Pyrolaser & Pyrofiber Infrared Temperature Measurement
With Automatic Emissivity Correction

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Abstract

Non-contact infrared thermometer temperature measurement metallurgical, chemical, ceramic and petroleum industries has been widely utilized with instruments operating in the visible and the infrared radiation portions of the spectrum. Regardless of the wavelength selected, uncertainty exists in the accuracy of the measured values due to unknown or changing surface emissivity. Besides influencing the emitted radiation the effects of reflected background radiation from furnace walls cannot be considered. Now, a direct and simple measurement technique utilizing a pulsed laser allows automatic correction for emissivity. While not applicable to all kinds of targets, for the last several years reliable infrared thermometer temperature measurements are being made in on-line manufacturing processes and sophisticated laboratories utilizing this new technique which has been implemented in portable and fiber optic instrument configurations.

INTRODUCTION

Measurement and temperature control is a routine but vital part of virtually every manufacturing process automation. The required temperature / time sequences for producing the desired results in a given process are generally the result of extensive experience producing that product of specific laboratory or pilot plant data which provide the proper temperature envelope for the process. Also the consequences of improper temperature control on product yield, product quality, plant energy use, plant maintenance costs or equipment service life are known. These factors allow one to quantitize or show the trade-off between the cost of proper temperature measurement and the cost of lost or poor product quality, higher energy use or premature equipment (furnace) maintenance or reduced service life. The technology described in this presentation was initially motivated by lower-than-predicted production of ethylene in a high temperature pyrolysis furnace and concurrent concern for furnace tube life if increased furnace temperature was the only way to achieve the rated production rate. In a large ethylene furnace a ten-degree low tube metal temperature measurement in the final pass compared to design temperature causes a decrease in the conversion process equivalent to a $500,000 loss in yield per year. If however, the furnace firing rates are increased there are risks involved that some furnace tubes will overheat and suffer premature failure. This example is not different from improper annealing temperatures in steel making or extrusion temperatures in wire drawing; the examples are infinite. Besides the economic driving forces, we have three other reasons for applying proper temperature control in our processes. First, there is the matter of pollution; poor temperature control in some processes can led to increased risk of pollution. Next, there is worker safety. Utilizing non-contact temperature measurement techniques inherently permits remote measurement. Remote measurement helps to keep workers away from unsafe process locations. Finally, there is possible product contamination when contact temperature probes such as thermocouples and RTDs are used. Infrared measurement clearly avoids that possibility.

Theory of Operations and Applicability

The fundamentals of infrared thermometry were established almost a century ago with Planck's radiation law and the Stefan-Boltzmann relationship; see Appendix A for detailed information. Virtually all temperature radiometers (full spectrum pyrometers) and spectral (infrared thermometers) depend on these equations or simplifications thereof. For industrial ir thermometers normally a selected bandwidth is employed based on the range of temperatures to be measured; Figure 1. Shows how the magnitude of spectral radiance emitted by a surface (a perfect emitter) varies with wavelength. To achieve sufficient sensitivity longer wavelengths (6.0+ microns) are used near ambient conditions while a bandwidth below 3.0 microns is adequate at typical industrial temperatures above 200°C (473°K). Industrial process automation realities impose very important restrictions on the waveband selection. Typically industrial processes involve flue gases, furnace flames and water vapor over long distances (2-10m). These media absorb and radiate infrared energy in selective wavebands. If the sight path from a pyrometer to the target contains any of the gases (CO, CO_2, H_2O or unburned hydrocarbons), particularly at elevated temperature, the measurement will be suspect. Engineers' handbook data on gas absorption/ emissivity are typically inadequate for the long path lengths involved in industrial furnaces. Figure 2. Provides NASA data, which illustrates the importance of using very narrow bandwidths preferably in the near infrared (below 1.6 microns). For Pyrolaser® and Pyrofiber® the two wavebands are centered at 0.865 and 1.550 microns and the bandwidths are 0.050 microns or less.

