

# Industrial Applications of a Fiber Optic Emissivity Measuring Infrared Thermometer

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## ABSTRACT

In 1987 the first laser-based emissivity measuring infrared thermometer was introduced. This instrument is currently in worldwide use in industrial and research applications. In 1990 a fiber optic sensor version was developed; this provided broader temperature measurement ranges, smaller target sizes, lower cost and most importantly flexibility of sensor head size, shape and materials. Furthermore the fiber optic sensor version meets the requirements for on-line infrared temperature measurement and temperature control in metallurgical, chemical, ceramic and electronics manufacturing where portable instrument access is prohibited and where the sensor environment is harsh. The convenience and reliableness of the fiber optic version is now a reality. Diffuse target temperatures from 200° to 3000°C with emissivities from 0.05 to 1.0 can be measured at multiple locations with stand-alone or computer controlled instruments.

## INTRODUCTION

Since this discussion deals with the manufacturing applications of fiber optic sensors and more specifically with the infrared temperature measurements, it is not necessary to present at length the well-documented development of the radiation energy equations upon which the pyrometer is based. <sup>1, 2</sup> Infrared pyrometers are based on Planck's equation:

$$W_{\lambda} = \frac{E_{\lambda} C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad (\text{W} \cdot \text{m}^{-2} \cdot \text{SR}^{-1} \cdot \mu\text{m}^{-1}) \quad (1)$$

where (E<sub>λ</sub>) is the spectral emittance of the target. For the measurement situation we have one equation with two unknowns. The pyrometer senses the target radiant energy W<sub>λ</sub> but the second unknown emissivity (E<sub>λ</sub>) has typically prevented precise determination. In the early 1980's with the availability of small, low powered pulsed lasers a direct means to determine the spectral emissivity of opaque diffuse surfaces was developed which subsequently resulted in a practical emissivity measuring pyrometer, PYROLASER®. <sup>3</sup> In 1991, it was recommended in a report prepared for the Department of Energy that the technology be enhanced via a fiber optic sensor version. <sup>4</sup> In the same period the former National Bureau of Standards (NBS) development of optical fiber thermometry (OFT) was being commercialized <sup>6</sup>. The (OFT) technology significantly advanced the utilization of fiber optic sensors and in this case via a coated precious metal tip behaves as a blackbody radiator thus resolving the emissivity problem for cases where the sensor can be in contact with the target.

For most practical industrial temperature measurement applications non-contact infrared thermometers are required due to concern for product contamination, inaccessibility and or questionable sensor life such as frequently experienced with thermocouples.

The spectral emissivity (E<sub>λ</sub>) of most materials is not constant; it changes with the method of shaping or forming, the temperature, the atmosphere and the length of time in that atmosphere. It also varies with wavelength. <sup>7</sup> Emissivity does not always increase with temperature and time and there is no visual means to intuitively estimate emissivity (snow is a good example). Even if a target is in an open environment i.e. no surrounding reflective walls, temperature errors due to emissivity errors are significant. If surrounding walls exist or if there are nearby other objects at or above the target, we have the additional error of reflected extraneous energy reaching the pyrometer causing erroneously high target temperatures. This is a very common problem in industrial furnaces which PYROFIBER® can handle.

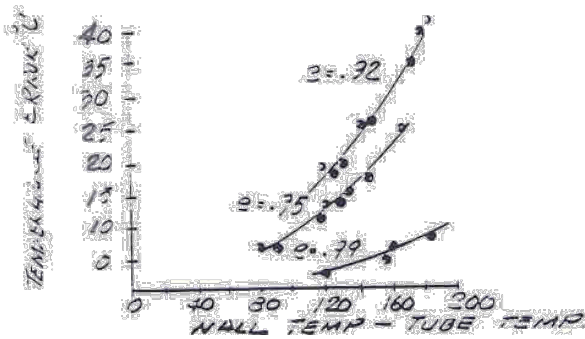


Figure 1. Temperature and Emissivity Values – Hydrogen Furnace

### FIBER OPTIC SENSOR DESIGN PARAMETERS

Before detailing specific desired sensor and fiber characteristics, it is first necessary to select the wavelengths to be used and the bandwidths. Two considerations are important: (1) avoidance of interfering gases and (2) availability of pulsed lasers and detectors that meet performance and economic requirements.

