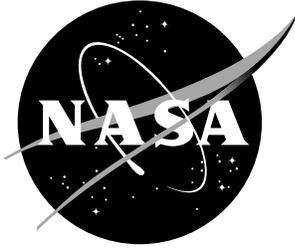


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# A Fiber-Optic Probe Design for Combustion Chamber Flame Detection Applications

*Design Criteria, Performance Specifications, and  
Fabrication Technique*

*Stephen E. Borg and Samuel E. Harper  
Langley Research Center, Hampton, Virginia*

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October 2001

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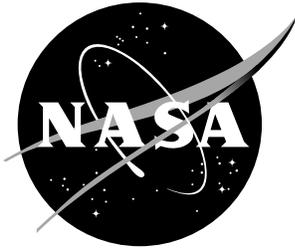
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## ABSTRACT

This paper documents the design and development of the fiber-optic probes utilized in the flame detection systems used in NASA Langley Research Center's 8-Foot High Temperature Tunnel (8-ft HTT). Two independent flame detection systems are utilized to monitor the presence and stability of the main-burner and pilot-level flames during facility operation. Due to the harsh environment within the combustor, the successful development of a rugged and efficient fiber-optic probe was a critical milestone in the development of these flame detection systems. The final optical probe design for the two flame detection systems resulted from research that was conducted in Langley's 7-in High Temperature Pilot Tunnel (7-in HTT). A detailed description of the manufacturing process behind the optical probes used in the 8-ft HTT is provided in Appendix A of this report.

## DEFINITIONS

8-ft HTT	NASA Langley's 8-Foot High Temperature Tunnel (B1265)
7-in HTT	NASA Langley's 7-inch High Temperature Pilot Tunnel (B1264)
OFD	Optical Flameout Detector
OPFD	Optical Pilot Flame Detector
LOX	Liquid Oxygen
PMT	Photomultiplier Tube Detector
SPD	Silicon Photodiode Detector
ZBLAN	Long-wave transmitting fluoride glass fiber doped with Zirconium (Zr), Barium (Ba), Lanthanum (La), Aluminum (Al) and Sodium (Na)

## INTRODUCTION

Optical based flame detection systems were developed as an alternative method for monitoring the presence and stability of the pilot and main-burner flame in the combustor of the NASA Langley Research Center's 8-Foot High Temperature Tunnel (8-ft HTT). This large-scale test facility utilizes air/methane combustion to simulate flight enthalpy conditions from 50,000 to 120,000 ft in altitude at Mach numbers 4, 5, and 7. This research facility also has the capability to serve as a test chamber for large hypersonic air-breathing propulsion systems. When operating in this mode, atmospheric oxygen that would normally be consumed during conventional air/methane combustion is replenished by the injection of liquid oxygen (LOX) directly into the combustor. This insures that the molar oxygen content of the test section medium is maintained at 21%. (1)

Safety concerns, along with reliability issues of previous flame detection systems, prompted the development of these optical-based flame detectors. In the case of the Optical Flameout Detector (OFD), it was determined that when utilizing LOX enrichment, the existing

thermocouple-based flame detection system would not be able to respond adequately in the event of an unplanned combustor flameout and re-ignition. (2)(3) Success with the performance of the OFD, and the unreliability of another thermocouple-based flame detector used in monitoring the low-level pilot flame, led to the development of the Optical Pilot Flame Detector (OPFD).

## OPTICAL MEASUREMENTS IN THE 7-INCH HTT

The 7-in HTT is a 1/12-scale version of the larger 8-ft HTT, and is used primarily as an engineering concept test bed. The combustion chamber in the 7-in HTT contains an oxidizing atmosphere of high-pressure air and methane along with combustion byproducts, primarily CO<sub>2</sub>, H<sub>2</sub>O, CO, and carbon. Peak combustion chamber pressures can reach about 2000-psi, and gas temperatures reach about 3100°F.