Unfortunately, one cannot determine a surface temperature with solely an input to the pyrometer of radiance. Solution of the equations requires knowledge of the target's efficiency as an antenna to emit thermal radiation; this is the emissivity. Emissivity is always less than unity thus pyrometers classically had an "emissivity know" for the user to set in any value (0.0 to 1.0); this severely compromises infrared pyrometer temperature measurements. In fact, it was this very weakness which focused Esso Research and Engineering Company's attention when the Esso ethylene crackers previously referred to were producing less ethylene than the feedstock and furnace conditions predicted. This in turn led to the development of the pulsed laser technique to simultaneously measure radiation and emissivity in order to determine the true temperature of tubes in a furnace

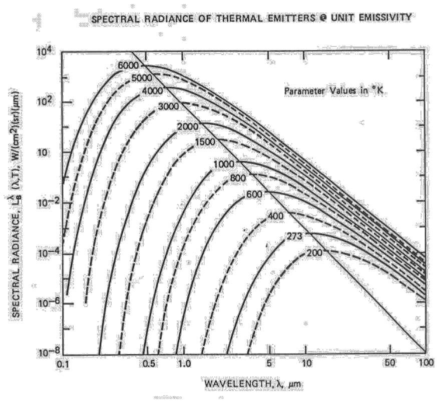


Figure 1. Spectral Radiance of Thermal Emitters at Unit Emissivity derived from Planck's equation. These curves give the radiance of a blackbody at various temperatures (in degrees Kelvin).

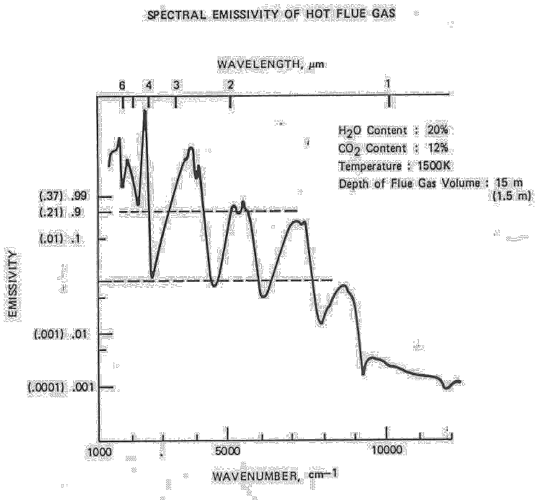


Figure 2. Spectral Emissivity of Hot Flue Gas showing absorption (emissivity) due to 20% H_20 and 12% CO_2 in an otherwise infrared inactive medium such as N_2. The Flue Gas Temperature is 1500°K.

The pulsed laser technique is quite simple but elegant. Incorporated in the Pyrolaser® and Pyrofiber® infrared non contact thermometer instruments is a small low powered (effective wattage=0.0025) pulsed laser. By sampling the laser-out signal on an internal detector and capturing a portion of the reflected laser-return signal we have a direct measurement of the surface reflectivity ® at the wavelength at the same location and temperature as was the radiance measurement. We thus have via Kirchoffs' law (e = I – r) the necessary input to solve the equations uniquely. One might ask about published emissivity data in handbooks and technical papers on heat transfer; why are not these data useful to the process engineer to 'set' the emissivity knob of a pyrometer? Our experience over the last eight years shows that published emissivity data are typically collected under pristine laboratory conditions such as polished target samples and vacuum or inert gas furnaces are used to set the thermal conditions. While useful for academic comparisons, such information is in fact misleading on the process line where no surface pretreatment has been applied and where the atmospheric conditions allow oxidation of the surface of hot materials. The oxidation process, which can commence instantly, will significantly change the emissivity value, most generally in an increasing manner. If handbook laboratory (e) values are used, the deduced values of temperature will typically be inflated. Our experience indicates that an (e) setting of 1.0 is the best choice if no means exists to directly measure emissivity if the target is in an enclosed furnace chamber.

For Pyrolaser® and Pyrofiber® the measurement of emissivity is based on the ratio of the (laser-return/ laser out) signal which is of very short duration. A pulse cycle is 120 nanoseconds, of which we make measurements during a 20 nanosecond period. This is electronically treated as an AC signal vs. the DC signal represents the target radiance. Thus the same detector is used for both signals and emissivity and radiance are sensed through the same optics. The two channels are independently calibrated, the emissivity against certified reflections targets and radiance calibrated with certified black body furnace sources. One must not use a black body furnace to calibrate the emissivity channel since a black body furnace does not have an (e= 1.0) or (e= 0.0) surface.

Before describing Applicability of limitations it is prudent to complete the theory of operation discussions. In most circumstances one additional factor must be included to understand the complete radiation picture. In most heating environments the target will be reflecting some radiant energy since no surface has (e = 1.0); a portion of this reflected energy may be "seen" by the measuring thermometer. The infrared laser thermometer cannot distinguish between emitted vs. reflected energy or background radiation it receives from the target. The net effect is an inflated uncorrected temperature which when corrected for emissivity is further inflated. In Figure 3, we show a hot wall as a source of stray energy of which a portion (r Lw) is incident on the pyrometer. Even with (e= 0.90), that is only 10% being reflected by the target, the error (inflated value) is 30 degree C above true tube metal temperature (TMT). Pyrolaser® and Pyrofiber® can both handle this error by first measuring the background radiation radiance of the source, in this case the wall, and then the target. An algorithm within these instruments will properly account for (deduct) the (r Lw) energy from the total seen by the instrument. This is only possible by virtue of having measured a target emissivity value which permits elimination of the reflected "wall shine" error.