On the first issue, industrial processes frequently involve absorbing gases in the region between the target and the sensor. Given sufficient abundance and path length these gases can significantly compromise the radiance and emissivity measurements and in turn the temperature determination. Figure 2 shows the emissivity of common gases found in a gas or oil fired furnace. We obviously wish to select the least interfering wavelengths; considering the laser availability wavelengths of 0.865 and 1.55 microns are obvious choices. Typically bandwidths of  $\pm 0.05$  and  $\pm 0.050$  micron respectively are utilized. Selection of the wavelength fixes the lowest temperature achievable and laser power influences the allowable target distances.

WAVELENGTH	TEMPERATURE RANGE	DISTANCE RANGE
nm	°C	cm
865	600 – 1500	0.1 – 1000
	850 – 3000	1.0 – 110
1550	200 - 700	.03 - 400

Upper temperature limits are based on the desired instrument resolution and saturation of the detector excluding filtering. Target temperature and distance of course influence the materials of construction of the sensor and the possible need for cooling.

### SYSTEM OPERATION

A schematic of the emissivity measuring fiber optic pyrometer is shown in Figure 3 . In this case a two- lens sensor head is illustrated, one for the laser outgoing pulse and the other for the radiance plus the laser return pulse. A single detector arrangement is used for these input signals with the radiance treated as a (dc) slowly varying input and the (ac) rapid laser pulse return signal. The speed of the system is fixed by the calculations rather than by the detection system; with calculations the unit cycle time is 28.6 ms. Since the laser output power can vary a sample of every pulse is internally taken facilitating a ratio treatment for each laser return pulse. It is possible from the key pad to change the data acquisition time from 1 to 1000 ms in which case the emissivity and radiance values are averaged over the selected interval. A set of specifications is presented in Appendix A.

The PYROFIBER® may be operated from the key pad or run from a remote computer via RS-232 communication.

### SENSOR HEAD CONFIGURATION

Two optical channels are required per measurement location, one for the laser-transmitted signal and one for the laser return plus target radiance. The simplest configuration is with two independent fiber optic lines and two objective lenses. The sensor heads may be fixed-focus or adjustable. Since target distances are generally known in manufacturing applications the fixed focal length sensors are more economical and less subject to incorrect use in the field. Four distances can be calibrated in one instrument thus providing some flexibility to the user via a set of fixed-focal length heads.