To obtain coherent radiometric data of the combustion process over a wide spectral range, several fiber-optic probes were used to monitor the flame activity. The probes gained optical access into the combustion chamber from the

rear to avoid direct contact with the main flame, and routed along the length of the fuel spray bar. Each of the optical probes were coupled to independent optical detectors located outside the chamber. The detectors were selected to monitor specific wavelength ranges, and their relative responses could be analyzed during combustor operation. Ultraviolet (UV), visible and infrared (IR) light measurements were made using photomultiplier tube (PMT), silicon photodiode (SPD), and lead selenide (PbSe) detectors, respectively. (3)

### **7-in HTT FIBER-OPTIC PROBE CONSIDERATIONS**

In order to characterize the relative responses of the individual detectors during combustor operation, it was necessary to design and fabricate an optical probe assembly to safely penetrate the pressure vessel. The probe assembly that was developed consisted of three individual fiber-optic probes – each having been optimized for the wavelength range of their specific detector. This probe assembly allowed the probes to safely penetrate the combustor pressure shell through a single 1/4-in diameter opening, and view the combustion process.

Each fiber-optic probe utilized a single, large core optical fiber. This offered several distinct advantages over a probe built from a multi-fiber bundle. First, due to the lack of interstitial void areas in a single fiber probe, transmission efficiency is increased since a larger percentage of incident light can be captured and transmitted by the core instead of being lost in the regions between adjacent fibers. Also, it would be easier to maintain a pressure seal in a single-fiber probe, once again, due to the lack of inter-fiber void areas.

The probes fabricated for the PMT (UV) and SPD (visible) detectors each contained a single 120-inch long, optical fiber. This fiber had an 800- $\mu\text{m}$  diameter fused-silica core, an 880- $\mu\text{m}$  diameter doped fused-silica cladding, and a 910- $\mu\text{m}$  diameter polyimide jacket for high temperature durability. The polyimide jacket extends the optical fiber's maximum sustained working temperature up to approximately 600°F.

To detect the hydroxyl emission peak at 312-nm from the oxidizing methane, a grade of fused silica optical fiber was selected which was optimized for transmission in the 220-nm to 700-nm range. The SPD optical probe utilized a low OH content grade of optical fiber with a broad transmission range in the visible/near IR region of the spectrum, typically from 400-nm to 2400-nm.

For transmitting the longer wavelength infrared energy, an aluminum fluoride glass fiber was used in conjunction with the PbSe optical detector. Aluminum fluoride glasses are part of the family of heavy-metal doped fluoride glasses. They have an amorphous structure similar to conventional glasses, but contain various fluoride compounds (e.g.,  $\text{AlF}_3$ , ZBLAN, etc.) rather than oxide compounds (e.g., silica), making them suitable for long wavelength transmission. This fiber has the ability to transmit out to approximately 4000-nm and had an 800- $\mu\text{m}$  diameter core, an 880- $\mu\text{m}$  diameter cladding, and a 910- $\mu\text{m}$  diameter polyimide jacket. (4)

For protection from the combustor environment, each fiber was inserted into a 1/16-inch diameter, thin-wall (0.006-inch), type-304 stainless-steel tube, and then potted in with a high temperature silicone RTV. This anchored the fiber optic to the stainless-steel sheath while providing a reliable pressure seal along the full length of the probe. The three fiber-optic probes were then brazed into a stainless-steel ferrule, then inserted and brazed into a larger 1/4-inch stainless-steel tube. Under hydrostatic pressure testing, the integrity of this probe assembly was not compromised despite being subjected to pressures of over 26,000-psi. (Figure 1)

### **FLAME DETECTION IN THE 8-ft HIGH TEMPERATURE TUNNEL**

Results from the 7-in HTT tests indicated that the PMT detector would be the most advantageous choice for the basis of the flame detection systems in the larger 8-ft HTT combustor. This 800-megawatt facility, when operating in air/methane mode, has a maximum

combustor pressure of about 4000-psi. Gas temperatures within the combustor can vary from about -100°F behind the methane spray-bar during LOX enrichment to over 3000°F. (Figure 2)