Applicability is the term used to describe the conditions where the infrared technology works and *also* circumstances which prohibit proper temperature measurement. For this infrared technology the predominant requirement, besides being within target distance and within the instrument temperature ranges, is the nature of target surface. There are two types of reflection processes, one is the mirror like specular process the other the diffuse reflection process also known as Lambertian reflection. The measurement of emissivity by Pyrolaser® and Pyrofiber® both require diffuse reflection. Fortunately many, but not all, important industrial surfaces are diffuse and one can easily determine if the target is suitable. A specular target typically "overloads" the detector giving (e = 0.0) if aimed perpendicular to the surface and (e = 1.0) when aimed greater than 10 degrees off the normal. While visible mirror like reflection may be suspected, fortunately many specular surfaces when heated, become diffuse targets. Stainless steel, aluminum, beryllium-copper are example materials that under process conditions can frequently be measured using the Pyrolaser®/ Pyrofiber® technology. Caution must be stated for liquid metals, for in addition to specularity very frequently (foam-like) oxides float as islands on the surface. These islands of foam may or may not be in good thermal contact with the molten metal, thus even with correct emissivity values the measured temperature will be incorrect due to reduced thermal radiation. If measurements are made on a number of islands and they are reasonably consistent then the thermal contacting is probably preserved and valid radiance values have been measured.

EMISSIVITY AND BACKGROUND RADIATION WALL SHINE

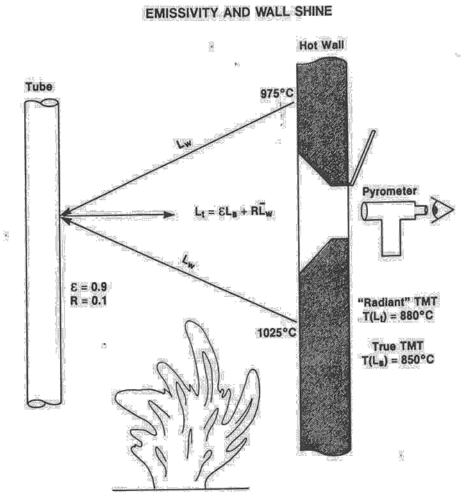


Figure 3, Pictorial Diagram of Emissivity and Background Radiation Wall Shine.

Conventional non contact infrared thermometers can not distinguish between radiation emitted by the tube or reflected radiation from the walls. All ir thermometer in fact measure the sum of the two, hence read high. To correct for background radiation wall shine and emissivity errors, one must measure the tube's reflectivity and the average radiation from the wall. Note, the average wall radiance is not the same as the average wall radiant temperature.

PYROLASER® AND PYROFIBER® INFRARED LASER THERMOMETER

A. Configurations

Pyrolaser® was designed as a portable instrument for use in the field to be manually transported and used for measuring and storing vital process temperature measurement information. The portability requirement requires ease of handling, a direct display and recall of the sensed values (emissivity, uncorrected and corrected temperature) and controls so the operator can change measurement parameters as he progresses from one measurement location to another. Besides an internal clock it is vital for the operator to be able to store, if desired, the location of the temperature measurement point or the identification of the target(s). Obviously the battery life must be sufficient to permit several hours of active measurement. Since various targets may be at different distances a means to focus the instrument is needed, and when necessary, the ability to change operating ranges (20cm) vs. 2-m-10m) if beyond the focusing span of permanently installed optics.

We have highlighted the word "store" and for good reason. It is very cumbersome to collect temperature measurement data in a hostile environment such as a steel plant while wearing gloves, hard hat, and goggles and then write it down in legible form on a scratch pad that has been stuffed in one's pocket. It is generally even more difficult to read the information once back at the office or where the data will be analyzed or entered into a computer. It is obvious that errors will be made by such a procedure; are the errors tolerable? No. The only practical solution is the built-in automatic data logging permitting positive data storage for recall or entry into a computer. Even in laboratory applications, direct data communications from sensing instrument to a computer is convenient and error free. In fact, both Pyrolaser® and Pyrofiber® can be operated from a computer keypad via the RS232C remote control communications capability.

