1 SUBASSY HOUSING AND TIP
2 PRISM RETAINER
3 3-SIDED PRISM
4 LENS
5 LENS RETAINER
6 COMPRESSION SPRING NO. 9655K22, S/S
7 SPACER
8 PROBE HEAD
9 INPUT FIBER OPTIC
10 OUTPUT FIBER OPTIC
11 NO. 5 HEX SOCKET SETSCREW S/S
12 ROD 0.100 in. DIA
13 HEX HD MACH BOLT, 0.190-32 UNF-3A x 1 in. LG S/S
14 HEX NUT 0.190-32 UNF-3B, S/S
15 LOCK WASHER FOR 0.190 in. BOLT, S/S
16 BELLOWS
17 PROBE FLANGE

Figure 8. MTCMD Probe Assembly.

The probe prism is located in the probe tip. The prism is held in place by the prism retainer. Tab locks at the tip of the retainer lock into the probe body to prevent radial movement of the prism. The probe lens is positioned at the opposite end of the prism retainer. The retainer is machined to accept the lens. A lens retainer ring fits on the probe head side of the lens. A spring and spacer are used to apply compression to the probe parts to prevent element movement after probe assembly. The probe head is a monolithic block that locks the fiber optic bundles in place. A fiber optic bundle strain relief bracket is used to prevent excessive flexing of the fiber optic bundles at the point of attachment with the probe head. For clarity, the bracket is not shown in Figure 8 but can be seen in Figures 6 and 7.

A gaseous nitrogen purge is used to cool the probe internal optics and prevent silting of the optical elements by engine combustion products. The GN_2 flow enters the probe through the probe head. The prism holder and lens retainer are notched to allow the GN_2 purge to flow past the optical elements and out the probe tip to be discharged in the engine gas path.

The tip of the prism retainer and the body of the probe spacer are slotted in the plane formed by the input and output light beams. The slots are cut through the parts and are the same width as the light beams. The slots enable more of the probe envelope to be used in that the light beams are restricted to the probe envelope inner diameter instead of the retainer and spacer inner diameters. The extra space allows more of the input light to pass through the probe lens without hitting the probe walls.

The probe prism is made of synthetic sapphire. Sapphire has a melting point of 3722°F and is therefore capable of withstanding the temperature environment encountered at the engine gas path interface. The probe lens is made of fused silica capable of a maximum continuous operational temperature of 1750°F and can withstand the temperatures of the probe body.

The calculations required to determine prism configuration and lens focal length are given in Appendix A.

INPUT LIGHT SYSTEM

The input light system parts are shown in Figure 9. The system assembly is illustrated in Figure 10. A ten-power microscope objective is used to focus the laser beam to a small spot. The fiber optic bundle is located so that the light spot is focused on a single fiber of the fiber optic bundle. The single fiber is used to transmit the laser light to the MTCMD probe head. Light emitted from the fiber end in the probe head is used as the "point source" of light described in the basic triangulation system.

The procedure used to focus the laser beam is given in Appendix B.

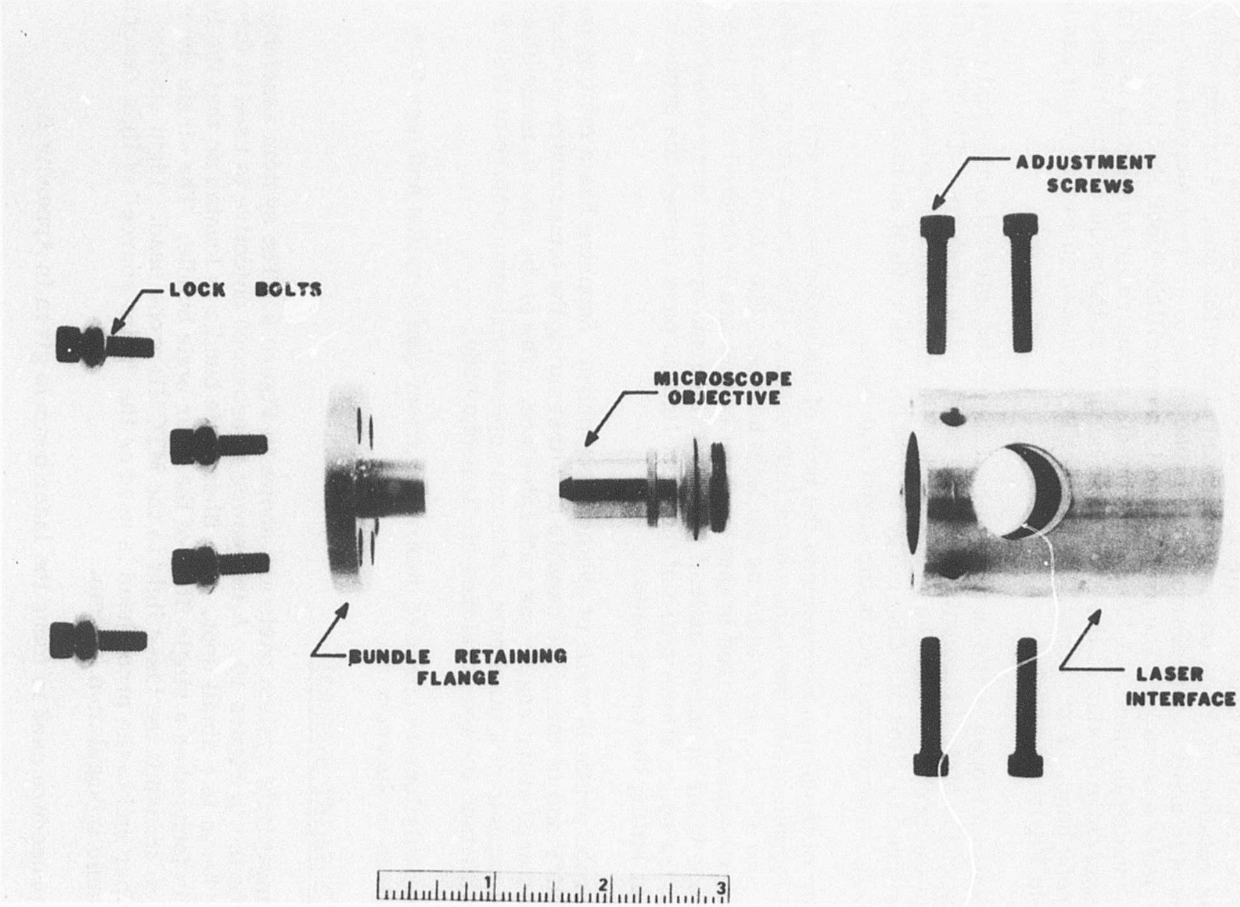


Figure 9. MTCMD Input Light Source Focusing Arrangement.

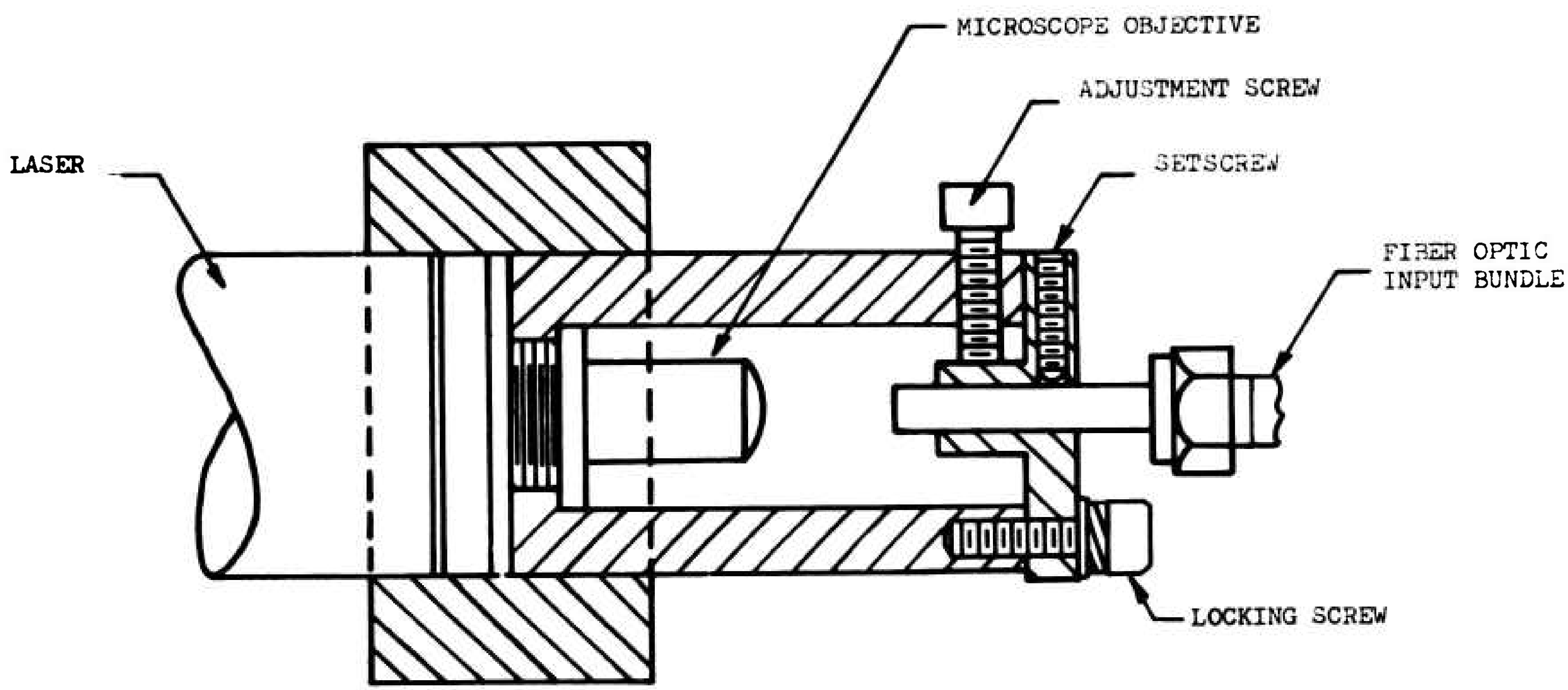


Figure 10. MTCMD Input Light System.

TELEVISION CAMERA INTERFACE

The television camera interface parts are shown in Figure 11. The interface assembly is illustrated in Figure 12. The coherent fiber optic bundle is interfaced with the camera by use of a commercial television camera lens and a small objective lens. The objective lens allows the fiber optic bundle to be brought in close proximity with the camera lens and still remain in focus. This allows the full 0.065-in. range of the MTCMD to be displayed along the vertical axis of the television monitor. A filter that passes only light of the laser light wavelength is used in front of the camera to prevent spurious light from entering the camera.

The procedure used to focus the data spot on the camera detector is given in Appendix B.

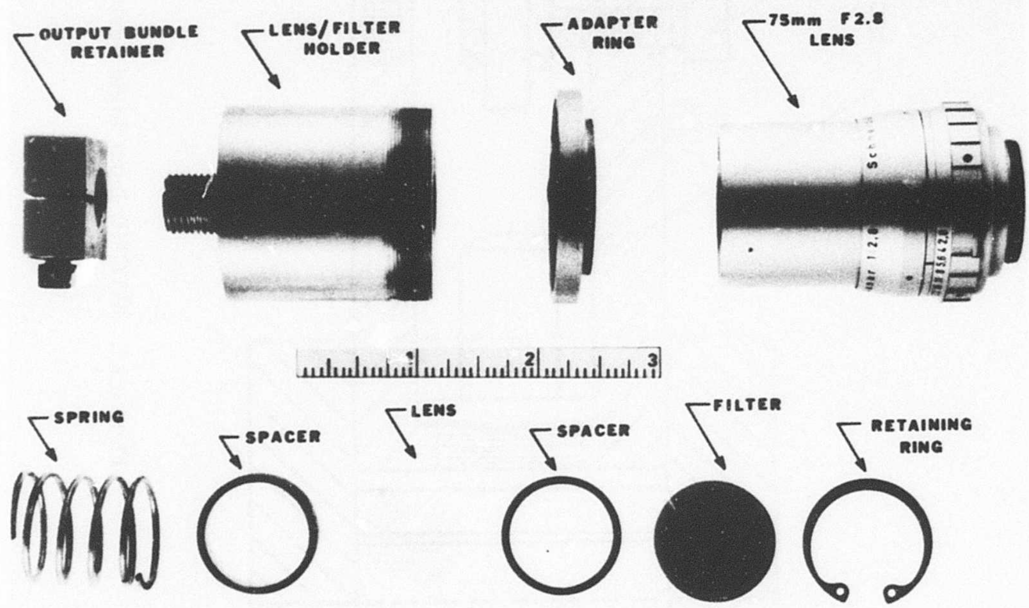


Figure 11. Camera Interface Fixture.

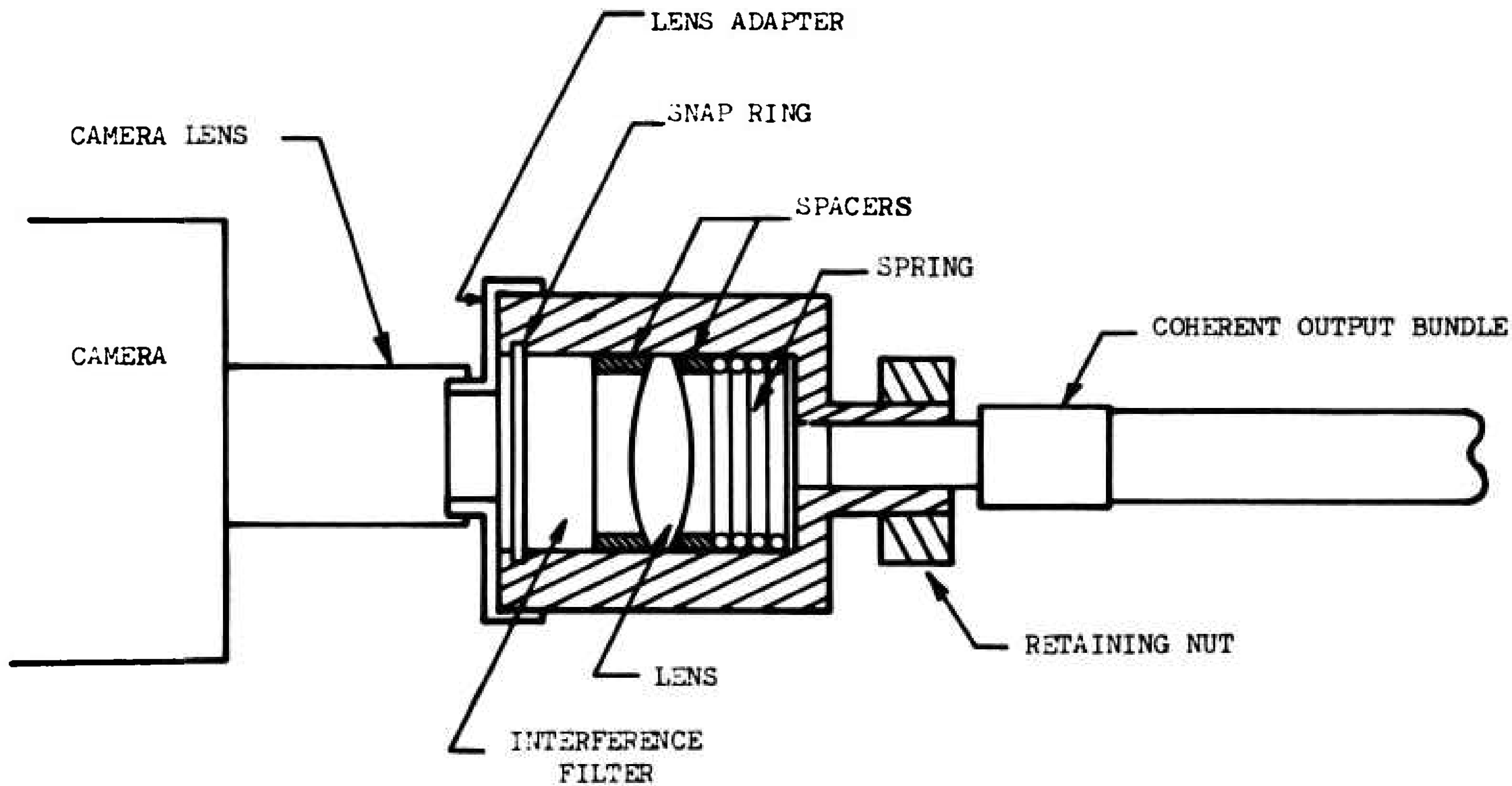


Figure 12. MTCMD Television Camera Interface Assembly.

EVALUATION OF OPTICAL COMPONENTS

Several system improvements were incorporated in the MTCMD over previous proximity probe system designs to meet the MTCMD operational requirements. The improvements were intended to:

- Improve the signal-to-noise ratio of the system
- Improve the spatial resolution of the system

SIGNAL-TO-NOISE RATIO

The signal-to-noise ratio of the probe is the ratio of the amount of light detected by the television camera at the reflected spot compared to the amount of spurious light received by the television camera. The contrast on the television monitor between the reflected spot and the monitor background is reduced as spurious light levels increase. The result is a spot image that is difficult to discern.

The background light is caused primarily by internal reflections on the probe body. Internal reflections become more of a problem as the probe envelope size is reduced. The restricted MTCMD envelope required a special effort to reduce background light level and ensure that the reflected spot image could easily be discerned on the television monitor. Several design changes were proposed to improve the MTCMD signal-to-noise ratio:

- Use of internal probe baffles
- Design of a low-loss, four-sided prism
- Specification of high quality optical components
- Use of antireflective coatings on probe lenses
- Development of a high efficiency three-lens probe

The above system modifications were evaluated, and, as a result, internal probe baffles, high quality optical components and antireflective coatings on probe lenses were incorporated in the final MTCMD design.

Internal Baffles

Internal probe baffles prevent strongly directional reflections from entering the probe output system (Figure 13). Baffles were fabricated on the inside of the probe prism retainer and probe spacer. The efficiency of the probe baffles was evaluated by inspecting the MTCMD television background for light spots in regions other than the image of the reflected laser beam. The monitor background indicated these baffles significantly improved the MTCMD signal-to-noise ratio, and they were incorporated into the final design.

Design of a Low-Loss, Four-Sided Prism

A potential source of background light in the MTCMD is the first surface reflection from the probe prism (Figure 14). A four-sided prism was a design that "folded" the basic triangulation system in the same way the three-sided prism does, but had a less intense reflected light beam. Analysis indicated (Appendix C) that:

- 9.4% of the incident beam intensity is reflected off the three-sided prism
- 7.6% of the incident beam is reflected off the four-sided prism.