The 8-ft HTT's main-burner flame is generated from a progressive sequence of higher-intensity flames. The first step in the process utilizes a hot-wire igniter to establish a low-intensity pilot-flame. Once the pilot-flame is detected and stable, the facility process control ignites a larger boost-flame from the existing pilot. The boost-flame is directed across the face of the methane spray-bar and serves as the ignition source for the main-burner flame. The main-flame provides the energy required for sustained hypersonic flow in the test section and consumes from 13 to 17-lbs/sec of methane fuel during operation.

The flame detection systems are each positioned to monitor the presence of specific flames (i.e., pilot, and main-burner) during the light-off sequence. The OPFD is aimed to detect the presence of the low-level pilot, and the OFD monitors the stability of the main-burner flame. The individual OPFD and OFD optical probes are routed along the length of the fuel spray-bar and transmit light energy to their respective optical detectors located outside the combustor.

### **8-ft HIGH TEMPERATURE TUNNEL FIBER-OPTIC PROBE CONSIDERATIONS**

Both the OFD and the OPFD systems are designed to monitor light emission in the UV-visible portion of the spectrum from combustion, and use optical probes of the same design. Optical access into the 8-ft HTT combustor is limited to a 1/16-in diameter pressure fitting at the rear of the combustor. Since the probes for both systems are integrated onto the methane spray-bar piping, it's important that they have a small cross-sectional area to minimize any gas flow disturbances.

The 8-ft HTT optical probes have several differences compared to the previously developed set. Due to the larger scale of this facility, these optical probes are constructed in

25-ft lengths. These probes also use a 0.065-in diameter, type-304 stainless-steel sheath; however, it must be rugged enough to resist deformation when a pressure seal is made around it exiting the combustor. To insure this, the wall thickness of the sheathing was increased from 0.006-in to 0.010-in.

The optical fiber selected for these probes is drawn from a high OH ion content glass for improved transmission in the 220-nm to 700-nm range. (Figure 3) It contains a 400- $\mu$ m diameter fused-silica core, a 1.2 cladding/core ratio and a polyimide jacket which gives it a 600°F maximum temperature rating. To compensate for the increased wall thickness of the sheathing, the maximum OD of the optical fiber was reduced from 910- $\mu$ m to 520- $\mu$ m.

In order to give the probe a 4000-psi pressure rating, the fiber is potted into the stainless-steel sheathing for the first 12-inches of length with an optically clear, high-temperature epoxy. The remainder of the probe is then filled with a transparent, optical grade RTV. This combination of epoxy and RTV form a pressure-tight, and supportive matrix around the fiber. In the event of a fiber fracture within the sheathing, light can still be transmitted through the optical grade RTV to the optical detector. (Figure 4)

Protecting the probes from the intense thermal radiation of the flame is critical. Fortunately, the time the probes are actually subjected to the flame's radiation is limited since this facility has a continuous run time of only about 60-seconds on test condition. (1) To minimize radiation heat transfer into the probe, the stainless-steel sheathing should have a low-emittance finish (i.e., polished) to reflect as much incident infrared energy as possible. The probes should also be in direct contact along their entire length with more massive, cooled structures in the combustor such as methane supply pipes, LOX lines, etc. This will help the probes maintain a relatively constant temperature by allowing them to conduct thermal energy into these heat sinks. (Figure 5) (Figure 6)

## CONCLUSIONS

The probes developed for the OFD and OPFD have proven to be reliable elements of these optical flame detection systems. The OFD has been in service in the 8-ft HTT since 1993 and is considered a critical interlock required for tunnel operation by the facility's process control system. The success of the OFD led to the development of the OPFD in 2000. The OPFD is scheduled to replace a less reliable thermocouple based flame detector after an in-situ evaluation. The optical probes described here have shown excellent durability and reliability during their service life. An explicit procedure detailing the fabrication of the optical probes, along with an itemized materials list, is given in Appendix A.