One final aspect of the Pyrolaser ® to consider. While embodied with all the capabilities for portable application, Pyrolaser® can be permanently mounted and set to run in a continuous on-line mode in which case an AC power source is required. In this case Pyrolaser® can take measurement at rates from (5 per sec) to the slowest rate of (1 reading per 24 hours). The combination of on-line and portable applications makes Pyrolaser® particularly suited for combined plant and laboratory applications.

The Pyrofiber® fiber optic sensor infrared laser thermometer is deigned for on-line applications, particularly for installed plant measurement and control. Since the fiber optic sensor can be hundreds of meters from the instrument this facilitates plants with central temperature control rooms. While providing some flexibility, each infrared temperature sensor head is built for the particular target distance-target size required by the application. Pyrofiber's® are built to withstand the dirt, dust, vibration, and electromagnetic radiation typically found in heavy industry. One version has been configured for light laboratory service and another in a rack mounted version. Figures 4 A-# show Pyrolaser ® and several configurations of Pyrofiber®.

For the Pyrofiber® ir digital thermometer configuration there are a multitude of sensor head designs available in order to meet the many specific customer needs. A few of these are shown in Figures 5 A-C; for in-plant industrial applications where ruggedness is required the configuration shown in Figure 6 is recommended. In addition to the sensor, the fiber optic lines and connectors are armored for plant use.

Various Temperature Measurement Configurations:

Figure 4A Tripod Mounted PYROLASER®

Figure 4B LAB TOP PYROFIBER®

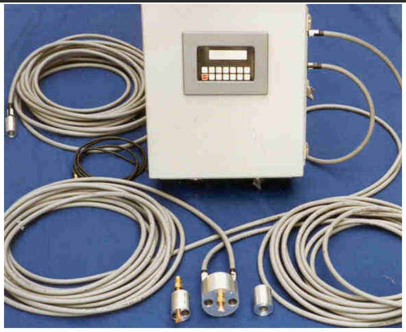


Figure 4C INDUSTRIAL PYROFIBER®

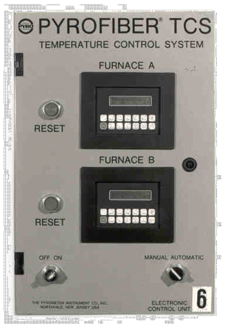


Figure 4D DUAL INDUSTRIAL PYROFIBER®

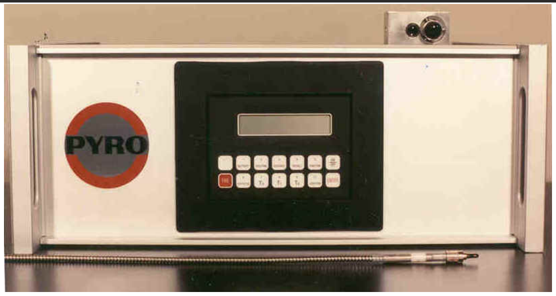


Figure 4E RACK MOUNTED PYROFIBER®

Figure 5A PYROFIBER® SENSOR HEAD LASER OUT + RADIANCE/ LASER RETURN

Figure 5B PYROFIBER® SENSOR HEAD WITH Tx SENSOR

Figure 5C PYROFIBER ® SENSOR HEAD FRONT AND BACK VIEWS

Figure 6A INDUSTRIAL PYROFIBER® WITH

FIBER OPTIC CABLES AND SENSOR HEADS

Figure 6B BRACKET & FLANGE MOUNTED SENSOR HEADS

B. Specifications

A detailed Specification Data Sheet is included as Appendix B, however, a data sheet does not provide the reasons for many important facts nor interrelationships between variables. Also, there are trade-offs which for some applications could be significant. The purpose of this discussion is to highlight these considerations again remembering the intended applications of each of the instrument systems.