In addition, the beam reflected from the four-sided prism is directed back into the probe input system and should not enter the output system (Figure 14).

The four-sided prism was compared with the three-sided prism. The comparison was made by installing each prism in the probe housing and viewing the MTCMD monitor to determine if the signal-to-noise ratio was noticeably improved.

The four-sided prism did not appear to offer significant improvement over the three-sided prism. It is believed the reflected beam from the three-sided prism is so directed that it does not actually enter the probe output system. Due to the higher cost of the four-sided prism, the three-sided prism was used in the MTCMD.

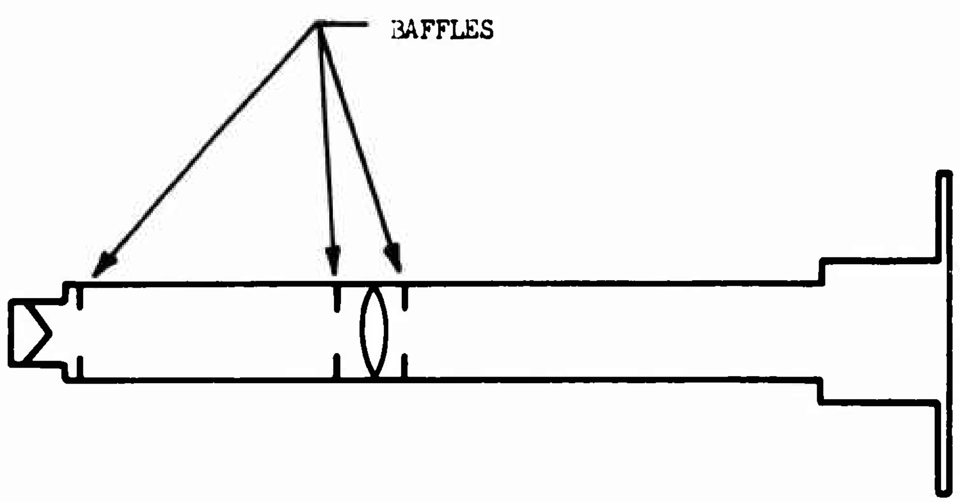


Figure 13. Proximity Probe Baffles.

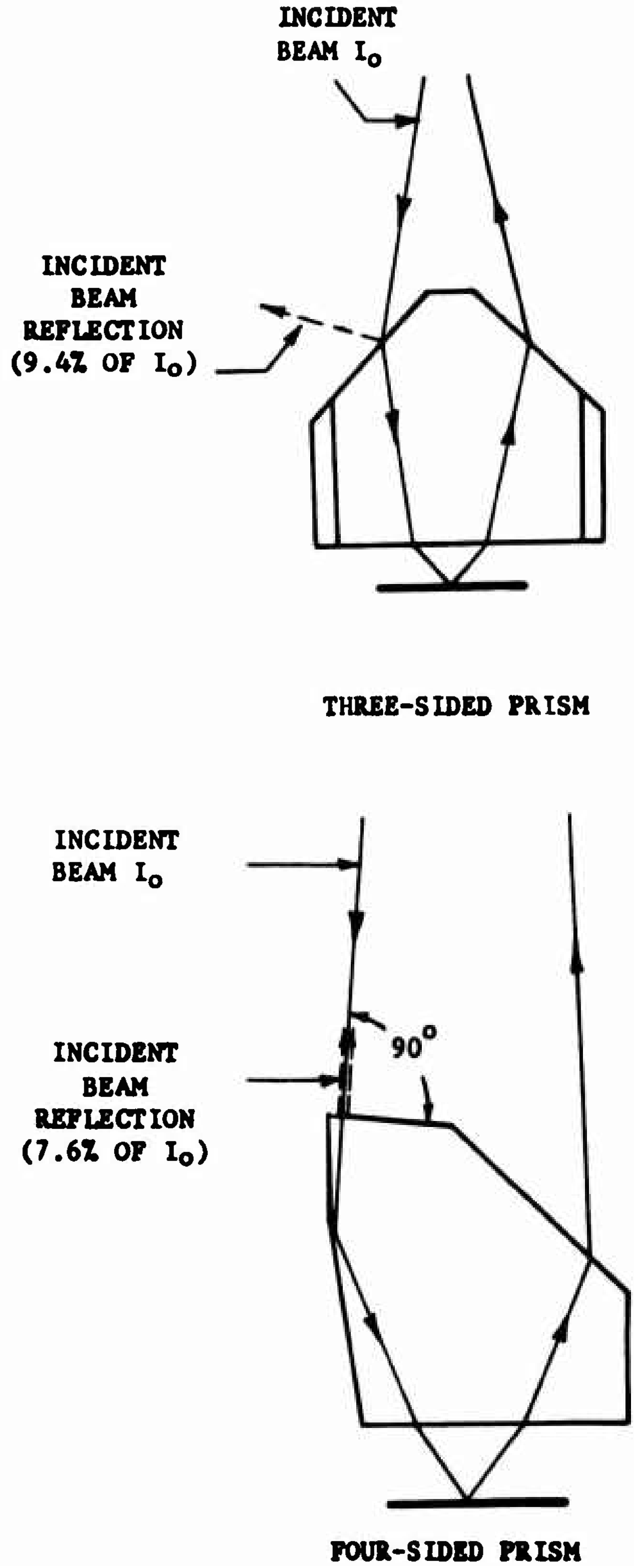


Figure 14. Prism Configurations.

Specification of Higher Quality Optics

Higher quality optics were specified for the probe prism and lens to eliminate probe flare (Figure 15).

Prism

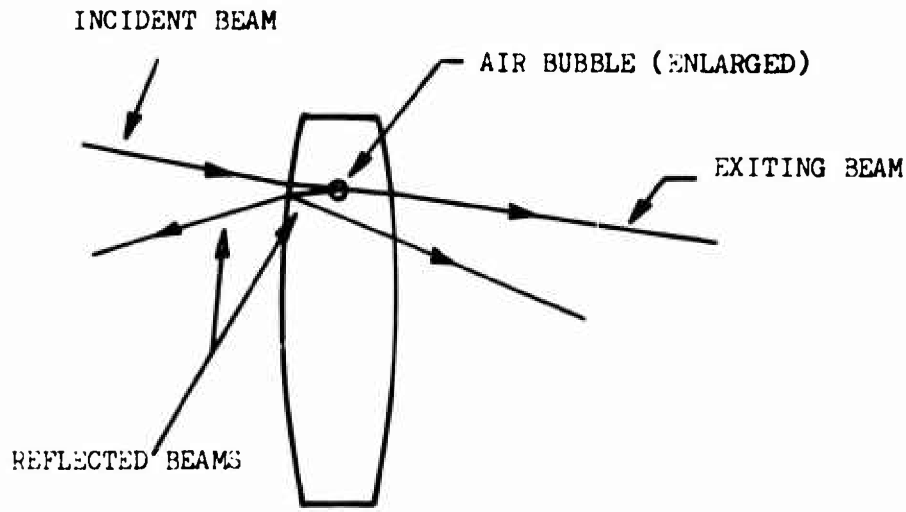
The probe prism is fabricated from synthetic sapphire. The optical quality specified for the sapphire is "scatter-free." Scatter-free material will not scatter any light when a low-power laser beam is passed through it. Comparison of the prism material with material used in previous proximity probes indicated a noticeable reduction in flare from the MTCMD prism.

Lens

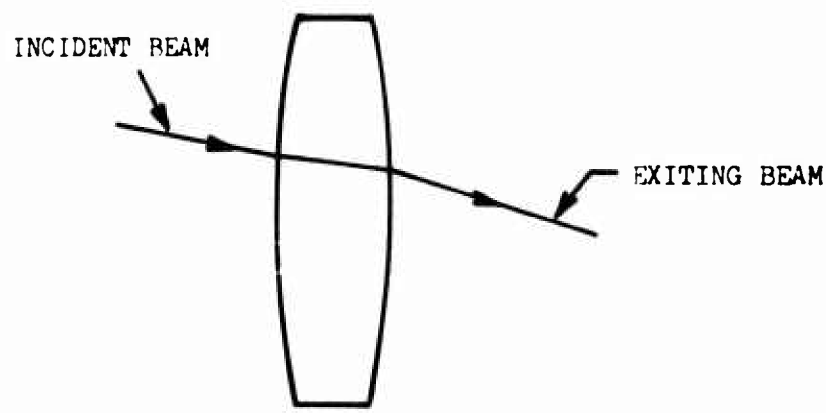
The MTCMD probe lens is fabricated from fused silica. The optical grade specified for the lens is "Schlieren grade". Schlieren grade material contains no visible striae streaks or cords when tested by the Schlieren method. Comparison of the MTCMD lenses with lenses used in previously developed proximity probes indicated less flare associated with the MTCMD lens.

Lens Coating

Lens coatings are used on optical elements to reduce light reflected from the element surface (Figure 16). The prism was not coated since no coating is available to withstand the high temperature encountered by the probe prism. Coatings are available that can withstand a 400°F environment. The MTCMD gaseous purge flow cools the fused silica lens element below this temperature, allowing the use of antireflective coatings. The coating was specified to reflect no more than 0.5% of a light beam with an incident angle of 15 deg. Uncoated optics will reflect approximately 4.5% of the beam at this incident angle. Laboratory evaluation indicated that when using a 10-milliwatt He-Ne laser with a 15-deg incident angle, 1.6% was reflected from the coated lens and 6% from an uncoated lens. Figure 17 is a visual comparison of coated and uncoated lens elements.



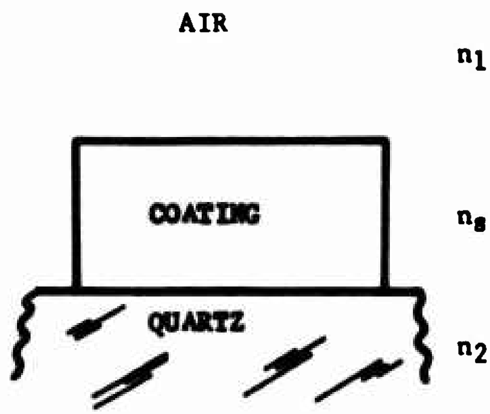
LOW QUALITY OPTICS



HIGH QUALITY OPTICS

IMPERFECTIONS IN LOW QUALITY OPTICS CAUSE THE INCIDENT BEAM TO BE REFLECTED. SUCH REFLECTIONS ADD TO THE BACKGROUND NOISE OF THE PROBE, AND REDUCE THE INPUT BEAM INTENSITY.

Figure 15. Lens Flare Comparison.



n_1 = INDEX OF REFRACTION OF AIR

n_2 = INDEX OF REFRACTION OF QUARTZ

n_s = INDEX OF REFRACTION OF COATING

LIGHT IS PARTIALLY REFLECTED WHEN TRAVELING FROM A SUBSTANCE WITH AN INDEX OF REFRACTION n_1 INTO A SUBSTANCE WITH AN INDEX OF REFRACTION n_2. IN THE PROXIMITY PROBE, THIS REFLECTED LIGHT ADDS TO THE BACKGROUND NOISE. THE USE OF A COATING WITH A SELECTED INDEX OF REFRACTION n_s CAN REDUCE THE AMOUNT OF REFLECTED LIGHT.

Figure 16. Antireflective Coating.

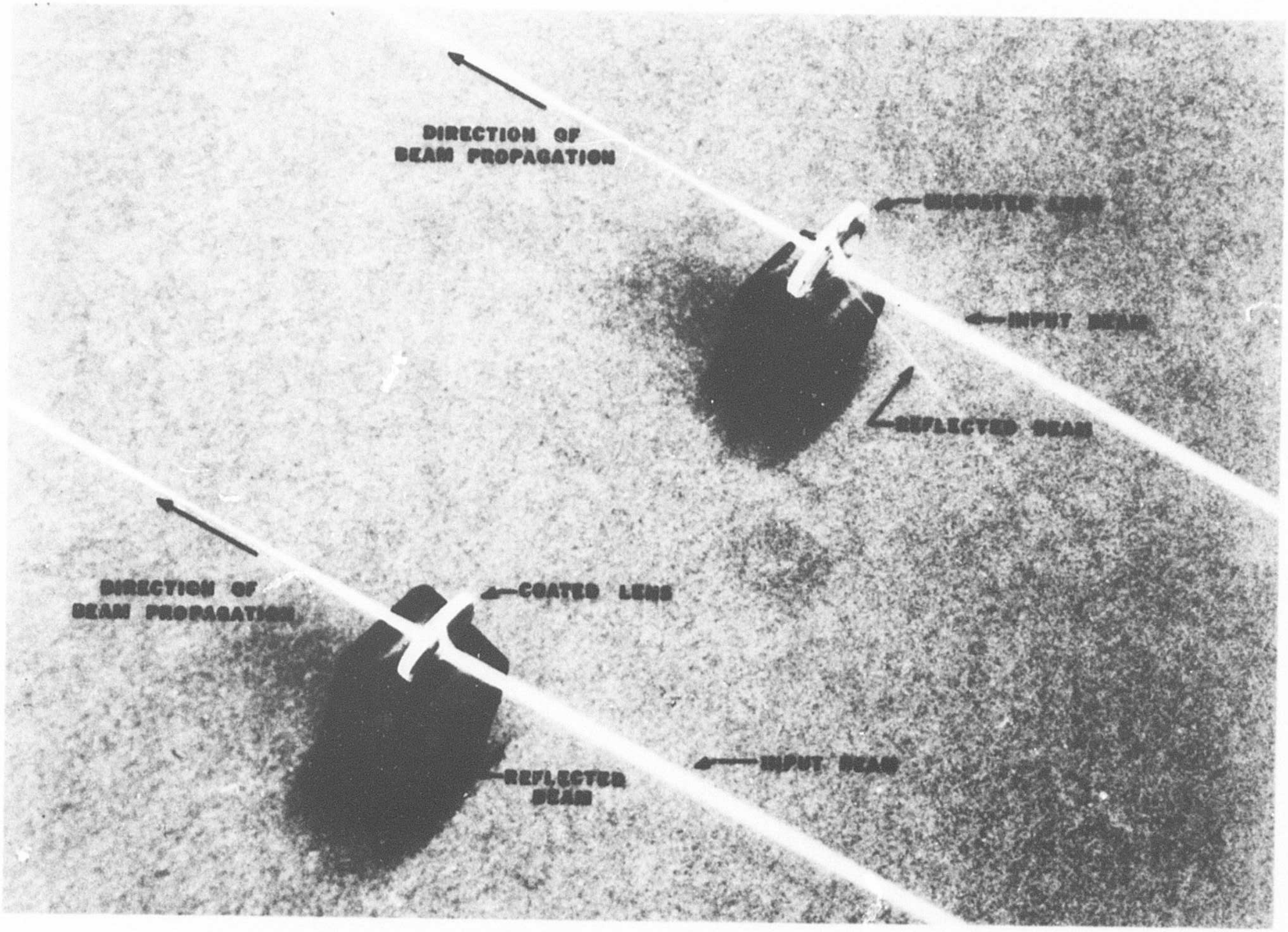


Figure 17. Surface Reflections From Coated and Uncoated Lenses.

Development of a High-Efficiency, Three-Lens Probe

Light scattered from the internal walls of previously developed proximity probes significantly added to the system background noise. In an effort to reduce this background noise, a three-lens probe was designed to collimate the input and output beams by use of input and output lenses located in the probe head (Figure 18). The collimated beams can be transmitted for long distances with negligible beam spread. Determination of the required lens focal lengths is discussed in Appendix D.

Figure 19 illustrates the laser beam shape as it passes through the three-lens probe optical elements. Figure 20 shows the beam shape as it passes through the single-lens MTCMD probe. Analysis (Appendix E) indicates:

- Optical efficiency of the single-lens system is 25%, in that 25% of the input laser light is available at the output bundle.

- Optical efficiency of the three-lens system is 50%, in that 50% of the input laser light is available at the output bundle.

The three-lens system was compared to the MTCMD single-lens probe. Figures 21 and 22 show the assembled three-lens probe and probe parts. Figure 23 illustrates the probe assembly. Evaluation of the two probe configurations indicated the single-lens probe was more practical than the three-lens configuration. The optical component assembly and alignment of the three-lens probe is more difficult than the single-lens probe.

Comparison of the two probes' signal-to-noise ratios by viewing the television monitor did not reveal any noticeable improvement in signal-to-noise ratio for the three-lens probe. The modifications discussed earlier have improved the single-lens system signal-to-noise ratio to a point that made it comparable to the three-lens system.

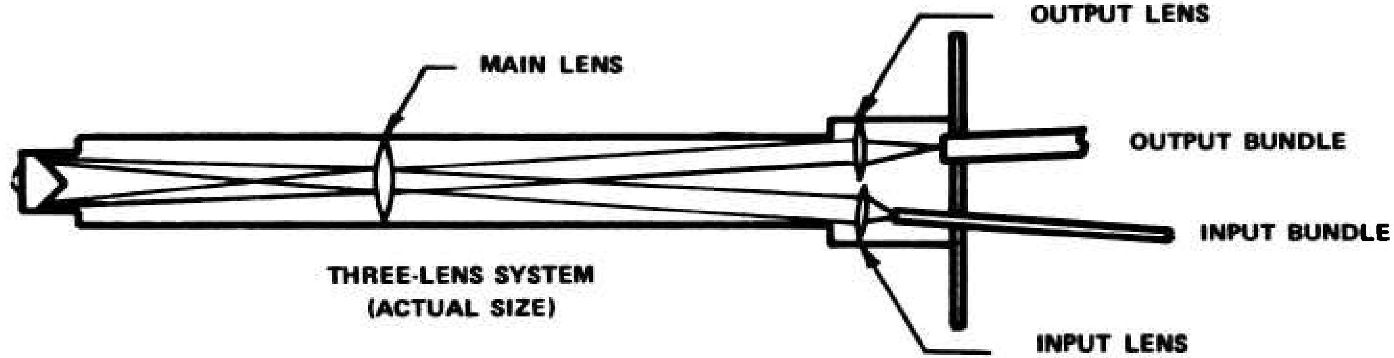
SPATIAL RESOLUTION

The spatial resolution of the system is a measure of the reflected spot size imaged on the television monitor. To meet the MTCMD accuracy and resolution requirements, the spot size was reduced compared to previously developed proximity probe systems. Spot size reduction enables tip clearances to be more accurately determined since the spot center position can be more readily discerned. The following system modifications were incorporated in the final design to increase the system spatial resolution:

- Specification of tighter tolerances on lens and prism surfaces

- Reduction of the input fiber optic diameter

- Reduction of the angle of incidence of the input beam between the input bundle axis and the probe lens centerline



THE MAIN LENS PERFORMS THE FUNCTIONS OF THE SEPARATE LENSES IN THE BASIC SYSTEM. IN ADDITION, LENSES ARE ADDED TO COLLIMATE THE INPUT BEAM AND FOCUS THE OUTPUT BEAM.