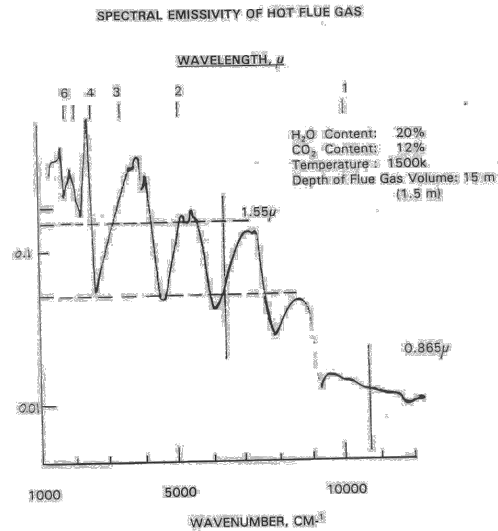


Figure 2 Spectral Emissivity Of Hot Flue Gas

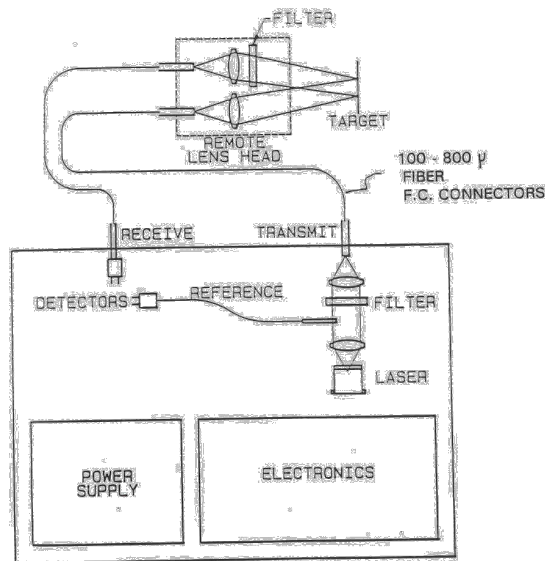


Figure 3 Schematics Of Emissivity Measuring Fiber Optic Pyrometer

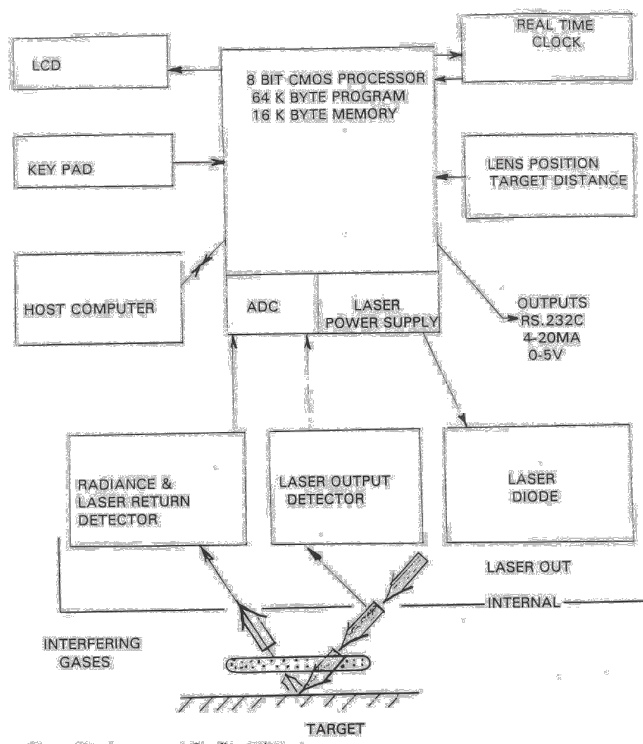


Figure 3a Instrument Configuration

For most applications aluminum or steel housings are used with fused quartz, BK-7 or sapphire lenses. However, temperature measurement levels or in some applications electromagnetic fields have required ceramic housings. In a few cases where the concept of target distance did not apply i.e. fluid bed reactors, systems have been delivered with no lenses but simply polished (1 mm) sapphire rods.

The very first industrial furnace application in a metal annealing furnace resulted in melted sensor heads within the first several hours of operation. Fortunately a simple radiation shield plus air cooling has provided sufficient temperature reduction; two units have been on-line since July 1991, taking one set of readings every second.

Reference Sensor Head Types, Figures 5, 6, 7

## SOME METALLURGICAL APPLICATIONS

### 1. Annealing

The first on-line commercial application of this technology was on two gas-fired annealing furnaces processing non-ferrous semi-precious sheet material in the 1750°F range. In addition to the target viewing sensor heads, there is a single channel sensor viewing the inside roof of the furnace to provide the extraneous (Tx) measurements needed for factoring out the roof refractory radiation which is reflected by the target to the dual target temperature sensor head. For the temperature involved and target reflectivity's (0.45 – 0.55) the correction amount to reduction of (80° - 100°F) in apparent target temperatures. This correction alone is vital since this annealing process involves a  $\pm 15^\circ\text{F}$  temperature range about the dense annealing temperature.

An important point involves the fact that both the target sensor heads and the (Tx) heads view through gas flames and combination products. The correct selection of wavelength (865nm)

in this case the flames and gases are transparent.

## 2. Liquid Metal

The ultimate application in this case is to determine liquid metal temperatures of an alloy in an induction furnace prior to pouring into the molds. The furnace cycle permits robotics insertions of a lance into the vacuum melt zone with the quartz tip inserted some 3" (75mm) into the melt. Preliminary tests were conducted on 99.9% molten zinc to determine sensitivity of fiber-to-tube end position and base tests in a black body furnace. The metal immersion tests provided temperature values of 539°C at PYROFIBER® radiance levels (13600-13800) depending on the distances of the fiber to the tip end. This confirms expected insensitivity to fiber position within (1cm) of the quartz tube end. Then, insertion into a black body furnace set at 539°C the positioned sensitivity was again checked. The measured PYROFIBER® radiance levels (13700 – 13900) occurred again with the highest radiance when the fiber optic tip was displaced 1 cm from the tip end. It appears this sensor configuration provides the expected characteristics of a black body.