1. Temperature Measurement Range

Infrared thermometer detectors sense radiance not temperature. The detector sensitivity in terms of signal-to-noise ratio establishes the lowest radiance level that can be used reliably. The upper radiance level is fixed not by detector performance but rather by the dynamic range and resolution of the associated electronics. The resulting temperature limits are presented below with the target distance limits which are a function of the laser power and the optical efficiency:

Standard Model	**Pyrolaser® IR Thermometer**	**Pyrofiber® Fiber Optic Sensor Thermometer**	
Wavelength (microns)	0.865	0.865	1.550
Temperature: min/ max C	600/1500	600/1500	250/800
Optional max C	2500	2500	1100

Distances: mm. Min/max	2000/10,000	200/4000	200/4000
Add-On-Lens mm	200/1000	Customized	< 200
Target Diameter mm	10-50	{ 1-2-4-10-20}	

It must be realized that the limits are not all freely interchangeable; the variables are interrelated. For example, if a 2500° max. temperature for a Pyrolaser® is specified, it is necessary to filter or cut-off some of the target radiance. This however, also reduces the laser return signal which is the distance limiting parameter; thus a Pyrolaser® calibrated for a 2500°C range and outfitted with a filter will (in that range) be limited to a target distance of 3 m. (Note: Pyrolaser® provides up to four separate operating ranges thereby not limiting the overall capability.)

1. Laser Measurement and Firing Rates

Since the emissivity measurement is based on the pulsed laser transmitted and reflected laser return signal, various laser firing rates and data integration times are available to the user. As integration time (data acquisition time) is increased the number of laser pulses used to calculate the average emissivity increases:

Integration Time (ms)	**No. of Laser Pulses**	**Details/ Comments**	
1	**1**	**Fastest Data Acquisition**	
17	12	12 pulses/ on 60 Hz cycle	
20	14	14 pulses/ on 50 Hz cycle	
--®		**50 Hz**	**60 Hz**
100	72	5 cycle	6 cycles
200	144	10 cycle	12 cycles
500	360	25 cycle	30 cycles
1000	720	50 cycle	60 cycles

With calculation of temperature and emissivity output from Pyrolaser® or Pyrofiber® the maximum measurement rate is (4 readings/sec.) In High-Speed mode, where output is accomplished after the data acquisition via the data logger, the maximum measurement rate is (35 readings/sec).

The ability to control the measurement rate allow the user to adjust the rate to the needs of the process, particularly if there is relative motion between the instrument and the target.

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.

Typical Applications

Over the past few years Pyrolaser® and Pyrofiber® temperature sensor each have been employed in the hundreds of different laboratory and industrial plant applications and on many different kinds of target materials. In this paper we can only present a few of the many applications, these were chosen to illustrate the wide flexibility of the infrared technology and /or unique results which have broad implications. Since the design was based on petrochemical furnace use, a hydrogen furnace use will be treated first.

1. Hydrogen Furnace Application

   In a hydrogen furnace increasing the product coil outlet temperature and the steam-to-carbon ratio improves the conversion to product (the yield) and the quality. As catalyst activity decreases with age more steam is introduced and finally tube metal temperatures become the limiting variable. Precise knowledge of the tube temperatures becomes vital and as stated one needs emissivity and radiance to obtain the temperatures. One would think that after 2-3 years exposure in a furnace all tubes would have about the same emissivity; not true. As is evident in Figure 7, the longer exposed tubes have a wider range of emissivity values (.82- .94) than the less exposed tubes comparing data from one year earlier (.87-.92). As shown in Figure 8 the wall shine error is greatly influenced by these variations. It is evident that reliable furnace tube temperature measurements cannot be made with assumed constant values of emissivity. Similar data for ethylene cracker furnace tubes show emissivity values for tubes ranging from (0.72- to0.99) even though the tubes were from one manufacturer’s lot and installed in the furnace at the same time.

2. Metallurgical Processes

   Aluminum: Whether ferrous or non-ferrous, most metals processing is at elevated temperatures. Applications of Pyrolaser®/ Pyrofiber® technology is not particularly suited to refining and/or smelting operations where wither the furnace combustion processes or the metal + reactants produce extensive smoke or sparks which interfere with both the laser as well as the radiance measurements. Smoke obviously scatters and filters the radiation resulting in artificially low readings of (Tu) the uncorrected temperature value. If sparks are present in sufficient density then the sparks are interpreted as very strong return laser signals which produces highly volatile and near zero emissivity values. Fortunately the resulting values are so out of line with common sense values there is no interest in using