Figure 18. Three-Lens System.

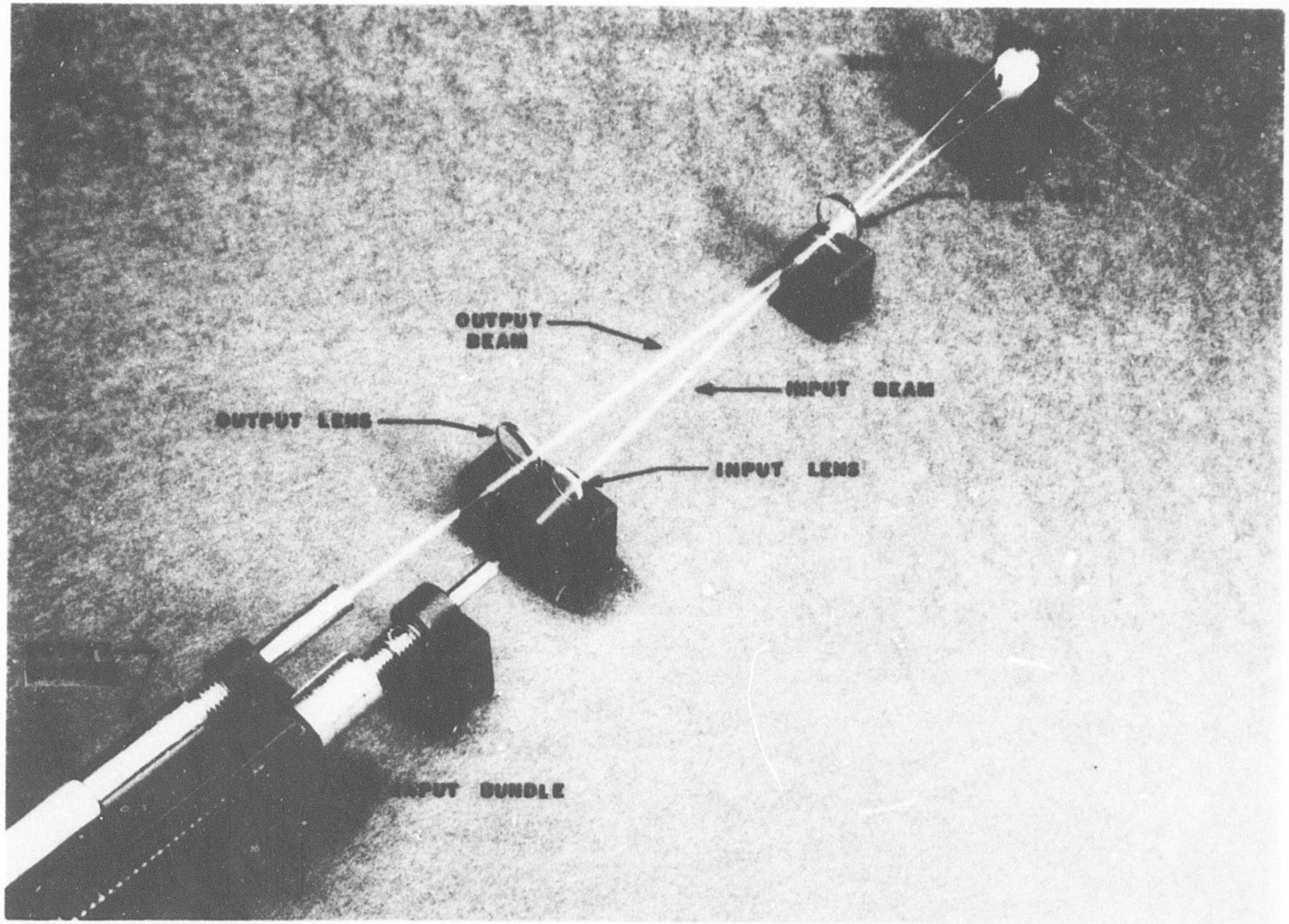


Figure 19. Light Path Through Three-Lens Probe.

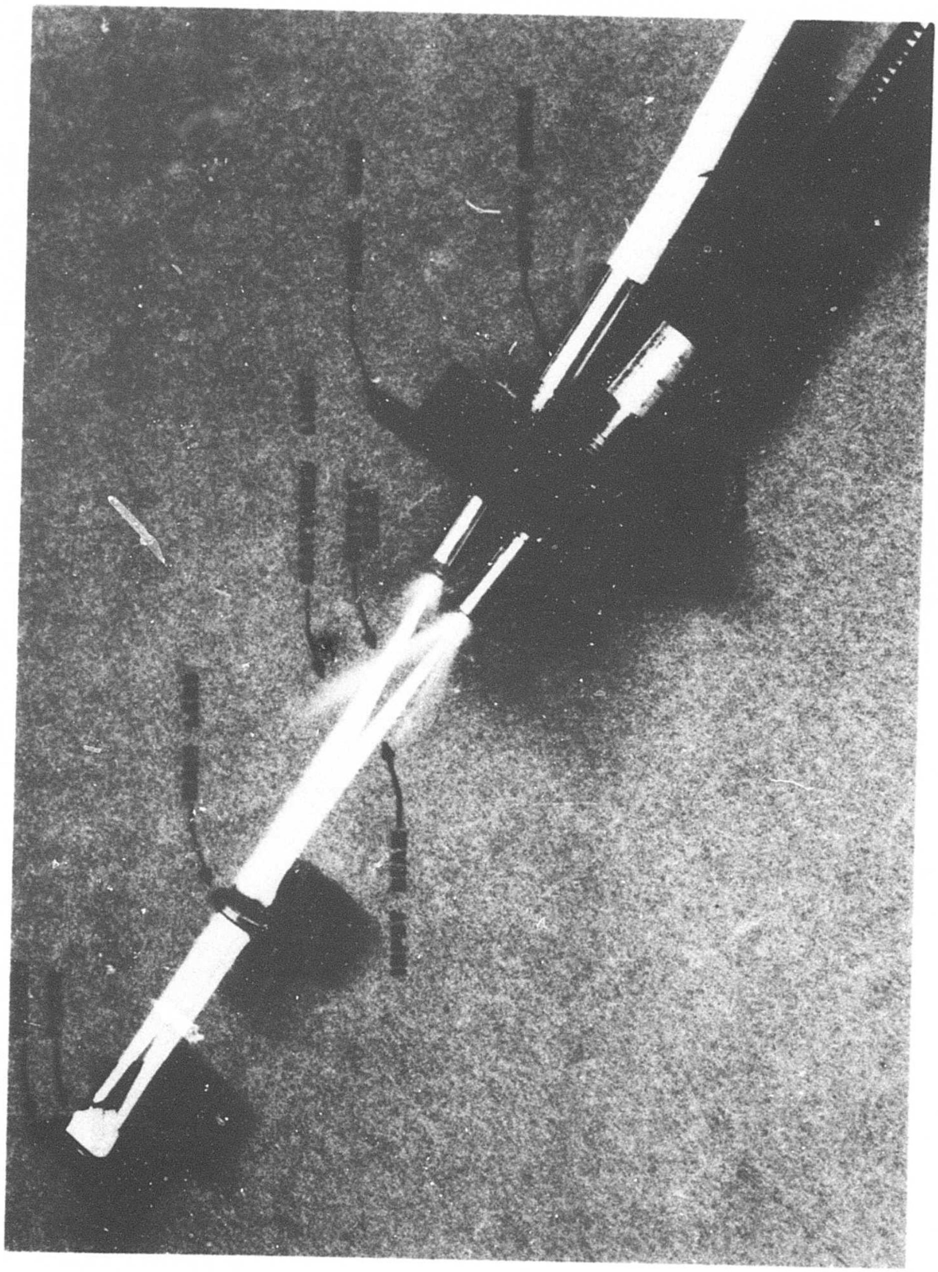


Figure 20. Light Path Through MTCMD Probe.

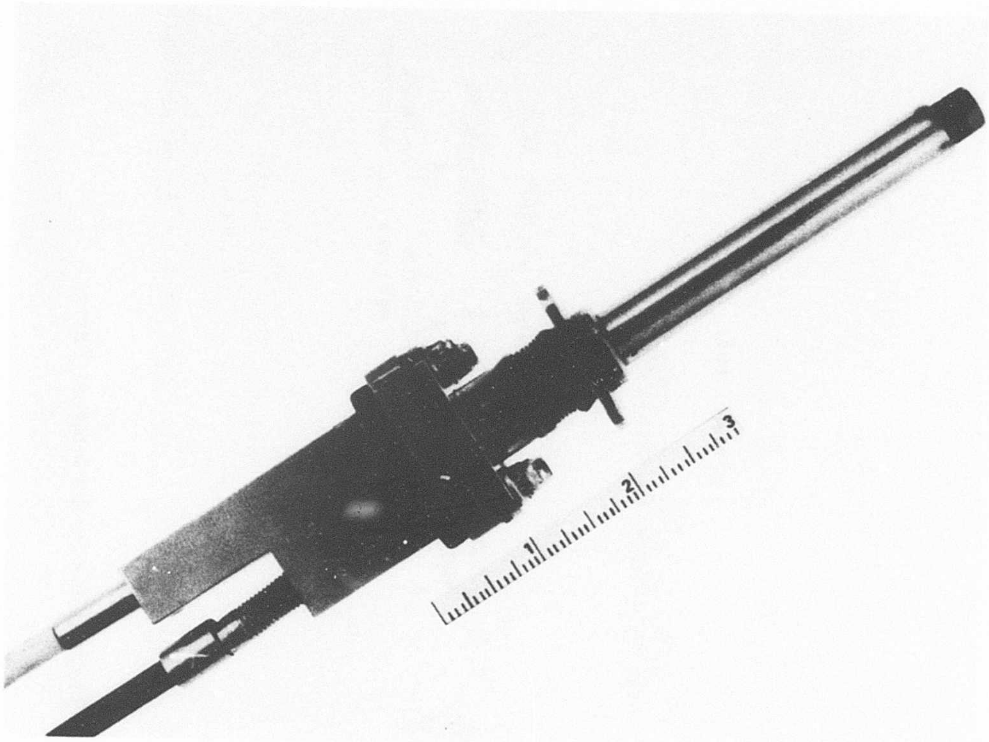


Figure 21. Three-Lens Probe.

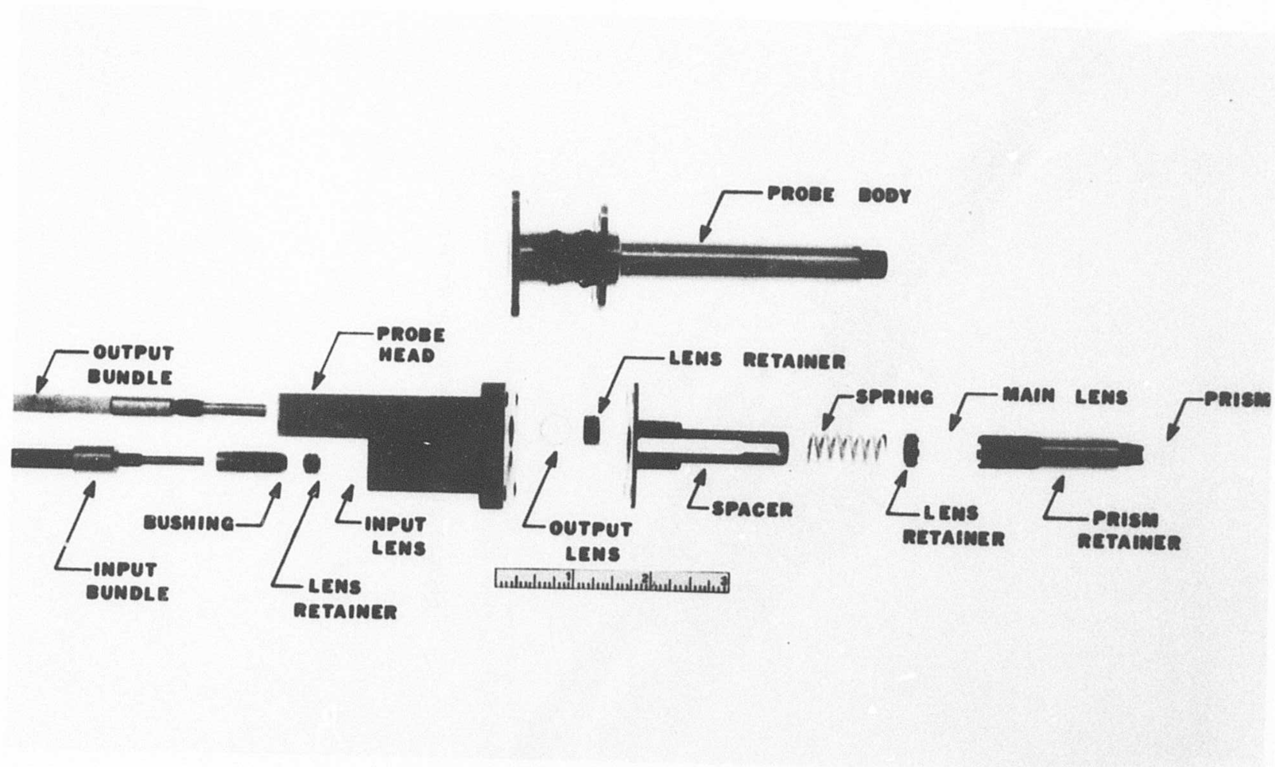
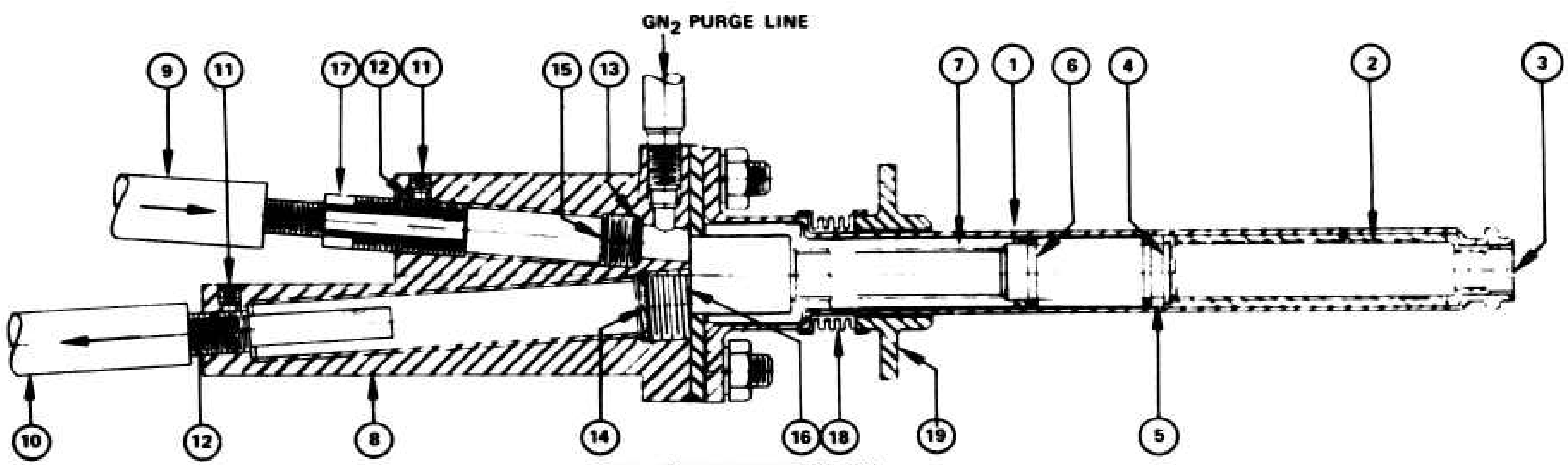


Figure 22. Three-Lens Probe Internal Parts.



1 SUBASSY HOUSING AND TIP
2 PRISM RETAINER
3 3-SIDED PRISM
4 MAIN LENS
5 LENS RETAINER
6 COMPRESSION SPRING NO. 9655K22, S/S
7 SPACER
8 3-LENS SYSTEM HEAD
9 INPUT FIBER OPTIC
10 OUTPUT FIBER OPTIC
11 NO. 5 HEX SOCKET SETSCREW, S/S
12 ROD 0.100 in. DIA
13 3-LENS SYSTEM INPUT LENS
14 3-LENS SYSTEM OUTPUT LENS
15 LENS RETAINER RING
16 LENS RETAINER RING
17 INPUT FIBER OPTIC RETAINER
18 BELLOWS
19 PROBE FLANGE

Figure 23. Three-Lens System Assembly.

Element Surface Tolerance

Specification of rigid optical component surface tolerances is intended to reduce system aberrations. Optical aberrations would prevent the MTCMD from imaging a well-defined circular spot on the television monitor. All surface elements were specified to have surface irregularities of less than 1/4 wavelength when tested by standard optical flats. More precise surfaces for this optical system will not be beneficial. The MTCMD with high-quality elements was compared to a proximity probe system with lower quality elements. The MTCMD produced a more nearly circular, better-defined spot than previous systems.

Reduction of the Input Fiber Optic Diameter

The spot size imaged on the television monitor is directly proportional to the diameter of the input fiber transmitting the laser energy. If the fiber diameter is reduced by a factor of two, the diameter of the spot on the television monitor is reduced by a factor of two. The fibers used in the MTCMD input bundle are 0.001 in. in diameter. Previously developed probe input fibers were 0.002 in. in diameter. Use of the smaller diameter fiber in the MTCMD does not reduce the amount of energy transmitted from the laser to the probe head since the microscope objective focuses the laser light to a near-point image much smaller than the fiber diameter. Evaluation indicates the spot seen on the television monitor using the 0.001-in.-diameter input fiber (Figure 24) is substantially smaller than the spot obtained using the 0.002-in.-diameter fiber (Figure 25).

Input Beam Angle of Incidence

System astigmatism is directly proportional to the angle of incidence between the input fiber centerline and the probe lens centerline. As this angle is increased, the aberration becomes worse, making the spot on the television monitor elliptical in shape. In the design of the MTCMD, the incident angle of the input beam was reduced by 20% over previous proximity probe designs. Reduction of the incident angle was possible due to the shorter range of the MTCMD as compared to earlier system probes. (See Appendix A.)

Comparison of the MTCMD spot shape to the spot produced by previous proximity probe systems as monitored by the television monitor indicates less ovalization of the MTCMD spot.