One may ask why not use conventional thermocouples for this application? There are three detriments to using the thermocouples.

a.	Compared to the infrared fiber optic sensor, took 10-30 seconds to reach stable readings.
b.	After 4-5 uses, noticeable degradation of the thermocouples occurs; the question for the manufacturer being – how long can I rely on the readings?
c.	For the high temperature (1500°C) alloy application replacement after each melt was economically not attractive.

For speed of temperature response and long term durability the (1mm) sapphire rods inserted in the quartz tube appears to be the safe, economical solution.

## 3. Upset Forging

A very common metallurgical application requiring non-contact temperature measurement involves open-air induction heating of metal pieces to within some desired temperature range immediately prior to forging. If too hot the part is metallurgically unsuitable (for some cases) and the final forged shape is beyond acceptable limits. If the work piece is below forging temperatures the proper shape will not be achieved, however, the material can be recycled.

The conventional approach is to mount an infrared pyrometer at the exit of induction furnace and to monitor part temperatures, as they are withdrawn. Control being achieved solely by varying furnace residence time for different sized products at different energy input levels. Use of a fiber optic, dual channel probe, imbedded in twin bore ceramic and inserted between the furnace induction coils provided consistent temperature measurements during the upset heating process.

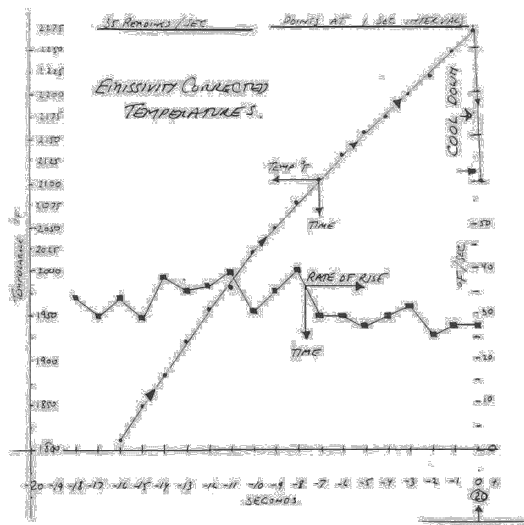


Figure 4 Surface Temperature and Rate of Rise Induction Heating of 1040CS

#### 4. Galvannealing

Application of the 1550mm emissivity measuring pyrometer is well illustrated in the vertical galvannealing process practical in many modern steel plants. The specular sheet steel is dipped into a molten bath and pulled vertically through rows of gas flames to maintain proper temperature-time relations for the process. Emissivity measurements of the steel near the bath are not reproducible due to the specular surface; as the steel rises the surface becomes more diffuse and the emissivity increase.

Figure 5 shows the first sensor head built for a small target (1mm) application requiring temperature measurements covering the 200°-1500°C span thus requiring use of both 865 and 1550 mm laser/detector and optical arrangements. We would expect simplification of this head in the future, but the user required completely non-coupled systems. (Electronically there is automatic switch over up or down at about 640°C.)

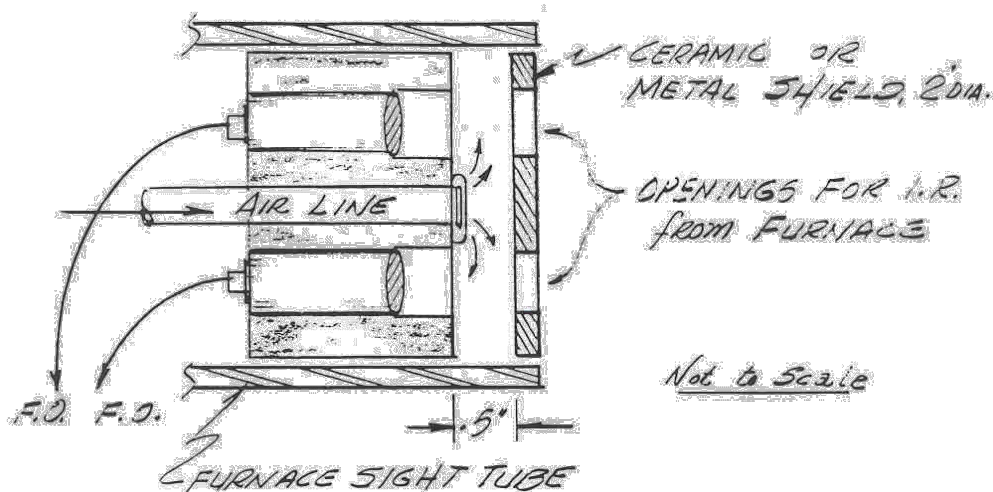


Figure 5 Simple Dual channel Shielded and Air Cooled Sensor

Figures 6 and 7 show more sophisticated sensor configurations. For application in a liquid metal the fiber optic lenses were held in a twin bore ceramic tube which in turn was inserted in a fused quartz sealed-end tube. Two fiber schemes were tried the first with 100m gold fiber and the second

with 1mm sapphire rods.