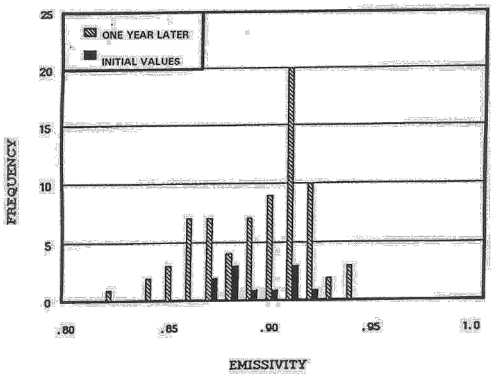


FIGURE 7 EMISSIVITY VALUES OF HYDROGEN FURNACES TUBES

FIGURE 8 WALL SHINE AND EMISSIVITY ERROR

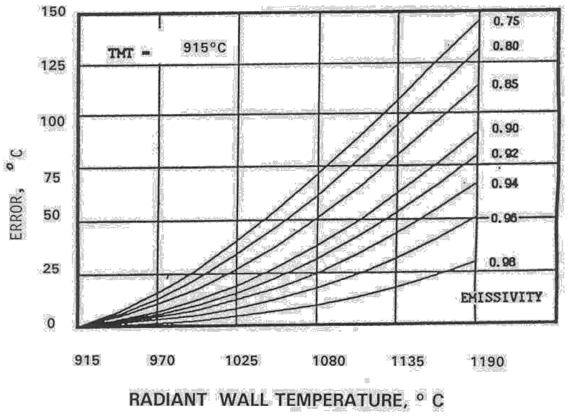


FIGURE 8 WALL SHINE AND EMISSIVITY ERROR

the values for process knowledge or control We have had limited success in liquid aluminum measurements of long as the target spot sizes were sufficiently large (30-10mm) so that local variations were averaged. It is also vital that the instrument be in secure mounting to eliminate volatility due to relative motion. In Appendix C the results of a Pyrolaser® test on molten aluminum are presented. The comments are quoted directly from the field test report of a major aluminum producer and the enclosed Figure C-1 show the close tracking with immersed thermocouples.

Continuing with aluminum applications PYRO recently conducted plant tests at a facility which inductively heats small aluminum cylinders as part of an assembly process. The vertically held cylinders are heated to their softening temperatures in a 2-3 minute process open to the atmosphere. Thus, even though the unheated cylinders are clearly specular and unsuitable for this infrared technology, after a brief heating interval a tight oxide coating has formed which provides a diffuse target surface very suitable for the Pyrofiber®. The small sensor head of Pyrofiber® makes it easy to secure to the rotating machinery, and the dramatic variations in emissivity clearly justify non-use of a conventional infrared device. Sample data set are presented in Appendix C

Steel Applications: A variety of applications in the steel making process and the steel users have been successful with Pyrofiber®. This unit being for a fixed installation can be ruggedized against moisture, dust, EMF, vibration, etc. as the situation requires. Steel making and steel applicators all tend to have facilities, which require such hardening.

An early Pyrofiber® infrared thermometer application was on eighteen induction furnaces used to heat 1040cs steel cylinders of different diameter prior to forging (upsetting). A single operator using two furnaces alternately and one forging machine develop a work rhythm producing two forges per minute. If for any reason the steel is under heated the forged product is generally not made to the proper dimensions; if overheated the product cannot be used due to possible metal failure in a truck or car steering system which could be fatal. While the per unit part is low value ($0.10) before forging and say ($0.25) after, there is a clear need to monitor, control and reject improperly heated parts. This was accomplished via Pyrofiber® technology, a small sensor viewing the part as it ejects from each induction oven. An instant readout is provided to the operator, and if the temperature is beyond the acceptable limits a coded alarm is provided. Furthermore if the rejection is due to overheat, the part must be placed in a segregated bin before the press can be restarted. Since the rise in temperature is quite rapid in the induction furnace, the read rate of the Pyrofiber® was increased to four values per second. A photo of a single installation is shown in Figure 9; each control box served two induction furnaces. Units 6A and 6B in this case.