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## APPENDIX A CONSTRUCTION AND PREPARATION OF THE OPTICAL PROBES

### MATERIALS & EQUIPMENT

- Stainless-Steel Tubing:  
Type: \_\_\_\_\_ 304 (LOX compatible)  
Outside Diameter: \_\_\_\_\_ 0.065-inch  
Wall Thickness: \_\_\_\_\_ 0.010-inch  
Length: \_\_\_\_\_ 25-ft per probe
- Optical Fiber:  
Core Diameter: \_\_\_\_\_ 400- $\mu\text{m}$  - fused silica (high OH content)  
Cladding Diameter: \_\_\_\_\_ 480- $\mu\text{m}$  - fused silica  
Jacket Diameter: \_\_\_\_\_ 520- $\mu\text{m}$  - polyimide  
Numerical Aperture: \_\_\_\_\_ 0.22 $\pm$ 0.02  
Source/PN: \_\_\_\_\_ Fiberguide Industries PN SFS400/480T
- RTV Primer: \_\_\_\_\_ Silicone Rubber Primer - General Electric Silicones PN GE-SS41 20
- RTV Silicone Sealant: \_\_\_\_\_ General Electric Optical Grade RTV #655 (Parts A and B)
- Adhesive: \_\_\_\_\_ Hobby-Poxy 2@ slow-setting epoxy glue or similar
- Cleaner: \_\_\_\_\_ Dehydrated Alcohol (200 proof)
- Sand: \_\_\_\_\_ Aluminum Oxide - #120 grit
- Pressure-operated caulking gun
- 1/16-inch Swagelok type fitting
- Sandblast canister
- Vacuum pump
- Polyethylene syringe
- 0.040-inch diameter drill bit

### ASSEMBLY PROCEDURE

Cut a twenty-five (25) foot length of stainless-steel tubing and sandblast the inside with #120 grit aluminum oxide sand. Designate one end of the tubing to be the “combustor end” and the other side to be the “detector end”.

Drill one 0.040-inch diameter hole about twelve (12) inches from the “combustor end” of the tubing. Drill a second 0.040-inch hole about fourteen (14) inches from the “combustor end”. De-burr both holes inside and out.

Cut a twenty-five-foot, three-inch (25-ft 3-in) length of optical fiber and insert it into the tubing to check for ease of insertion. Repeat step 1 if insertion of the optical fiber is difficult.

Remove the fiber-optic. Clean the inside of the tube and the fiber-optic with solvent and let dry.

Place the 1/16-inch Swagelok-type fitting on the “detector end” of the tubing one (1) inch from the tip.

Lightly coat the inside of the stainless-steel tubing and the optical-fiber strand for their entire length with RTV silicone primer. Allow the primer to dry for a minimum of thirty (30) minutes.

Insert the optical fiber into the stainless steel tubing so it protrudes about one-and-a-half (1 1/2) inches on each end.

Load the pressure-operated caulking gun with RTV silicone sealant and connect it to the 1/16-inch Swagelok-type fitting.

Attach a vacuum pump to the “combustor end” of the optical probe with a length of vacuum tubing and seal the 0.040-inch diameter holes with masking tape or equivalent.

Start the vacuum pump and apply suction to the “combustor end” of the optical probe. Wait momentarily for a vacuum to form in the probe, and then begin injection of the RTV sealant into the detector end.

Continue pumping RTV sealant into the detector end of the optical probe until it appears at the 0.040-inch diameter hole fourteen (14) inches from the combustor end. Stop the pumping process at this point and allow the silicone sealant to cure for a minimum of twelve (12) hours.

Disconnect the vacuum pump, caulking gun, and the 1/16-inch Swagelok fitting, from the stainless-steel tubing.

Fill the polyethylene syringe with the epoxy adhesive and attach the polyethylene syringe to the combustor end of the stainless-steel tubing.