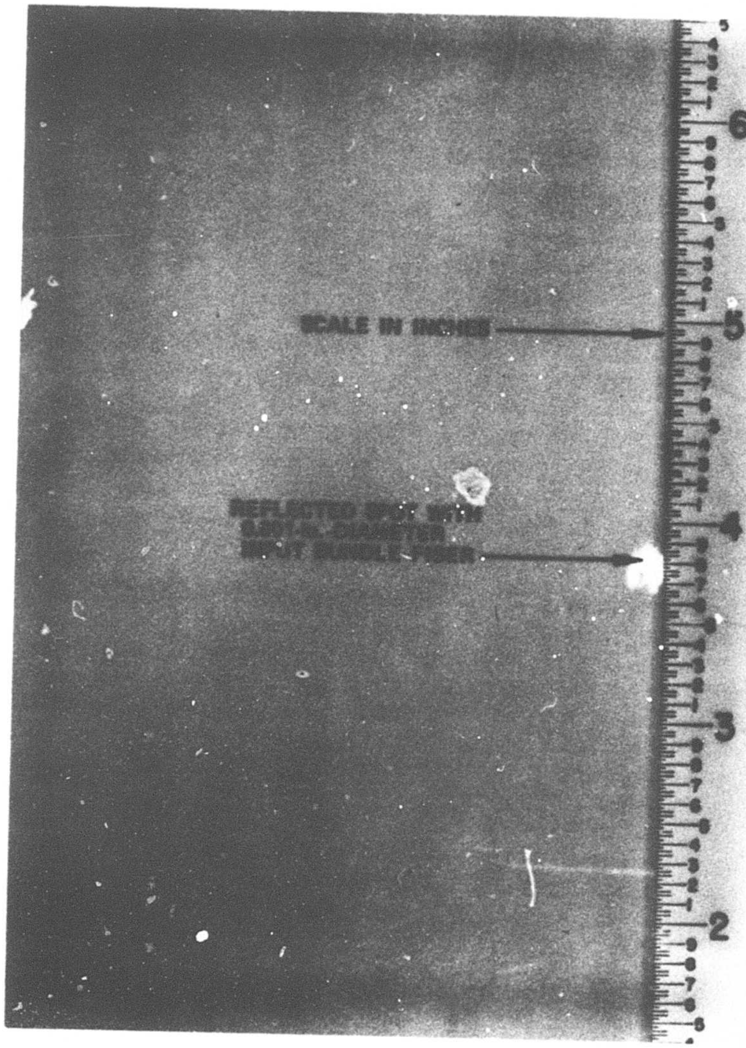


Figure 24. Television Monitor Data Spot With 0.001-in.-Diameter Input Fiber.

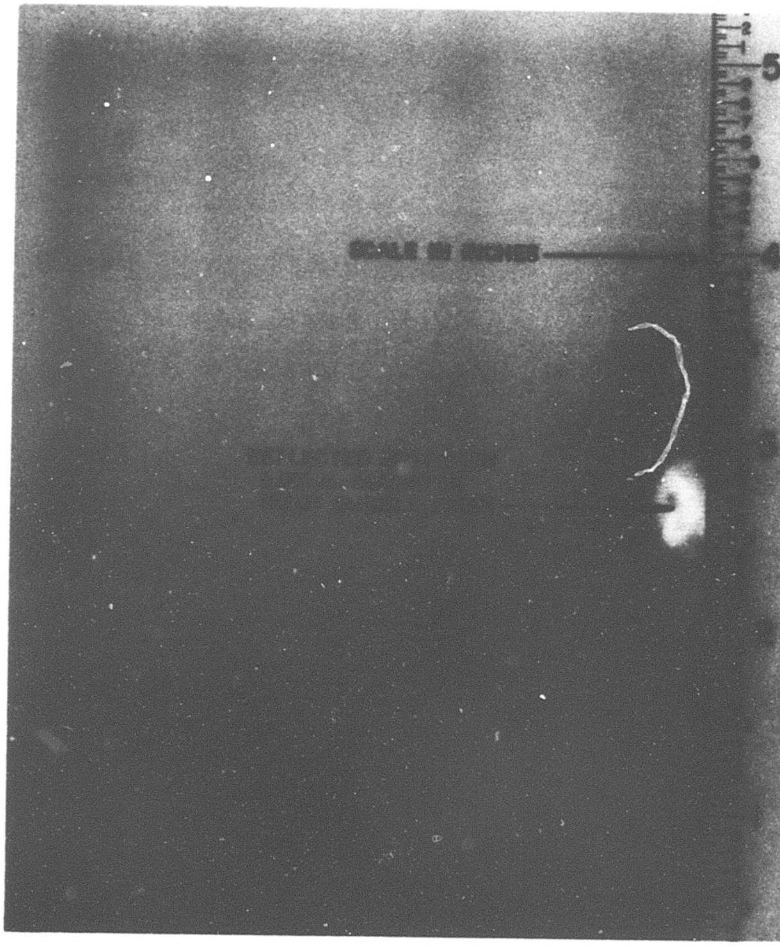


Figure 25. Television Monitor Data Spot With 0.002-in.-Diameter Input Fiber.

DEMONSTRATION TESTING

The MTCMD was evaluated to confirm that the system meets the design criteria. The evaluation consisted of:

- Room-temperature demonstration and calibration
- High-temperature demonstration
- Vibration endurance demonstration
- Cost
- Life.

These tests demonstrated that the MTCMD meets all the design criteria. All instrumentation used in the performance of these tests had up-to-date calibrations traceable to the National Bureau of Standards.

ROOM-TEMPERATURE CALIBRATION AND EVALUATION

The MTCMD room-temperature calibration and evaluation demonstrated that the system met the design requirements for:

- Range
- Accuracy
- Sensitivity
- Time response
- Pressure
- Power consumption.

Range

The MTCMD design range is 0.065 in. Figure 26 illustrates the test fixture used to confirm the probe range.

A calibrated micrometer with a resolution of 0.0001 in. was used for the range measurement. The micrometer face was positioned perpendicular to the probe axis and used as the probe target. The probe zero position, representing zero blade clearance, was established by bringing the face of the micrometer in contact with the probe tip. To measure the probe range, the micrometer face was moved away from the probe tip until the reflected spot was no longer visible on the television monitor. The reflected spot remained a constant size and intensity for 0.065 in. of micrometer travel. The spot became indistinguishable on the monitor between 0.065 and 0.075 in. of micrometer travel.

Accuracy

The MTCMD accuracy is ±0.001 in. The system accuracy was determined using the experimental fixture used to measure system range (Figure 26).

Figure 27 illustrates a typical MTCMD calibration. To establish the calibration curve, the reflected spot zero position was marked on the television monitor. The micrometer face was then moved away from the probe tip in 0.005-in. increments, and the distance from the reflected spot zero position to the new reflected spot position for each increment was recorded and the position of the spot marked on the monitor screen. To establish probe accuracy, clearances were set using the micrometer, and the clearance was determined using the spot location markings on the monitor screen. The clearances read from the monitor corresponded within 0.001 in. with the actual clearance measurements as determined by the micrometer.

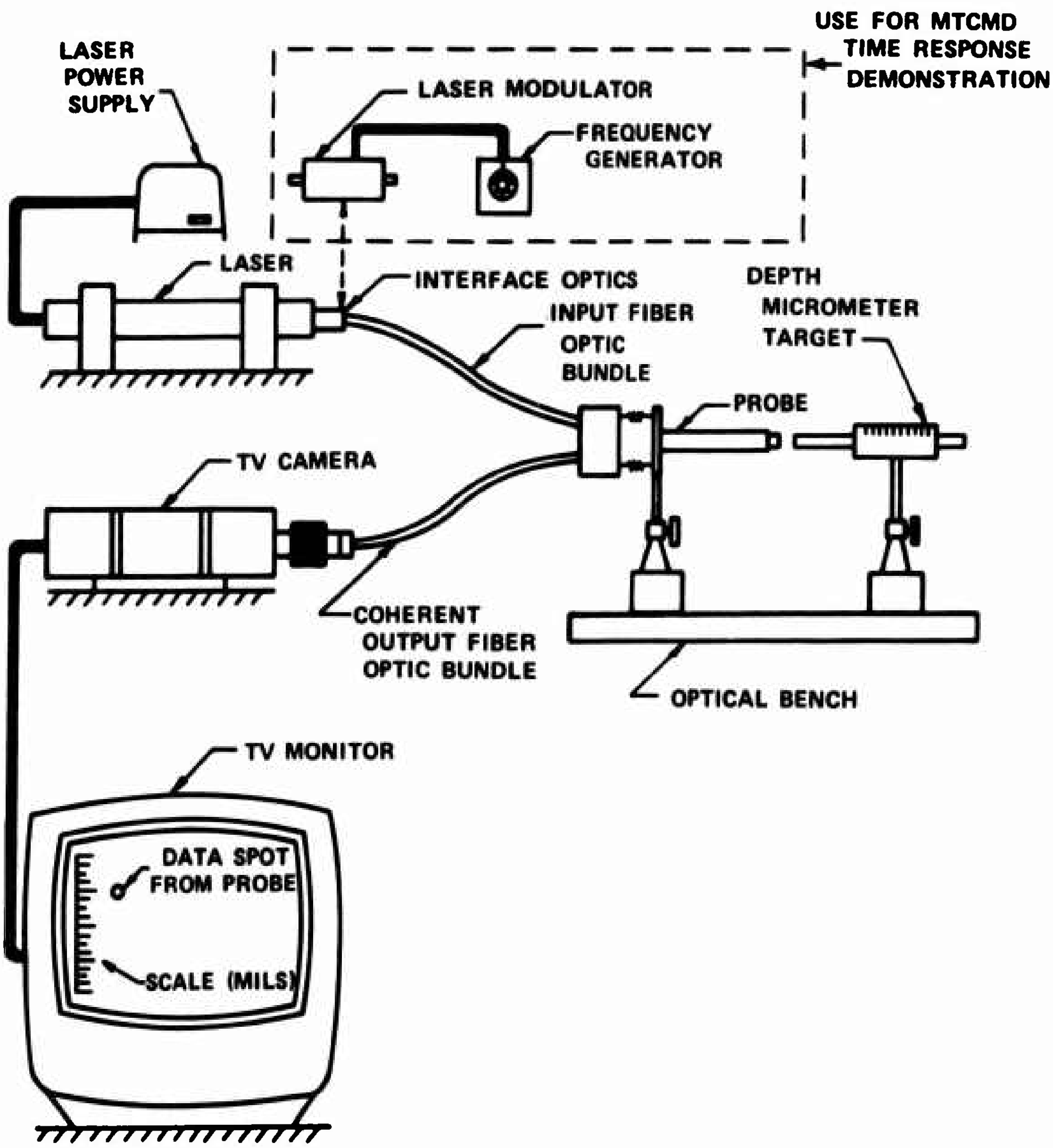


Figure 26. Room-Temperature Demonstration.

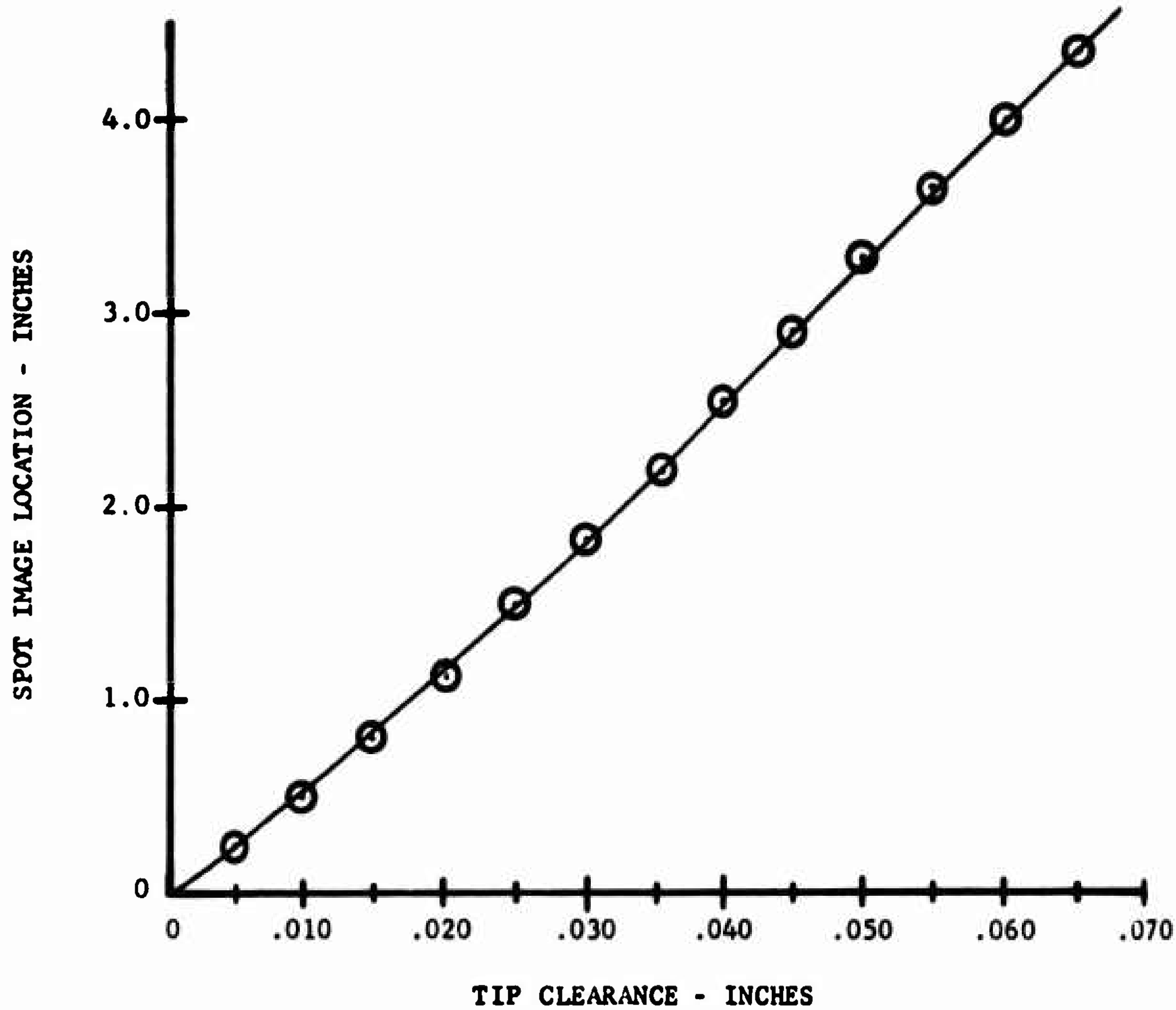


Figure 27. Typical Room-Temperature Calibration Miniaturized Tip Clearance Measurement Device.

Sensitivity

The MTCMD sensitivity is 0.0005 in. The sensitivity was determined using the same fixture used during the system range and accuracy evaluations (Figure 26). A micrometer face movement of 0.0005 in. resulted in a 0.032-in. movement of the spot on the television monitor.

Time Response

The MTCMD time response was found to be fast enough to allow measurements of the clearance between turbine blade squealer tips and the engine case. In actual engine operation, turbine blade tips are in the field of view of the MTCMD for only a short duration as the engine rotor turns. For the potential engine application at maximum rotor speed, the blade squealer tips will be in the probe field of view for 0.4×10^{-6} sec once every 38×10^{-6} sec.

Figure 26 illustrates the test setup used to demonstrate the system time response necessary to detect the squealer tips.

A laser modulator was installed in the MTCMD optical train to "chop" the system light in a manner similar to turbine squealer tip passage. The laser modulator is an electrically controlled filter that allows light to pass only when an electric potential is applied. Wave generators provided a pulsed electric signal to the modulator of the same duration and repetition rate as the squealer tip passage. The reflected spot intensity and shape as viewed on the television monitor did not change during the test from the spot size and shape obtained during steady-state operation. This confirms that the MTCMD response is sufficient to measure the clearance between the turbine blade squealer tips and the engine case.

Pressure

The MTCMD probe was hydrostatically tested to 200 psig and found structurally sound. This pressure exceeds the ten-atmosphere (132 psig) design requirement. The pressure test fixture is shown in Figure 28.

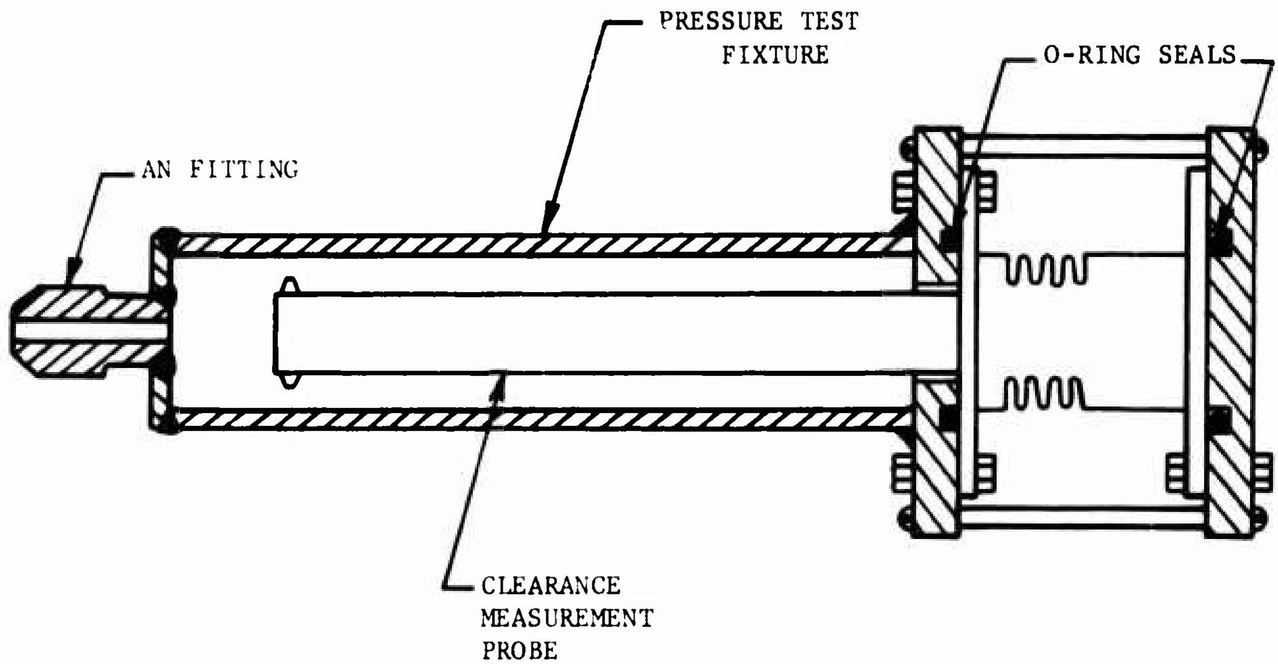


Figure 28. Pressure Test Fixture.