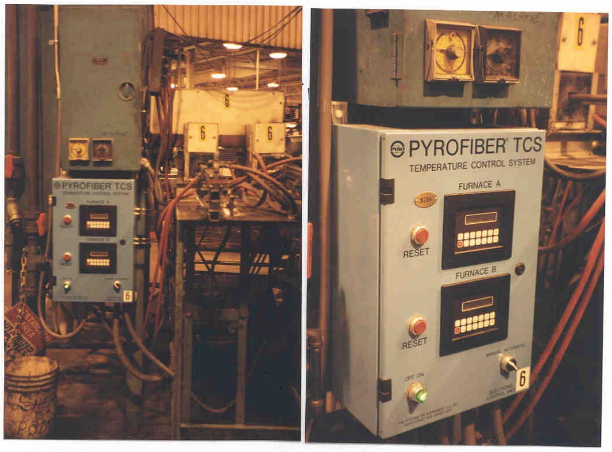


Figure 9 PYROFIBER® TEMPERATUE CONTROL SYSTEM

Galvanizing / Galvannealing; A very common steel industry process is hot dipping sheet steel in zinc bath to provide a corrosion resistant coating to the steel. The dipped steel sheet is typically pulled vertically upward 20-30m and at various locations gas flames are applied to assure proper temperatures for the zinc-steel bonding. It is thus vital to know the temperature of the steel prior to each gas heating station to determine the need for or amount of energy to be applied. If rolling contact thermocouples wire used the new zinc-steel surface would be marred thus non-contact infrared is the solution. Again however, the surface emissivity is changing very rapidly as the galvanizing proceeds. Working with a major Canadian steel maker, Pyrofiber® was shown to provide accurate and reliable surface temperatures at all vertical locations except immediately after the zinc bath at which point excess liquid zinc is dripping from the surface back into the bath. As seen in Table I there is a significant emissivity change as the coated steel moves vertically after the bath. It should also be noted that since gas firing is used there is no background radiation wall shine effect since Pyrofiber's® operating wavelength does not "see" or detect the gas flame or combustion products; these are transparent to Pyrofiber®.

Table 1. Temperature Emissivity on In-Process Galvanizing of Steel

Distance Above Zinc Bath, m	Readings #	Emissivity @ 1.55 mic.	Correct Temp Te, Deg. C
1	*	SPECULAR	*
5	400	0.35 sd (0.07)	494 sd (6 Deg.)
10	50	0.54 sd (0.08)	394 sd (3 Deg.)

Notes: Readings were taken at acquisition times of 1 ms. The term sd means standard deviation.

If a conventional infrared pyrometer had been preset with e= 0.35 at the 5 meter height the correct temperature would result. However, using that same value at the 10 meter location would give a temperature value of 470°C an error of 76°C. Also it should be noted that the target is moving at a speed of 2.5 m/s parallel to the focal distance but lateral motion (towards and away from) also existed due to the vertical "hanging" of the steel sheet. Thus the small values of standard deviation (sd) in both emissivity and temperature are quite satisfactory.

In Appendix D emissivity data on steel under vacuum, at elevated temperatures and at different wavelengths are presented. It is very clear from this information that use of handbook values of emissivity for presetting pyrometers is indeed risky. Only by simultaneous measurement of radiance and emissivity can one expect to achieve meaningful infrared temperature determination.

Metal Oxide Coatings: An important adjunct to steel applications is the wide use of metal oxide coatings to provide corrosion resistance and thermal protection to the steel or more typically improved wear resistance. Thin hard coatings can be applied via open environment flame or plasma spray and sometimes in high vacuum deposition processes. The coatings are typically blends of alumina, chromia, magnesia, titania, and zirconia; their visual appearance can be from mat white to dull black. The emissivity values do no conform to any visual white-to-black scale however most provide very good diffuse targets for Pyrolaser® and Pyrofiber®. Furthermore, the emissivity values of these materials are far more stable with temperature (up to around 1000°C) even in an air atmosphere.

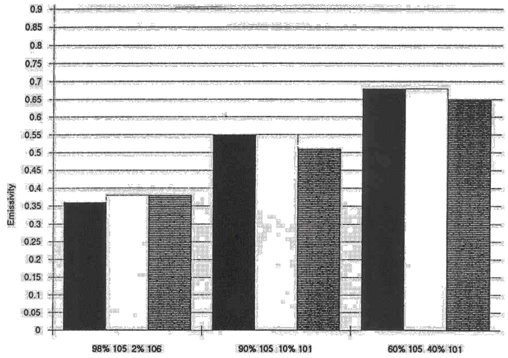


Figure 10 Emissivity of Blended Metal Oxide Coatings on Steel

The examples presented are formulations of:

Coating	%	Primary Constituent
# 101	97	Alumina
# 105	98.5	Aluminum Oxide
# 106	96	Chromia

which have been flame sprayed onto untreated 1040cs.

3. Refractory Materials

Refractory materials are vital as insulators in industrial furnaces. They therefore play an important role, not only keeping the heat losses to a minimum but also how they behave as emitters and reflectors in the furnace. Generally the work-in-process in a furnace "sees" more refractory than any other item. Furnace manufacturers want to produce efficient furnaces, but frequently the specifications for refractory are based primarily on insulation values and expected useful life, with little interest for the role of the refractory in the heat transfer processes. This section will only point out that various refractory materials do have substantially different emissivity/reflectivity properties. A recent test illustrates the point. Typical industrial refractory materials have emissivity values in the (0.35-0.65) range at 0.865 micron wavelength. Also, they tend to be quite stable over the temperature range of intended use. Two samples from a furnace manufacturer showed emissivity values below 0.15 over the entire working range of the refractory but there were no other significant property variations.