Pump the remaining length of the stainless-steel tubing full with epoxy adhesive until it purges from the 0.040-inch hole located twelve (12) inches from the “combustor end” of the optical probe.

Disconnect the polyethylene syringe and seal both 0.040-inch holes with several drops of epoxy adhesive. Let the optical probe cure for twelve (12) hours.

After the probe has cured, cleave the protruding one-and-a-half (1 1/2) inches of optical fiber at both ends as follows:

Place the optical probe on a flat surface and support the protruding fiber.

Score the surface of the fiber about one-half (1/2) inch from the sheath with a razor blade.

With even pressure, gently snap the optical fiber at the point the nick was scribed. (Note that it might be necessary to iterate this process until a flush, clean surface is finally obtained.)

The optical probe is now tested for physical integrity with an eight thousand (8000) psi hydrostatic pressure test. Test the optical probe to make sure that it passes light by shining a source in one end and observing the intensity at the other.

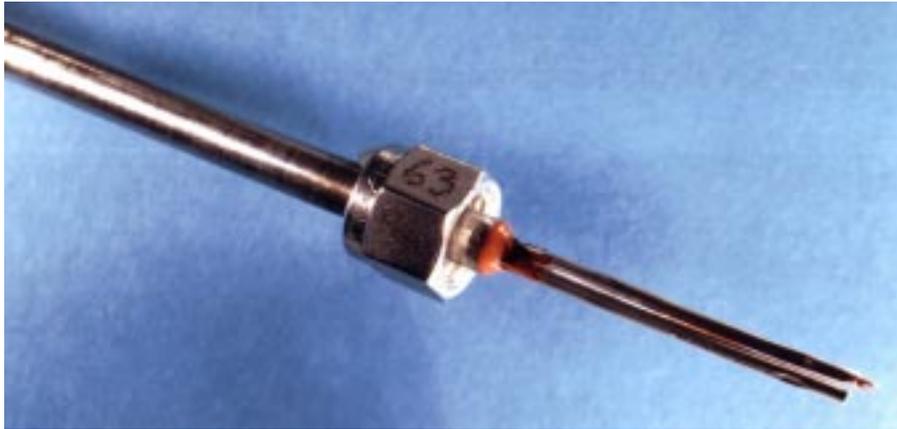


Figure 1. Optical probe concept for the 7-in High Temperature Pilot Tunnel

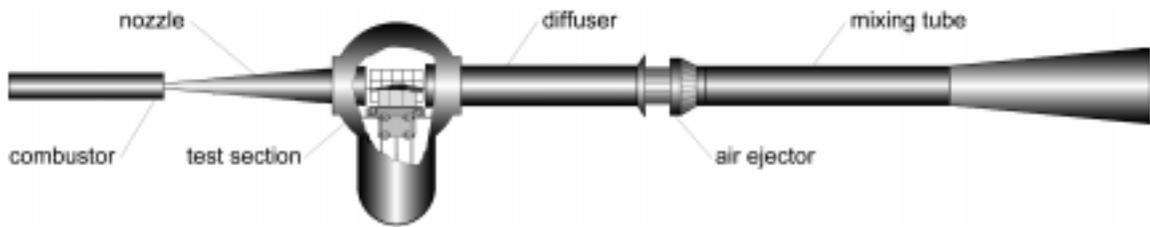


Figure 2. Schematic of the NASA Langley 8-ft High Temperature Tunnel

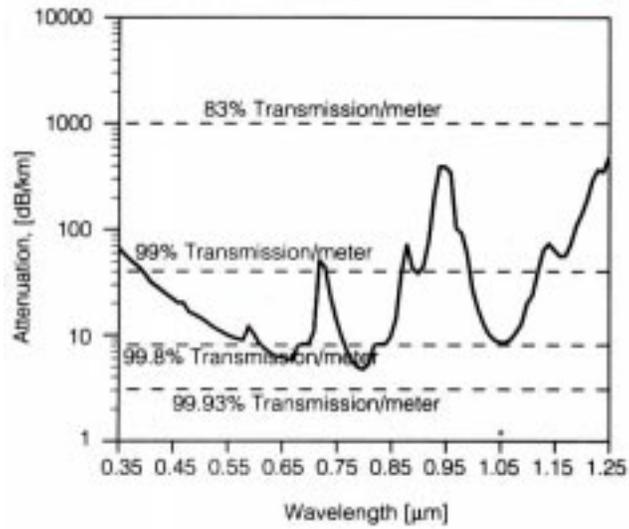


Figure 3. Typical optical fiber spectral transmission data (Courtesy of Fiberguide Industries)