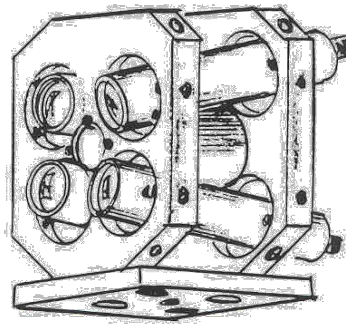


Figure 6 Small Target (1mm) Dual Wavelength Sensor Head

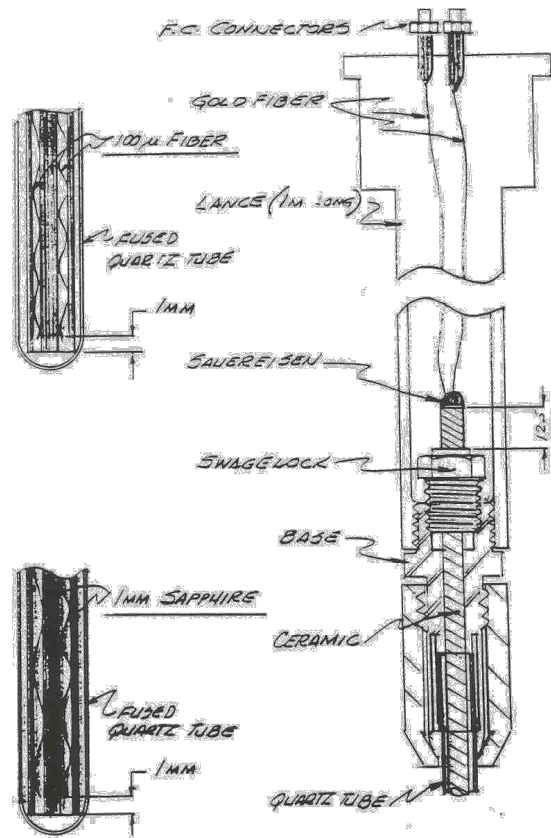


Figure 7 Immersion Probe

<u>Location</u>	<u>No. of Readings</u>	<u>Emissivity</u>	<u>TE</u>	<u>°F</u>
2 <sup>nd</sup> Elevation	400	0.35 STD 0.07	922	11
3 <sup>rd</sup> Elevation	50	$\frac{0.54}{D + 0.19}$ 0.08	$\frac{741}{-281}$	6

The above are readings taken at acquisition time of 1ms with each set five seconds apart. The very large increase in emissivity (0.35 to 0.54) in such a short interval (» 2 seconds between elevations) points out the need to measure emissivity as well as radiance; a pre-set emissivity would produce

large temperature errors.

The steel strip is approximately ten feet wide thus the need to have multiple sensor heads which can be achieved conveniently with fiber optic multiplexing.

## CONCLUSION

This paper has discussed just a few of the many applications of fiber optic based temperature measurement in manufacturing processes. Emphasis has been on the metallurgical industry for it is here that the upgrading of measurement and control is needed both for energy conservation and product quality. It is also in metallurgical applications that the material properties such as emissivity change over a very large range – making precision non-contact temperature measurement difficult. The advent of the low powered pulsed laser affords a simple and direct means to measure emissivity – at least on diffuse surfaces. Coupled with the flexibility of sensor head location, materials, size and shape the new technology affords the end user considerable freedom at reasonable costs.

[View Product Selection Guide to see complete line of temperature measurement non contact infrared thermometer products that measure emissivity including on line temperature control fiber optic sensors for industrial and laboratory applications.](#)

## REFERENCE

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- PYROLASER ® is a trademark owned by The Pyrometer Instrument Co., Inc.
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