Power Consumption

The total power consumption of the MTCMD system was measured as 157 watts. The design criteria required a maximum power consumption of 280 watts. All system electrical components operate on 110-volt, 60-cycle power. The power consumption was determined by measuring the total component current drawn while operating at 110 VAC.

HIGH-TEMPERATURE DEMONSTRATION

The high-temperature tests were conducted to:

- Determine the gaseous purge flow required to cool and clean the MTCMD optical components.

- Demonstrate the high-temperature capabilities of the MTCMD.

Temperature capabilities of the system were demonstrated using high-temperature test rigs. A combustor burning JP4 was used as a hot gas source to simulate expected turbine gas temperatures.

During testing, the gas temperature of the burner was measured using a calibrated platinum vs platinum 10% rhodium thermocouple. Test rig wall temperatures were measured using an optical pyrometer.

Gaseous Purge Flow

To determine the required MTCMD gaseous purge flow, the MTCMD probe was installed in the test fixture without the optical bundles connected to the probe head. A thermocouple was installed in the probe head to monitor the head temperature.

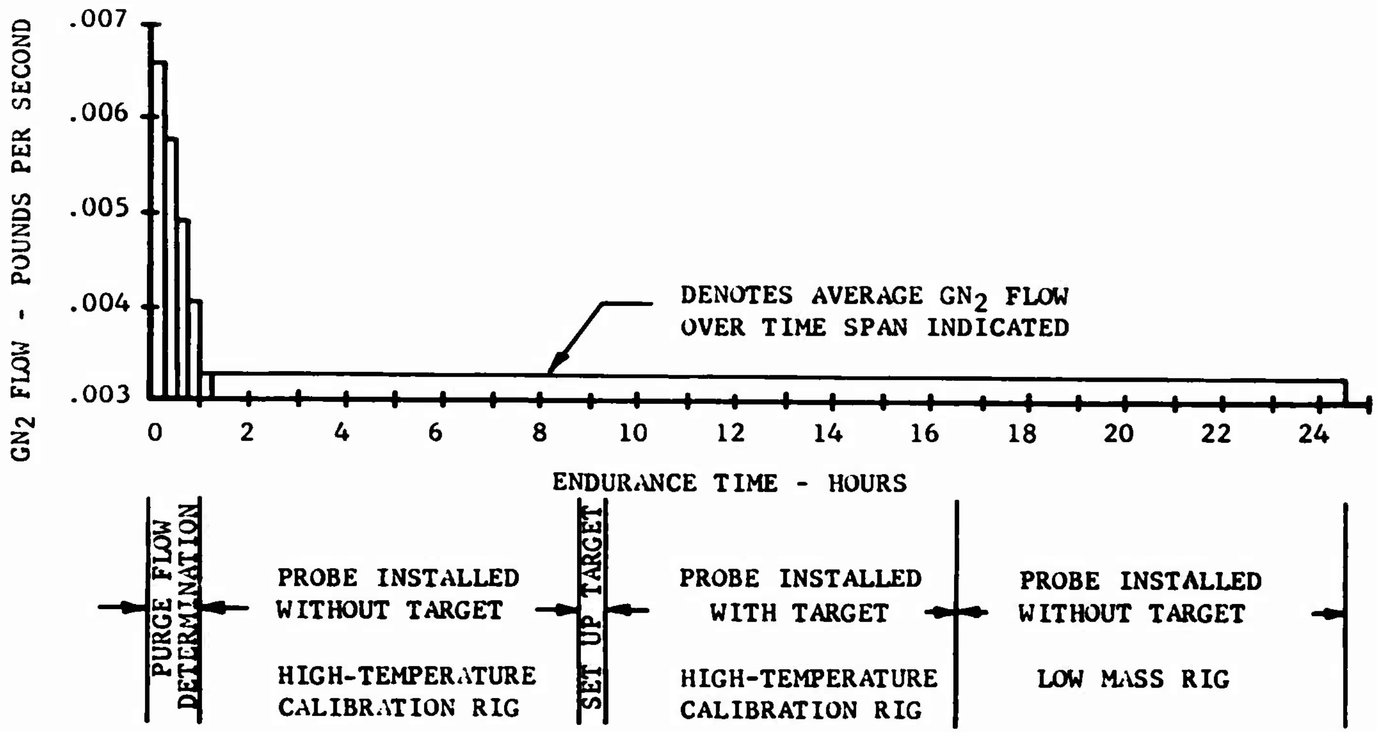
The maximum allowable purge flow rate was set by use of a needle valve, which was installed in the purge line. The flow rate was measured by a calibrated rotameter. The burner fuel/air ratio was adjusted to obtain a gas temperature of 2400°F. The probe was tested under these conditions for 15 minutes. During the run the head temperature was monitored and did not increase above the prerun ambient. At the end of the run the probe optics were inspected and found to be clean.

The purge was reduced in steps while the above test procedure was repeated. The final purge flow rate tested was 0.0033 lb/sec, which is only 21% of the maximum allowable flow rate specified in the design criteria. Even lower flow rates were not attempted in order to prevent any damage to the internal structure in the probe tip that might delay the test program. The probe tip could not be instrumented internally for this test without modifying the optics.

At no time during these tests did the probe head temperature increase as the purge flow rate decreased, and no silting of the optical system occurred. Figure 29 illustrates the probe purge flow rate used during the entire elevated temperature demonstration.

High-Temperature Endurance Test

The MTCMD was tested for a total of 24.5 hours at gas temperatures ranging from 2300°F to 3150°F (Figure 30). The intent of the demonstration was to verify that the MTCMD could operate for 7 hours in a test rig with a hot gas temperature of 2400°F and a wall temperature of 1900°F.



MAXIMUM ALLOWABLE PURGE FLOW RATE - 0.016 POUND PER SECOND OF GN_2

ACTUAL PURGE FLOW RATE USED - 0.0033 POUND PER SECOND OF GN_2

Figure 29. High-Temperature Calibration Demonstration Nitrogen Purge Flow Rate Determination.

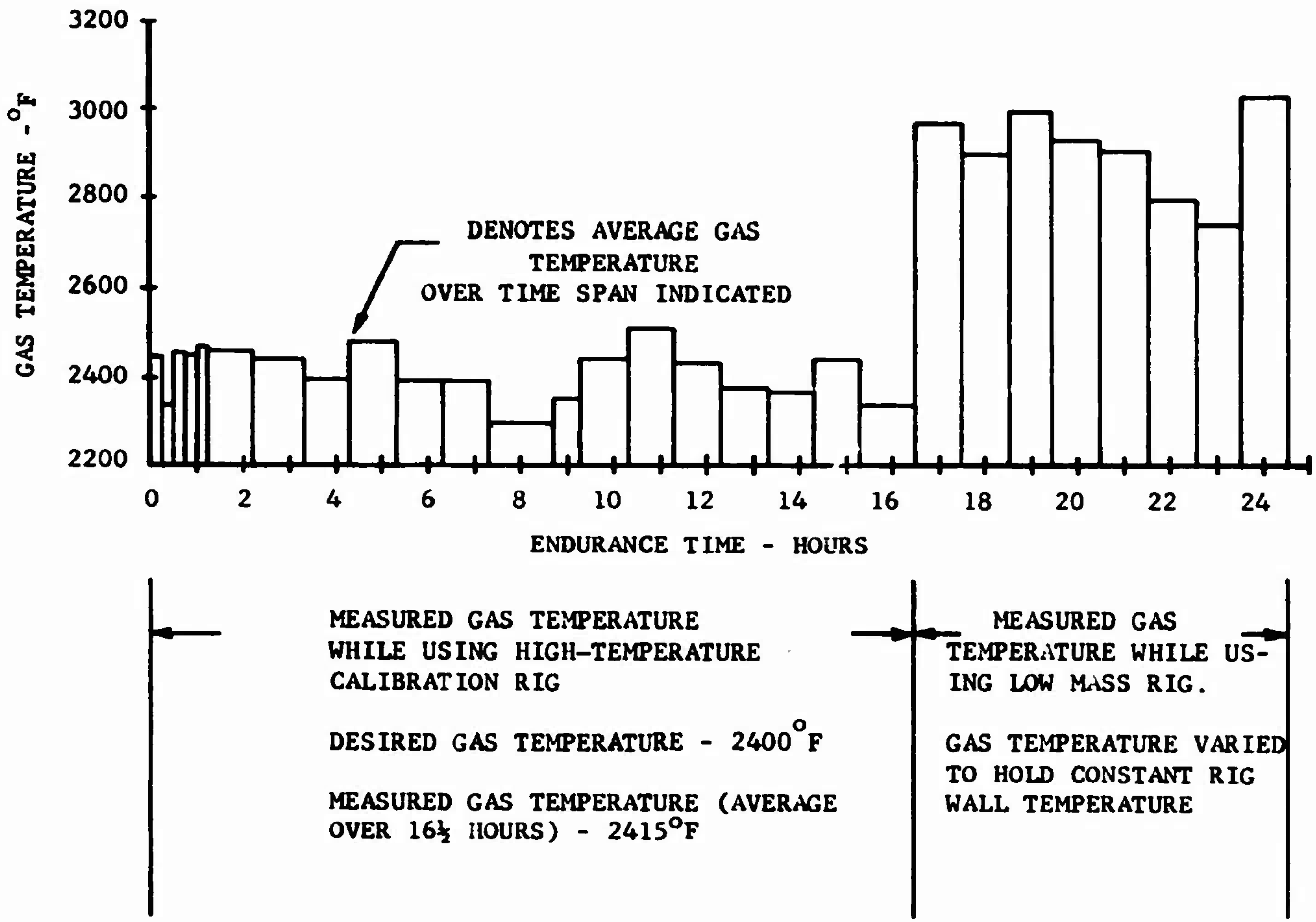


Figure 30. High-Temperature Calibration Demonstration Variation of Gas Temperature With Time.

A test fixture with a target positioned by a micrometer was fabricated and is illustrated in Figure 31. The target is fabricated of the same material and has the same coating as the turbine blades in the potential engine application. The fixture was air and water cooled to enable simulation of shroud inner and outer wall temperatures. The MTCMD was tested for a total of 16.5 hours in this rig. The laser modulator was used to simulate squealer tip passage during the test. The test apparatus is shown in Figure 32. The MTCMD continuously monitored the position of the target set in a fixed location during 7 hours of this test.

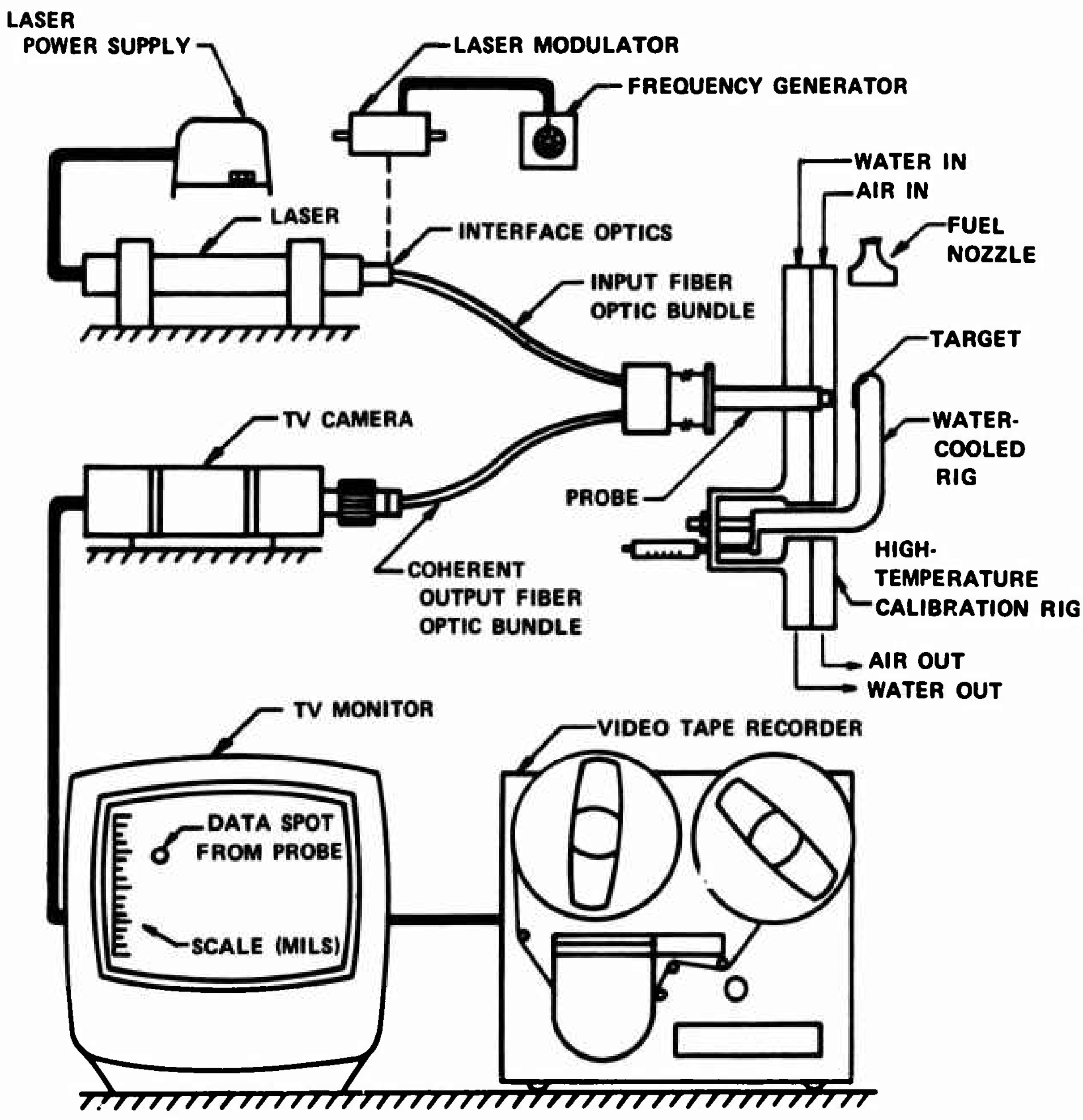


Figure 31. High-Temperature Demonstration Tests.

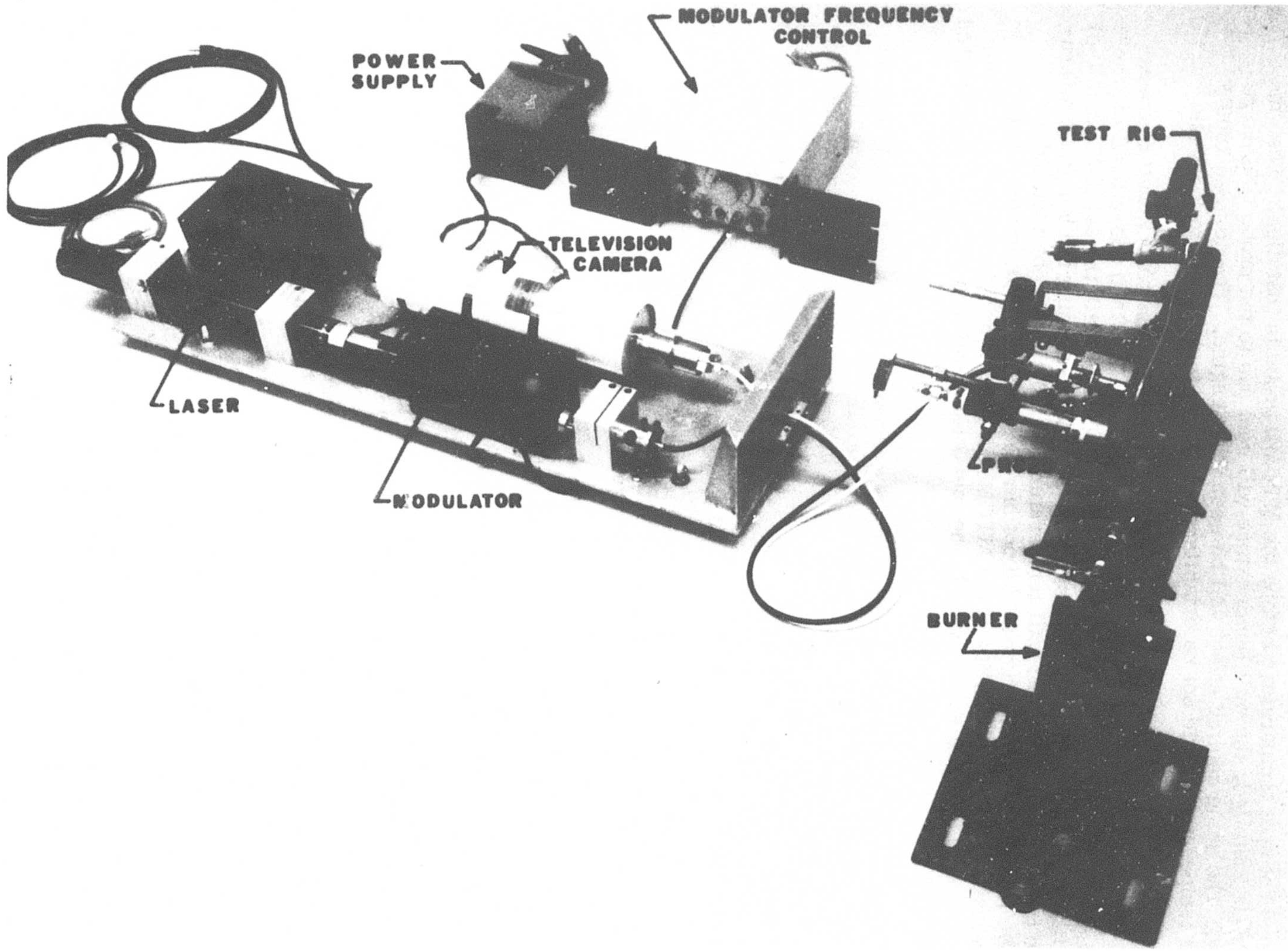


Figure 32. Equipment Used in Hot Calibration Demonstration.

To simulate engine conditions, the test rig wall must be established at the 1900°F shroud hot spot temperature before the MTCMD probe is installed. When the probe is installed, the wall temperature will cool due to the probe GN_2 purge flow. The same cooling effect will be seen in an engine. The desired 1900°F wall temperature could not be established with this test rig due to its mass.