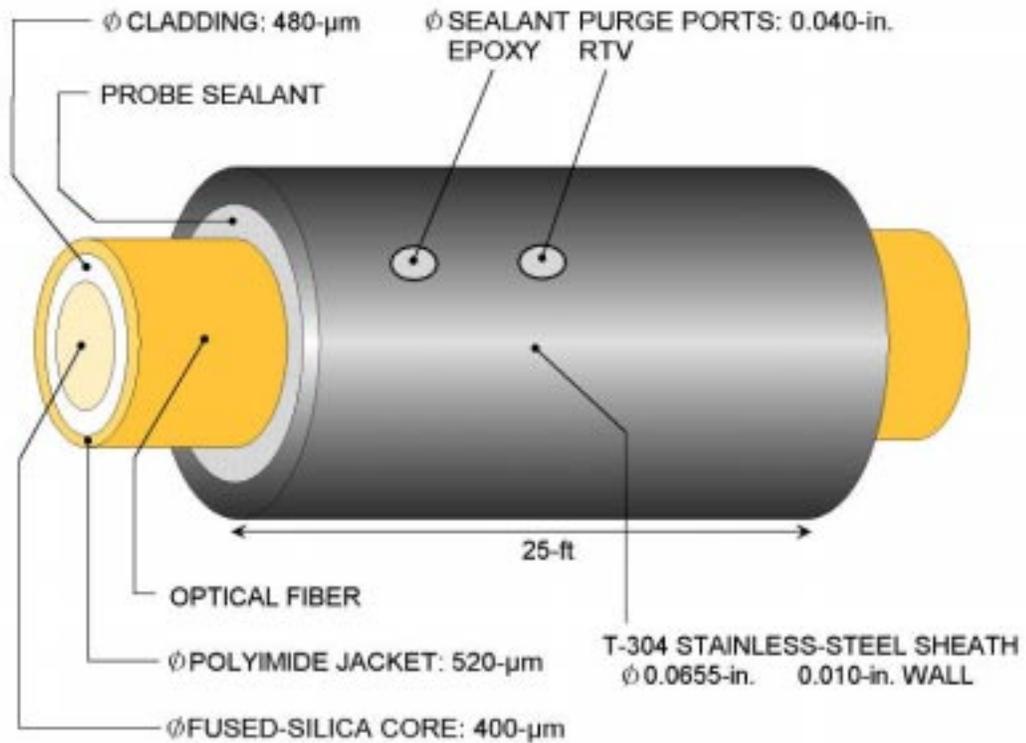


Figure 4. OFD and OPFD fiber-optic probe construction detail

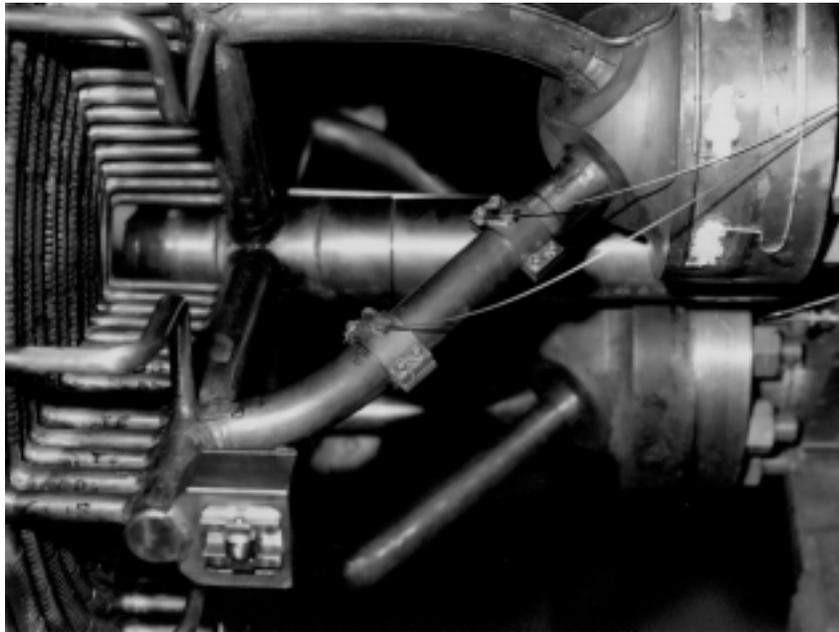


Figure 5. A pair of OFD optical probes integrated onto the 8-ft HTT methane injector

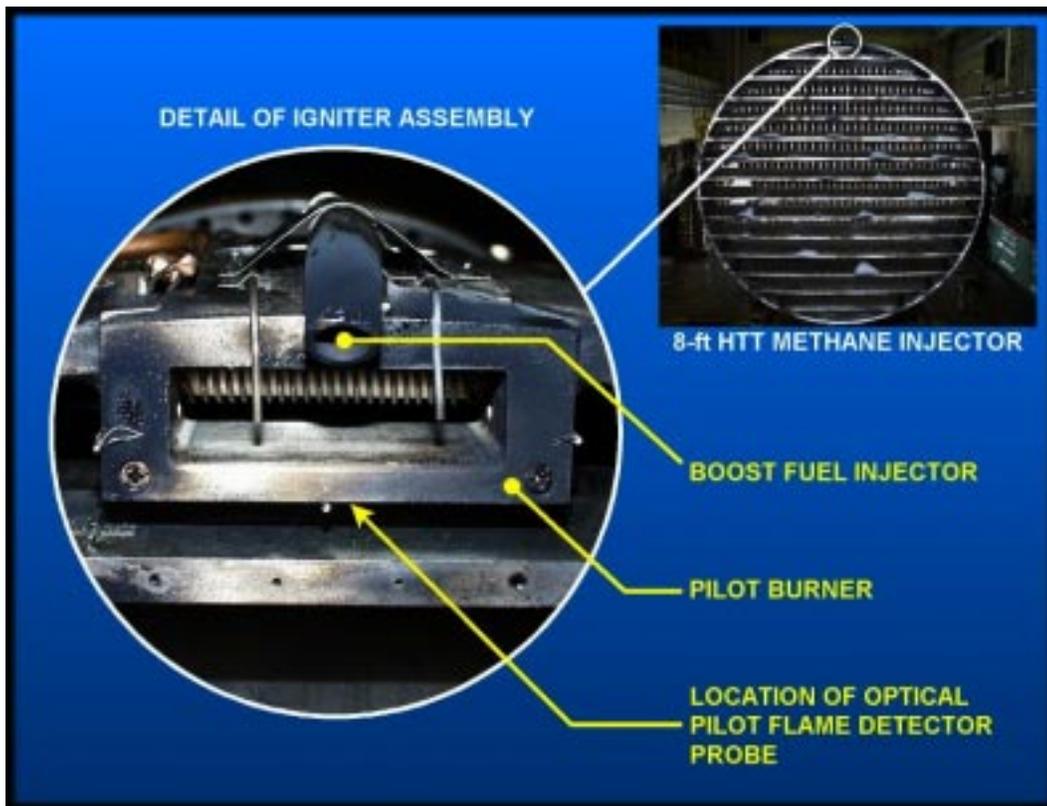


Figure 6. Integration of the OPFD optical probe on the methane injector igniter assembly

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