A second lightweight test rig was fabricated to achieve the 1900°F wall temperature, while the original rig was used to evaluate the MTCMD operational characteristics at temperature. The lightweight test fixture (with the MTCMD installed) is illustrated in Figure 33. By using this rig and increasing the hot gas temperature to 3150°F, the desired wall temperature of 1900°F was obtained before probe installation. This fixture did not have a target and was intended only to demonstrate the survivability of the MTCMD at 1900°F wall temperature. When the GN_2 cooled probe was installed, the metal temperatures dropped, as indicated in Figure 34.

Testing with the first test rig indicated the system-reflected spot quality did not deteriorate during the extended higher temperature operation. Clearance measurements made with the MTCMD during the high-temperature tests were invalid. The test rig warped during testing due to temperature gradients (Figure 35), and this damage increased with time. This warpage caused variations in the clearance between the MTCMD probe tip and the target that could not be measured with the target micrometer.

Figure 36 shows the wall temperatures measured during the entire hot calibration demonstration. A prerun and postrun system calibration indicated the MTCMD system calibration was not changed by the high-temperature demonstration test (Figure 37).

During the high-temperature demonstration tests

- MTCMD endurance was demonstrated by a total 24.5 hours of testing at gas temperatures ranging from 2300°F to 3150°F.
- Engine wall temperatures were realistically simulated using a lightweight test rig for 8 hours of testing.
- A GN_2 purge flow rate of 0.0033 lb/sec was established. This is only 21% of the maximum allowable flow rate.

VIBRATION DEMONSTRATION

A shaker capable of simulating typical engine vibrational levels was used to vibration test the MTCMD.

The MTCMD was subjected to sine sweep vibration tests in the frequency range of 50 to 2500 Hz in each of three mutually perpendicular planes. The duration of each sweep was 20 minutes for each plane at the following levels:

± 1 G from 5 - 250 Hz
± 2.5 G's from 250 - 500 Hz
± 10 G's from 500 Hz - 1 KHz
± 20 G's from 1 - 2.5 KHz

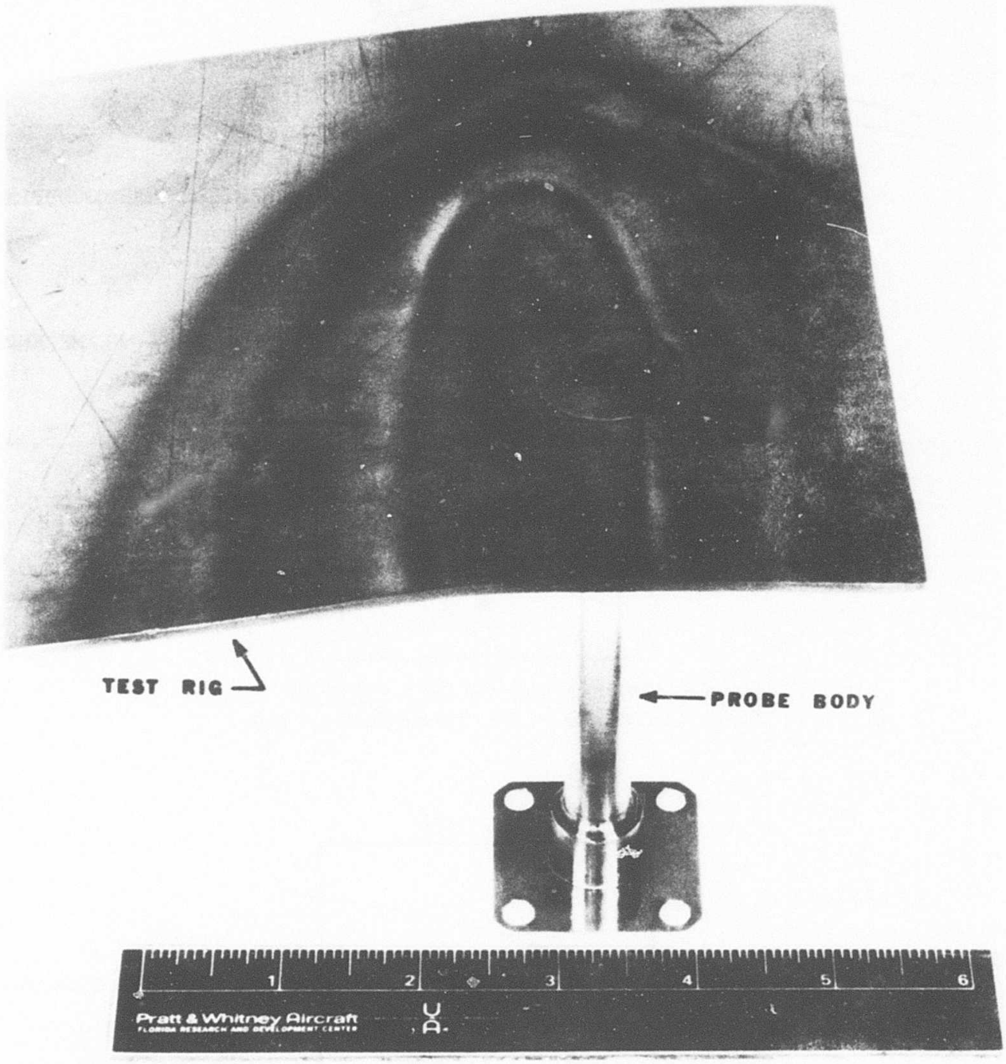


Figure 33. Second Hot Calibration Rig.

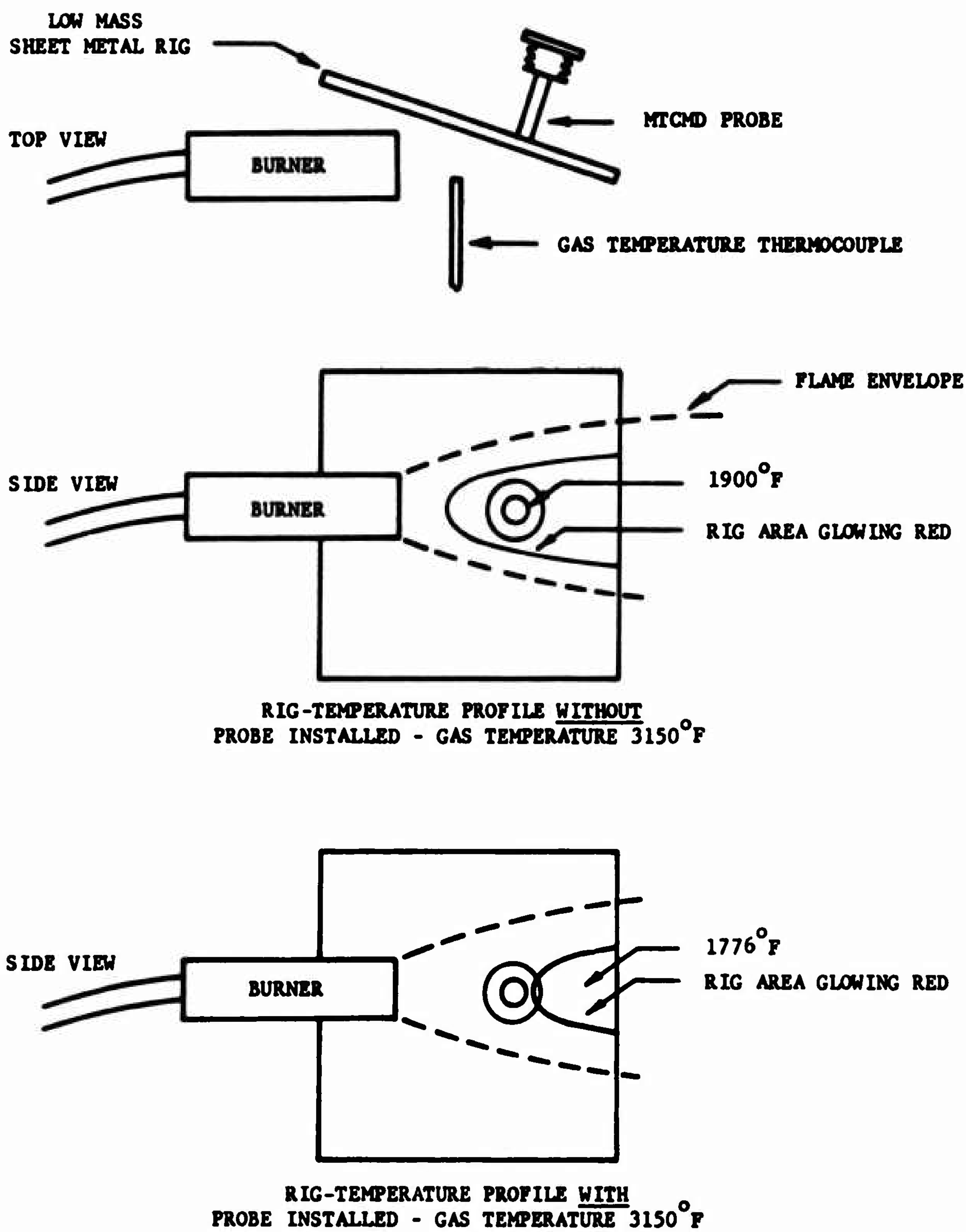


Figure 34. Second Hot Calibration Rig-Temperature Profile.

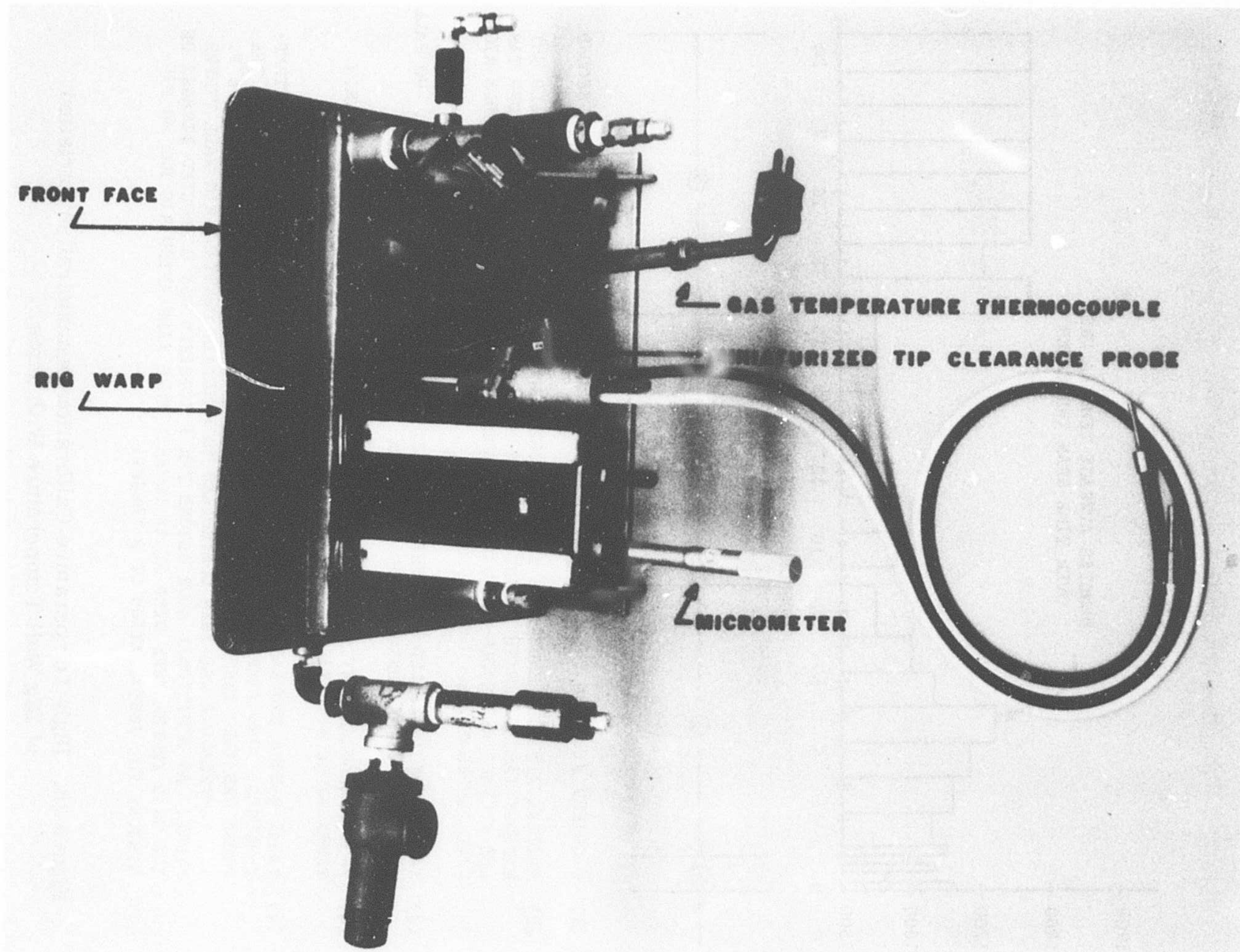
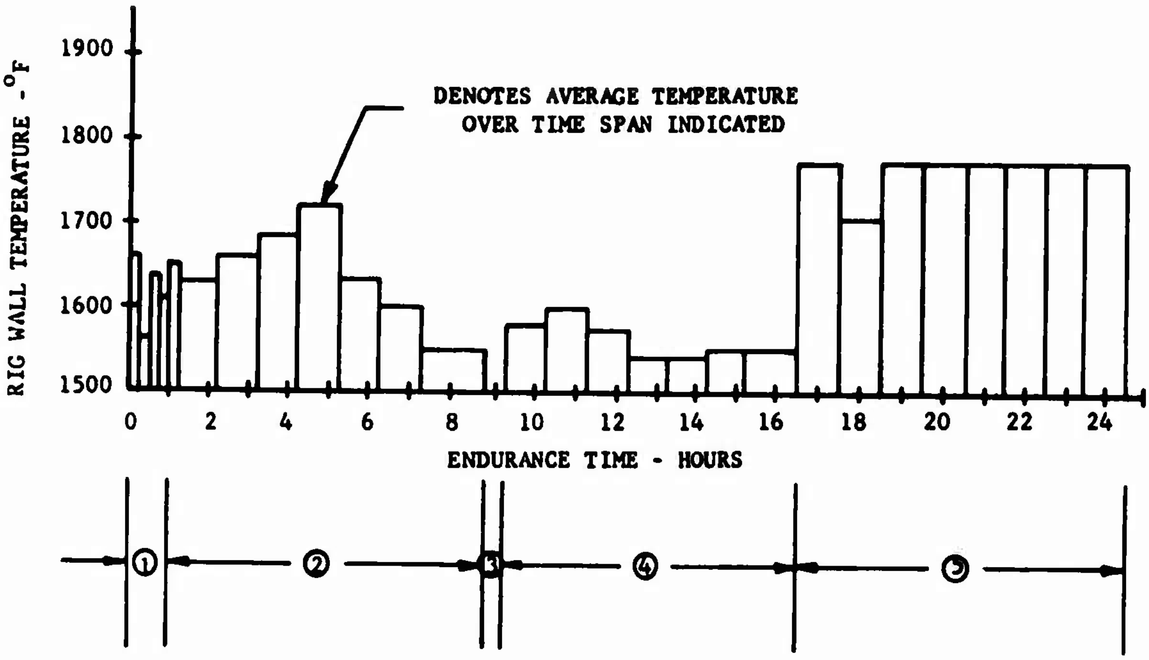


Figure 35. Miniaturized Tip Clearance Measurement Probe Installed in First Hot Calibration Rig.



(1) REQUIRED NITROGEN PURGE FLOW RATE ESTABLISHED AT 0.0033 POUND PER SECOND.

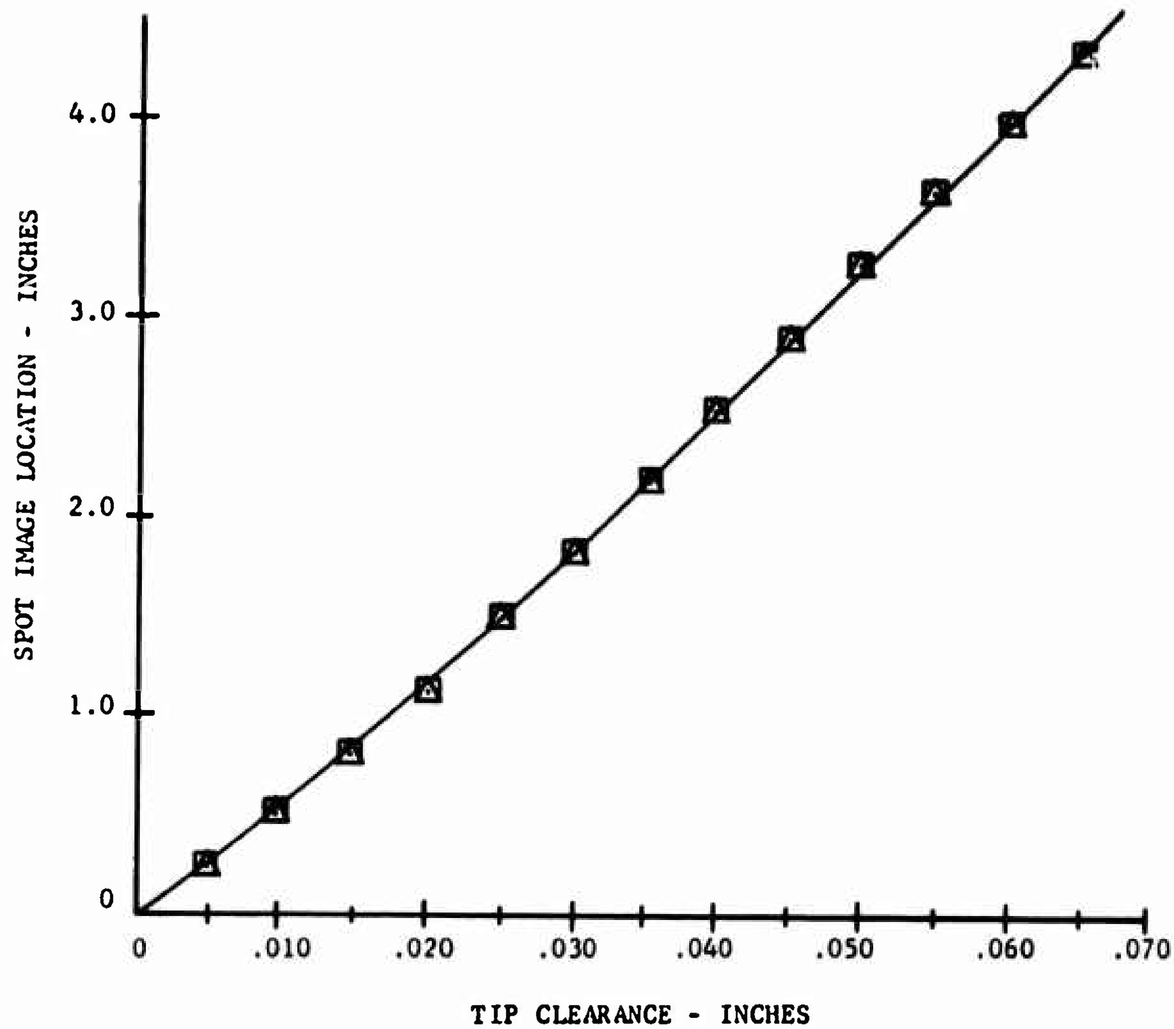
(2) INITIAL 7.5-HOUR ENDURANCE TEST PERFORMED WITH PROBE OPTICS INSTALLED BUT WITHOUT TARGET. WITH TARGET IN PLACE NITROGEN PURGE IS REFLECTED OFF TARGET SURFACE AND COOLS RIG WALLS. TARGET WAS REMOVED TO OBTAIN HIGHER RIG WALL TEMPERATURES.

(3) TARGET WAS INSTALLED AND SYSTEM ALIGNED. OPTICS WERE NOT CLEANED. NO WALL TEMPERATURES MEASURED DURING THIS TIME.

(4) 7-HOUR ENDURANCE WITH TARGET INSTALLED. NOTE DROP IN AVERAGE RIG SKIN TEMPERATURE WITH TARGET INSTALLED.

(5) FINAL 8-HOUR ENDURANCE USING LOW MASS RIG TO OBTAIN HIGHER RIG WALL TEMPERATURES. GAS TEMPERATURE WAS INCREASED UNTIL RIG WALL WAS 1900°F. THE PROBE WAS THEN INSTALLED AND THE RIG WALL TEMPERATURE DROPPED TO 1776°F. GAS TEMPERATURE WAS THEN CONTROLLED TO MAINTAIN CONSTANT RIG WALL TEMPERATURE. AN ADDITIONAL HOUR BEYOND THE 7 REQUIRED WAS CONDUCTED BECAUSE OF THE SKIN TEMPERATURE DROP AT 18 HOURS. THIS SIMPLIFIED RIG HAD NO PROVISIONS FOR INSTALLATION OF A TARGET.

Figure 36. High-Temperature Calibration Demonstration Variation of Rig Wall Temperature With Time.



□ SPOT IMAGE LOCATION BEFORE HIGH-TEMPERATURE ENDURANCE TEST

△ SPOT IMAGE LOCATION AFTER HIGH-TEMPERATURE ENDURANCE TEST

Figure 37. High-Temperature Endurance Test Calibration Miniaturized Tip Clearance Measurement Device.

The probe vibration test fixture is shown in Figure 38. During tests the MTCMD monitored a fixed target located 0.035 in. from the probe tip. Figure 39 shows the test fixture located on the shaker. During the vibration test the reflected spot did not change in intensity or position. Inspection of the probe after the test program did not indicate any damage to the probe.

COST

The cost of the MTCMD probe optics, laser, fiber optic bundles, television camera, television monitor, and video recorder totals $5,388.11. Table 2 is a list of the systems parts and cost. This cost does not include probe fabrication and assembly since this may vary between users.

TABLE 2. MTCMD HARDWARE COST

Item		Cost ($)	Required
Laser	Hughes 3070 H/R	1950.00	1
Television Camera With Vidicon Tube	EDO 9100	1163.00	1
F2.3 75mm Lens	Schneider CM 100	133.00	1
Prism	Adolf Meller Co.	175.00	1
Lens	Adolf Meller Co.	98.00	1
Output Fiber Optic Bundle	American Optical Co.	500.00	1
Input Fiber Optic Bundle	Electro Fiber Optics	58.00	1
Interference Filter	Oriel Optics Corp.	145.00	1
Microscope Objective	Jodon Engineering Associates, Inc.	10.65	1
Television Monitor	Sony CVM 112	247.00	1
Video Recorder	Sony AV 3600	774.00	1
Microphone	Sony F-98	13.00	1
Bellows	Flexible Metal Hose Manufacturing Company	121.46	1

LIFE

During system evaluation the MTCMD operated for 24.5 hours at elevated temperatures. After testing, the system was inspected and no contamination of the optical components could be seen. It is believed that the MTCMD system could operate well beyond the 50-hour life established for the system. Experience with previously developed proximity probes indicates the life is on the order of 100 to 200 hours under operating conditions defined by the design criteria.

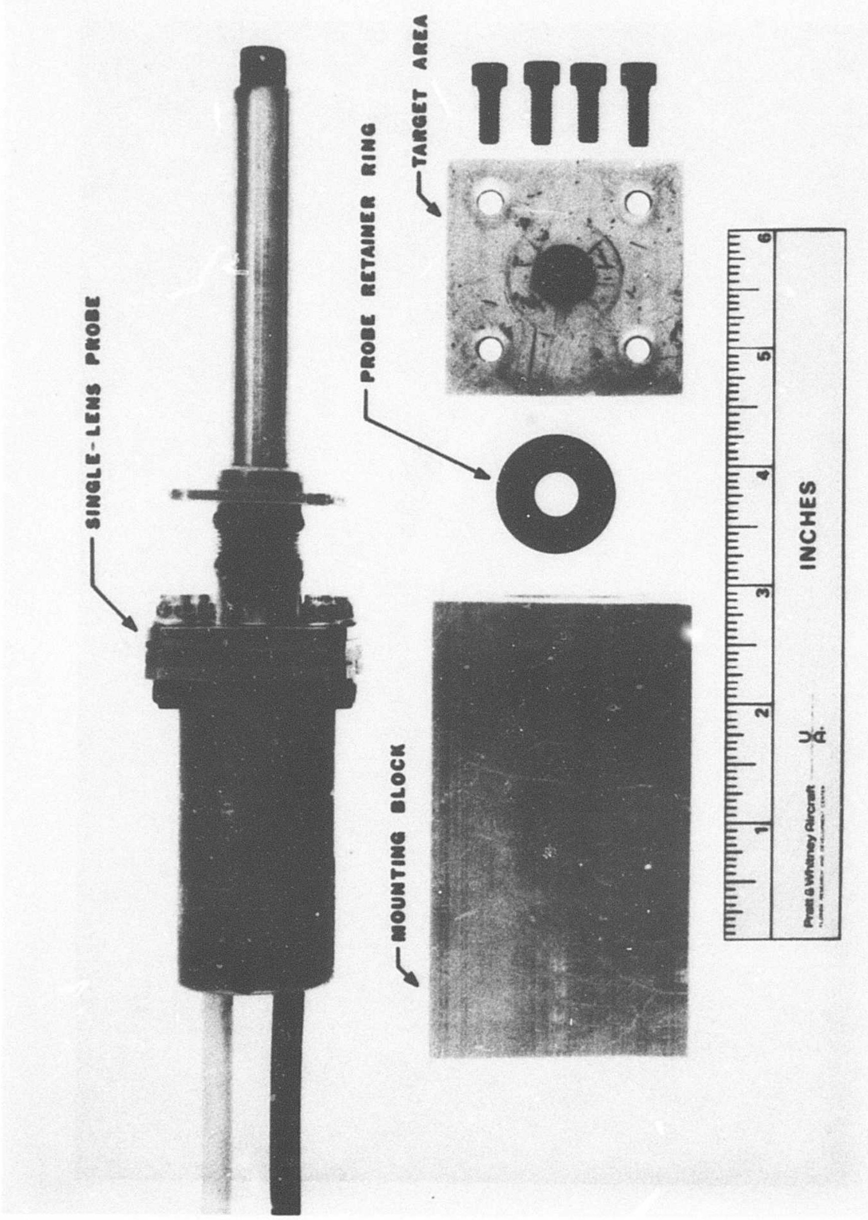


Figure 38. Vibration Test Fixture.

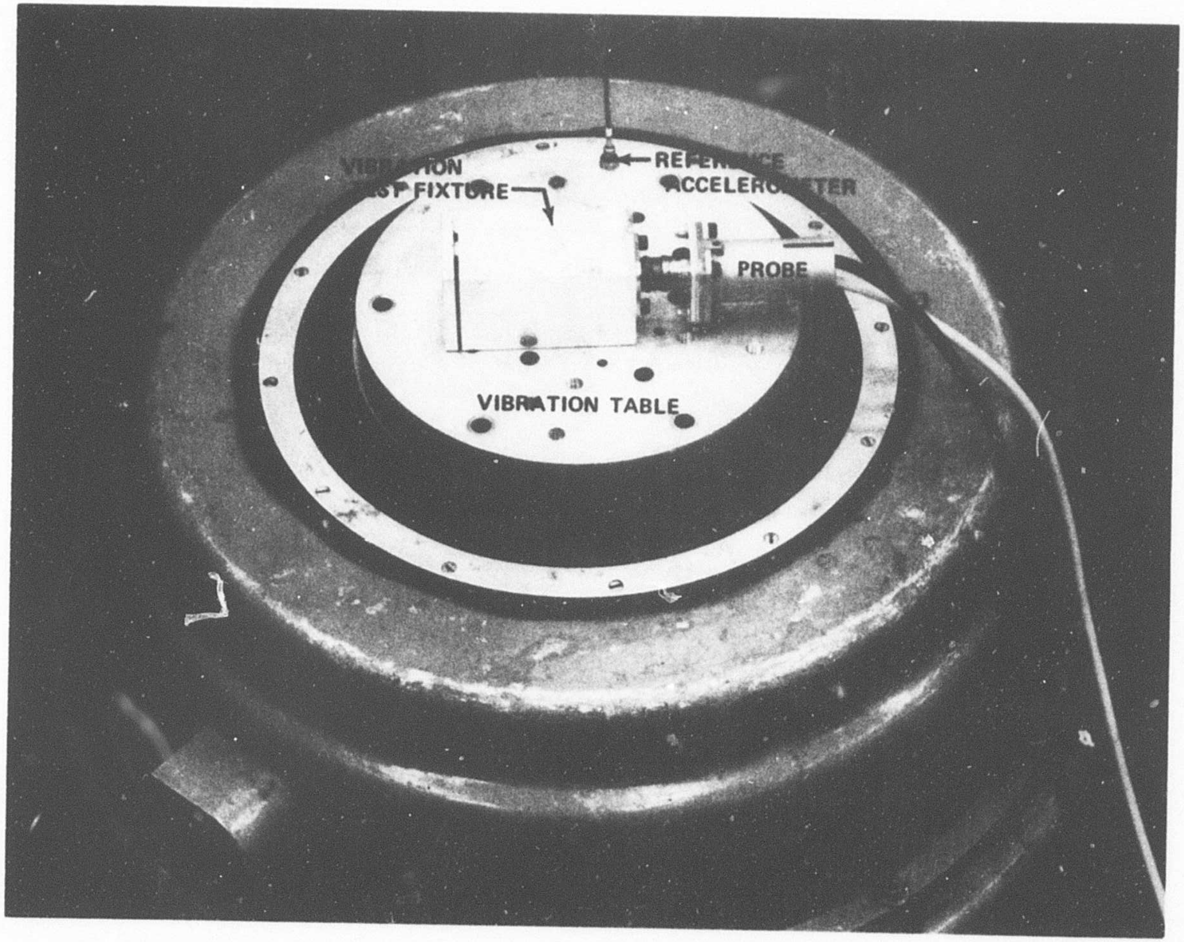


Figure 39. Vibration Test.

CONCLUSIONS

The following conclusions were reached as a result of the test program:

1. An optical turbine blade tip clearance measurement system has been miniaturized and successfully demonstrated for use on small engines in the 3 to 5 lb/sec airflow class.

2. The miniaturized optical turbine blade tip clearance measurement system meets all requirements for

   - range
   - accuracy
   - response rate
   - sensitivity

   necessary to provide correlation information between variations in turbine blade tip clearance and variations in steady-state engine performance.

3. System operational requirements for

   - electrical power
   - cooling flow
   - temperature environment
   - pressure environment
   - vibration environment
   - life

   have been defined and the system successfully tested for conformance to these requirements.

4. System component costs have been defined.

RECOMMENDATIONS

The following recommendations are offered:

1. Evaluate the optical turbine blade tip clearance measurement system on a small gas turbine engine and utilize as a diagnostic tool during tests.

2. Continue development of the optical turbine blade tip clearance measurement system to provide:

   - Faster response for analysis of clearance measurements during rapid transients

   - Recording compatibility with standard data recording systems for correlation of rapidly varying blade clearances with dynamic strain and vibration data

3. Modify probe envelope and optics as required for use with other small gas turbine engines whose physical configurations make use of the MTCMD probe impractical.

GLOSSARY

1. Aberration - Characteristics of a lens system that prevent a true image of an object from being formed. Various aberrations are:

   - Astigmatism - A lens aberration that gives the image of a point source of light an elliptical shape. The degree of astigmatism is proportional to the displacement of the point source of light from the lens axis.

   - Chromatic aberration - A lens aberration caused by the differences in index of refraction of a material at various light wavelengths. This aberration causes light of different wavelengths from a point source to be focused at different distances from the lens.

   - Coma - A lens aberration caused by variations in magnifying power of different annular lens sections.

   - Spherical aberration - A lens aberration caused by the spherical shape of the lens element. This aberration causes light passing through different annular sections of the lens to be focused at different distances from the lens.

2. Angle of Incidence - The angle formed between a light beam and an axis perpendicular to a lens element at the point of intersection of the beam and the element.

3. Coherent Fiber Optic Bundle - A light transmitting device made up of fine glass fibers. The fibers are arranged such that an image can be transmitted through the bundle to allow remote viewing of an object.

4. Index of Refraction - The property of an optical material that is determined from the ratio of the velocity of light in a vacuum to the velocity of light in the material.

5. Flare - The light scattered when a beam of light strikes a flaw in an optical lens or prism.

6. Prism Dispersion - A measure of the bending of a light beam when passed through a prism.

7. Schlieren Test - An optical test that can accurately determine the presence of flaws in an optical element. Light from a point source is passed through the element and projected onto a photographic plate behind the lens focal point. A pinhole is placed at the focal point of the lens. Flaws in the lens will be seen as dark areas on the photographic plate.

APPENDIX A
DETERMINATION OF MTCMD OPTICAL COMPONENT CONFIGURATION

Figure A-1 is a ray trace diagram for the MTCMD probe. The probe prism and lens geometries are established by the system range and probe envelope requirements.

PRISM

Design Criteria

The system probe range is determined by the prism geometry and input bundle incident angle. The constraints of the system are:

- The prism width, W, as determined by the probe envelope
- The probe range, R, as determined by the probe application.

The system variables are:

- The prism height, L
- The prism angle, A
- The input bundle incident angle, θ.

In addition to solving the system range requirements, the prism and input bundle incidence angle are selected such that:

- System astigmatism is reduced
- Internal reflections in the prism are reduced.

System Astigmatism

System astigmatism and range are directly proportional to the magnitude of the input fiber optic bundle incident angle, θ. This angle is minimized during system design to reduce astigmatism by designing the system for only the maximum required range.

Prism Noise

Prism noise is caused by secondary reflections in the prism. The reflected beam, E_R (Figure A-1), accounts for most of the prism noise. The prism is designed such that the beam, E_R, strikes the rough ground prism apex. The apex is then blackened to prevent this beam from exiting the prism.

Calculations

The probe geometry is solved by a successive approximation approach. The following relationships (Figure A-1) are established to ensure that the reflected beam, E_R, strikes the prism apex and that the probe range is established.

$$\tan I_2 = Y/L \quad (1)$$

$$\tan I_2' = Y/R \quad (2)$$

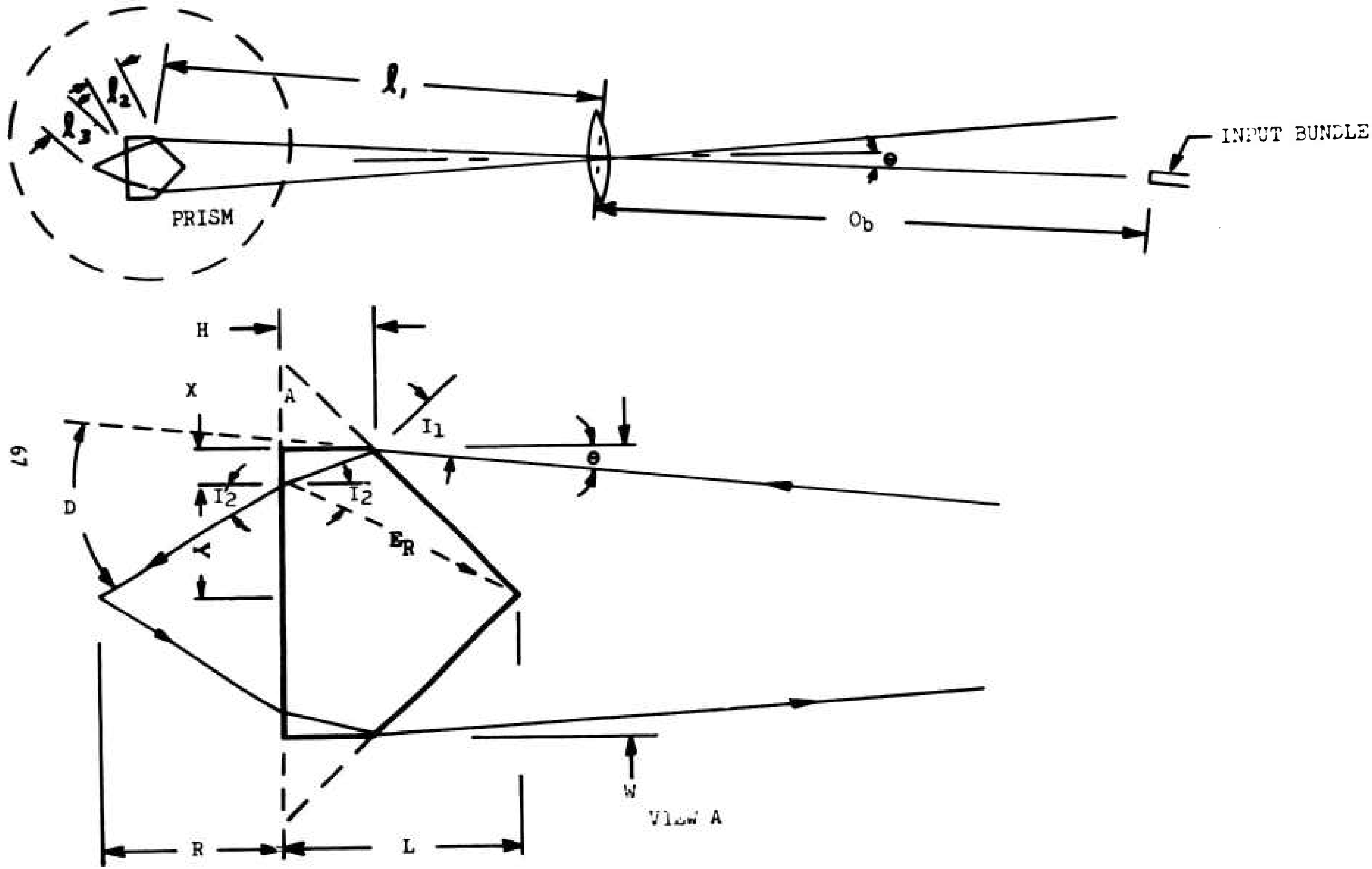


Figure A-1. Ray Trace Diagram For MTCMD Frobe.

thus

$$R \tan I_2' = L \tan I_2 \qquad (3)$$

from Figure 40

$$I_2' = D-\theta \qquad (4)$$

and

$$L = \frac{R \tan (D-\theta)}{\tan\{A-\text{arc } \sin[1/N_p \sin(A+\theta)]\}} \qquad (5)$$

where D is the prism dispersion angle given by

$$D = I_1 - A + \text{arc } \sin \left[(N_p - \sin^2 I_1)^{1/2} \sin A - \cos A \sin I_1\right] \qquad (6)$$

N_p is the index of refraction of the prism material.

To determine the prism height, L, from equation (5)

Set θ equal to 0

Assume a prism angle A of 45 deg

Substitute the established probe range, R, into equation (5) and calculate the prism height L.

The value of X (Figure 40) is determined from

$$X = (L - \frac{W}{2} \tan A) \tan I_2 = (L - \frac{W}{2} \tan A) \tan \left\{A - \text{arc } \sin[\frac{1}{N_p} \sin(A + \theta)]\right\} \qquad (7)$$

where I_2 is solved in terms of A, N_p and θ using Snell's law.

Substitute the values of L and θ into equation (1) and determine the value of Y.

Check to ensure the prism configuration solution will fit the probe envelope:

$$Y + X \leq \frac{W}{2} \qquad (8)$$

If equation (8) is not satisfied, assume a new value of θ and repeat the process until it is satisfied.

LENS

Design Criteria

The MTCMD lens is designed such that:

- The lens diameter is as large as possible to allow the maximum amount of light to pass
- The lens focuses the input light source at the blade tip nominal clearance.

Calculations

The lens is located in the MTCMD probe at the point where the input light beam incident at an angle, θ, crosses the probe axis. The lens focal length, f, is determined from the Gaussian form of the image equation

$$\frac{1}{f} = \frac{1}{\ell_m} + \frac{1}{O_b} \tag{9}$$

In the case of the MTCMD, O_b is the distance from the input bundle tip to the lens, and ℓ_m is the optical ray trace distance from the lens to the nominal tip clearance position.

$$\ell_m = \ell_1 + (N_p-1)\ell_2 + \ell_3 \tag{10}$$

where

ℓ_1 is the length of the input light path from the main lens center to the prism surface.

ℓ_2 is the length of the input light path in the prism.

ℓ_3 is the length of the input light path from the prism to the target surface.

N_p is the index of the refraction of the prism material.

APPENDIX B
SYSTEM ASSEMBLY

The assembled MTCMD system is shown in Figure B-1. The system television camera and laser have been mounted on an aluminum plate. Assembly of the system requires assembly and adjustment of the

- Laser focusing fixture
- Probe
- Camera interface fixture

LASER FOCUS FIXTURE

The laser focus fixture hardware is shown in Figure 9. The unit is assembled as shown in Figure 10. The input fiber optic bundle is adjusted in the fixture until the focused laser light passes through a single fiber of the fiber optic bundle. A bundle of several fibers is used because of easy commercial availability and the availability of spare fibers in case of breakage. To determine when a single fiber is transmitting light, a supplementary lens is used to image the end of the bundle away from the laser onto a flat surface. Several bright dots representing the fibers transmitting light will be seen. The system is adjusted until one bright dot is obtained. The bundle is then locked in place by use of the setscrew and lock bolts.

PROBE

Figure 7 shows the parts that make up the MTCMD probe. The parts are assembled as illustrated in Figure 8. To adjust the system, the probe tip is positioned at a distance one half of the design range from a black target. The target is black to more nearly simulate the reflectivity of a turbine blade.

The input fiber optic bundle is adjusted in the probe head until the light spot on the target is in focus. The bundle is then locked into place by a setscrew located in the probe head. The fiber optic output bundle is adjusted in the probe head until the reflected spot is in focus when viewed through the other end of the fiber optic bundle. The bundle is then locked in place by the setscrew in the probe head. The probe head is then removed from the probe body, the fiber optic bundles passed through the fiber optic bundle strain relief bracket, and the system reassembled as in Figure 6.

Camera Interface Fixture

The camera interface fixture hardware is illustrated in Figure 11. The fixture is assembled as shown in Figure 12. The MTCMD probe is set to view a target at a distance one half of the design range. The television camera is connected to the television monitor and the output bundle adjusted until a sharp spot is obtained on the monitor. The bundle is locked in place by the retaining collar.

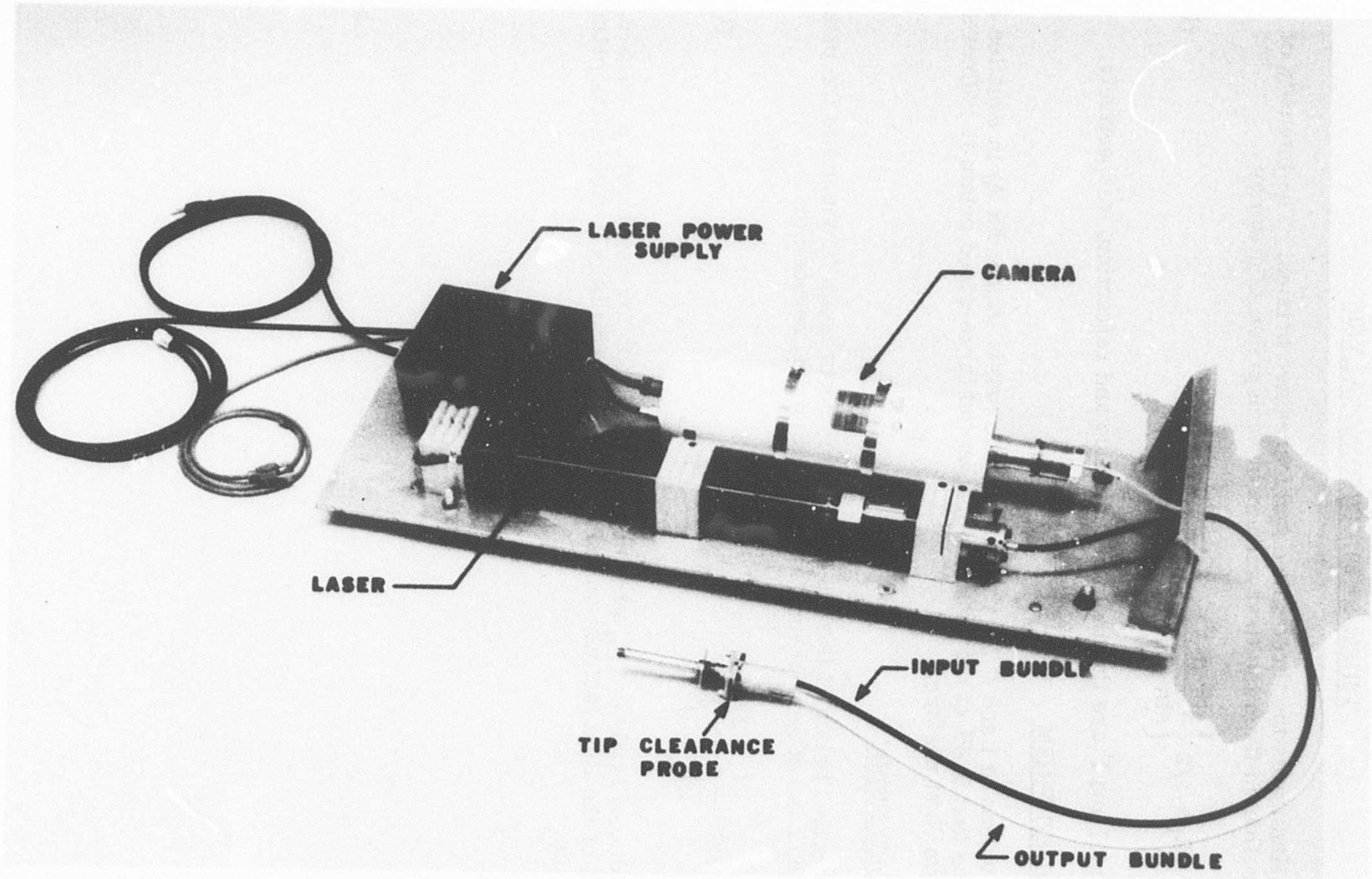


Figure B-1. Miniaturized Tip Clearance Measurement System.

APPENDIX C
PRISM REFLECTION ANALYSIS

Figure 14 illustrates the three-sided and four-sided prisms. The intensity of the beam reflected from the first surface of each prism is given by

$$R_f = 1/2 \left\{ \frac{\sin^2(I-I')}{\sin^2(I+I')} + \frac{\tan^2(I-I')}{\tan^2(I+I')} \right\} \tag{11}$$

where I and I' are the angle of incidence and refraction, respectively.

THREE-SIDED PRISM

Using the values of I and I' for the three-sided prism (Appendix A) in equation (11), it was found that 9.4% of the light incident on the three-sided prism is reflected at the prism first surface.

FOUR-SIDED PRISM

In the four-sided prism, I is zero since the incident beam is normal to the prism face. In the case of normal incidence, equation (11) reduces to

$$R = \frac{(N_p - 1)^2}{(N_p + 1)^2} \tag{12}$$

Using a value of 1.765 for N_p (the index of refraction for sapphire), R = 0.076. Thus 7.6% of the light incident on the four-sided prism is reflected at the prism first surface.

APPENDIX D
DETERMINATION OF THE THREE-LENS SYSTEM OPTICAL COMPONENT CONFIGURATION

Figure D-1 is a ray trace diagram of the three-lens probe. The prism configuration is the same as for the single-lens probe in Appendix A. The system lens diameters are as large as the probe envelope will allow. The lens focal lengths are determined as follows.

MAIN LENS

The light received by the main lens is collimated by the input lens. For the main lens to focus the beam of the average expected clearance distance,

$$f_m = \ell_1 + (N_p - 1)\,\ell_2 + \ell_3 \qquad (13)$$

where

f_m is the focal length of the main lens.

ℓ_1 is the length of the input light path from the main lens center to the prism surface.

ℓ_2 is the length of the input light path in the prism.

ℓ_3 is the length of the input light path from the prism to the target surface.

N_p is the index of refraction of the prism material.

Input Lens

The input lens focal length, f_i, is made as short as practical. The minimum focal length is generally limited to the lens diameter for reduced cost and ease of fabrication. The input fiber optic bundle is then placed at the lens focal point. The light passing through the lens from the input bundle will be approximately collimated. The beam is not perfectly collimated due to the finite size of the input fiber. The distance from the input lens to the main lens is not critical.

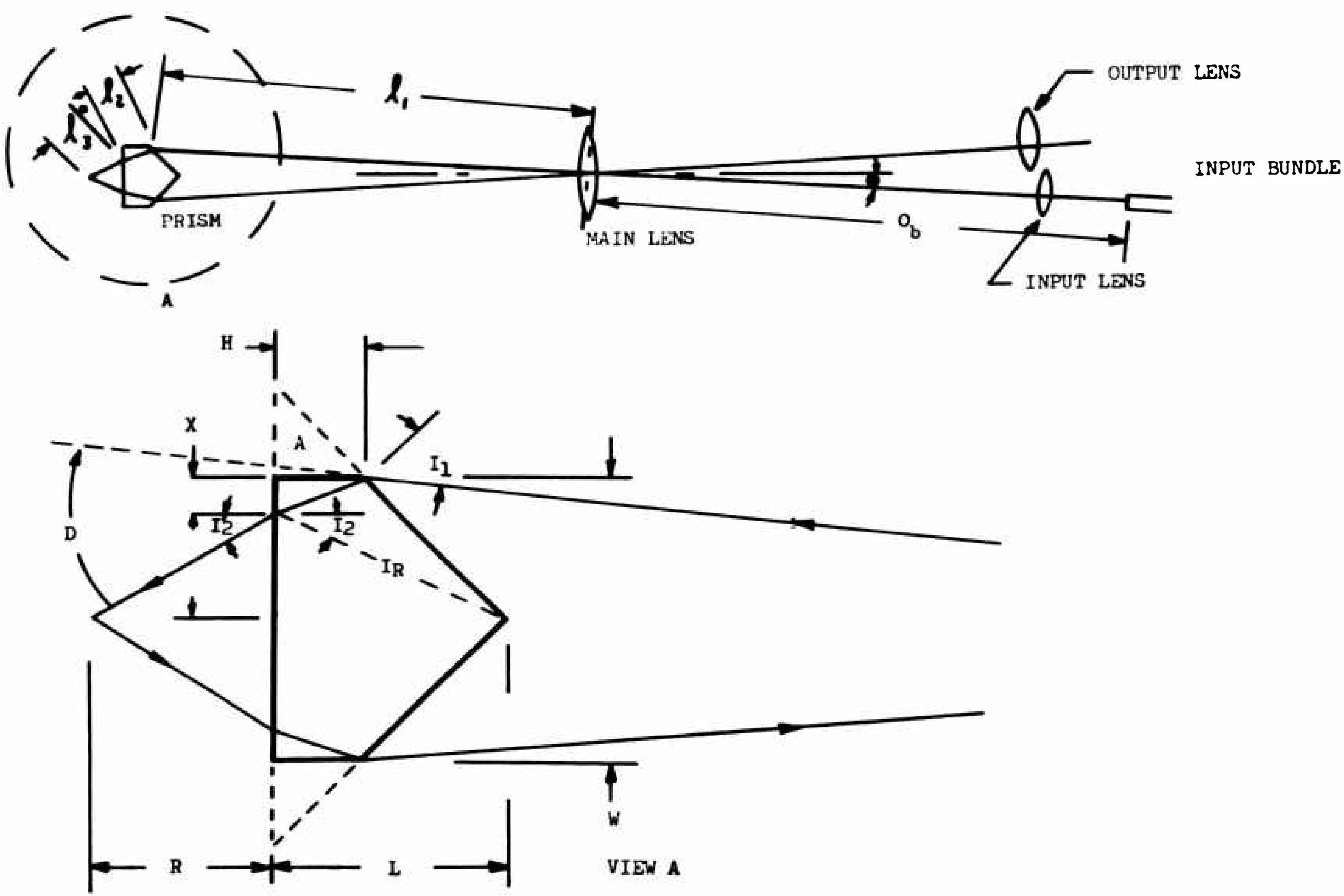


Figure D-1. Ray Trace Diagram For Three-Lens Probe.

Output Lens

The output lens focal length is designed such that the travel of the reflected spot covers the entire output coherent fiber optic bundle end. The focal length is given by

$$f_o = f_m \left(\frac{D}{R}\right) \tag{14}$$

where

f_o is the focal length of the output lens.
f_m is the focal length of the main lens.
D is the diameter of the coherent output bundle.
R is the design range of the probe.

APPENDIX E
OPTICAL EFFICIENCY

The comparison of the optical efficiency of the single-lens probe and the three-lens probe is based on the percent of input light energy transmitted by the input lens of the three-lens probe and the main lens of the single-lens probe.

The intensity of the energy exiting the fiber optic input bundle is given by

$$E_{(r)} = E_o (e)^{\frac{-2r^2}{w^2}} \qquad (15)$$

where

$E_{(r)}$ is the beam intensity at distance, r, from the beam axis.

E_o is the beam intensity on the beam axis.

r is the radial distance from the center of the beam.

w is the radial distance at which the intensity falls to E_o/e^2 for a fiber optic bundle with a 30-deg acceptance angle.

$$w = (\tan 30 \text{ deg})(L) = (0.577)(L) \qquad (16)$$

where

L is the distance from the fiber optic input bundle to the lens surface.

For a lens of diameter "a" the energy passing through the lens is

$$P_{(a)} = 1/2 \quad E_o w^2 \left[1 - (e)^{\frac{-2a^2}{w^2}} \right] \qquad (17)$$

Using the lens diameters and values for L in the single-lens probe and three-lens probe:

- 25% of the available laser input energy will pass through the main lens of the MTCMD.
- 50% of the available laser input energy will pass through the input lens of the three-lens system.

APPENDIX F
LIST OF DRAWINGS GENERATED UNDER CONTRACT DAA J02-73-C-0084

AX 64308	Laser Mount Front for 10MV-3070H
AX 64309	Laser Mount Rear for 10MV-3070H
AX 66905	System Components Identification
BX 66236	Probe Tip
BX 66237	Subassembly - Probe Housing and Tip
BX 66238	Probe - 4-Sided Prism Revised
BX 66239	Probe - 3-Sided Prism
BX 66240	Lens - For Single-Lens System
BX 66241	Main Lens - 3-Lens System
BX 66242	Input Lens - 3-Lens System
BX 66244	Probe - Input Fiber Optic
BX 66245	Probe - Output Fiber Optic
BX 66246	Probe - Single-Lens Head
BX 66248	Probe - Lens Retainer Ring and Input Fiber Optic Retainer
BX 66249	Probe - Field Stop
BX 66250	Probe - Lens Retainer
BX 66251	Probe - Prism Holder
BX 66884	Probe - Bellows
BX 66885	Probe - Flange
BX 66886	Probe - Filter Holder
BX 66887	Probe - Output Bundle Clamp
BX 66888	Probe - Input Bundle Retaining Collar
BX 66889	Probe - Lens Spacer
BX 66890	Probe - Microscope Objective Holder
BX 66893	Probe - Adapter Camera Lens
BX 66894	Probe - Support Fiber Optics
BX 66898	Assembly - Output Optics
CX 66235	Probe - Housing
CX 66247	Probe - 3-Lens System Head
CX 66895	Probe - Bundle Retainer
CX 66897	Probe - Camera Mount
CX 66900	Assembly - Input Optics
DX 66252	Miniaturized Tip Clearance Measuring Device