From a practical viewpoint furnace gases and dirt will significantly change the effective emissivity/ reflectivity of refractory. The general result is areas where "clean" gases pass at sufficient velocity retain near original values. Dead Zones where gas flow is blocked or reduced generally collect the soot leaving the refractory under a layer of porous particulate material, which in effect becomes a heat trap. The porosity has the effect of being a huge receiving area compared to its true geometrical dimensions; it becomes a honeycomb of small black bodies. Unfortunately it is the non-uniformity of the soot layer, which leads to hot and cold zones in radiant dependent furnaces.

4. Graphite

Most of us think of graphite as a "very black" material, and would expect it to have emissivity values near (1.0). In the infrared spectrum graphite is not nearly so "black." Emissivity values in the (0.75 – 0.85) are more common than higher values. More importantly however is the fact that the emissivity of graphite varies significantly with temperature. At temperatures above 1850°C which are common for graphite furnace chambers there is considerable variation with temperature. Vacuum furnace tests provide repeatable data similar to Figure 11, which shows the heating-up and the cooling-down emissivity variations. It is remarkable how closely the curves track each other.

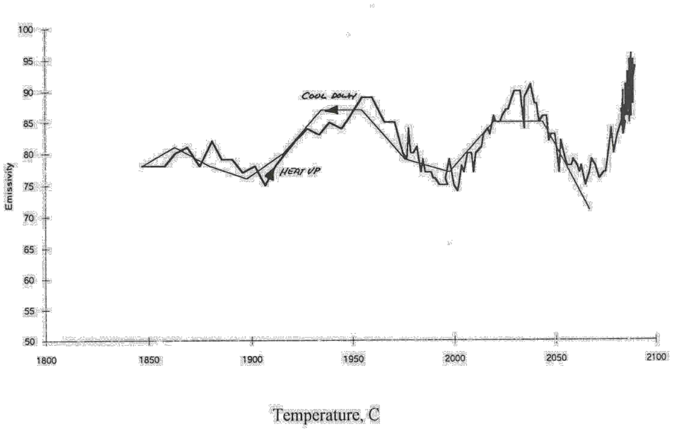


Figure 11 – Emissivity of Graphite in a Vacuum Furnace Test

Conclusions

1. Infrared temperature measurement technology provides a non-contact means to monitor and control industrial process temperatures. Considerable care must be exercised to assure that measurements are not adversely effected by interfering gases, poor transmission through sight-ports etc. which are wavelength sensitive.
2. In most cases the emissivity of the work-piece target is unknown and high variable; this has heretofore made infrared temperature measurements inaccurate and highly suspect. New technology, a pulsed laser technique incorporated in PYROLASER® and PYROFIBER®, now permits direct and simultaneous emissivity measurement and automatic correction of temperature.

3. Radiant energy reflected by the target must be measured and subtracted from the total energy incident to a pyrometer; to do this one must know the reflectivity of the target at the same wavelength and temperature. The new technology facilitates this correction.
4. The new technology has been utilized in a variety of industrial applications including metallurgical, ceramic, and petrochemical furnaces. The technology does not work on specular targets.
5. The technology is implemented in both portable and fixed configurations, the latter utilizing the fiber optic transmission of the sensed infrared signals.

Appendix A – Theory of Operation

It is not the intent of this Appendix to provide the reader with a complete understanding of radiative heat transfer theory; that information is available in an abundance of textbooks. Instead, it is important to convey to the Pyrolaser ®/Pyrofiber® infrared thermometer user the fundamentals involved and the significant limitations.

When aimed at a surface, thermal radiation from that surface will be "seen" by the instrument temperature sensor, collected by the receiving (objective lens) and internally focussed on a detector. The radiation "seen" is a function of the optical geometry (target distance and spot size), the radiation emitted by the target based on its absolute temperature and emissivity plus energy reflected by the target such as from furnace walls, combustion flames or other heat sources. Internally, filters are employed to define the wavelength and bandwidth of the energy which the detector will collect. The equations in simple form are:

$$Lt = \in L B + R/\pi \int Lw \propto \Omega \quad (1)$$

$$Lt = \in L B + R \overline{Lw} \qquad (2)$$

Where Lt is the total radiance received by the instrument within the selected bandwidth and $\overline{Lw}$ is the average wall radiance, R is the reflectivity of the surface at that wavelength and $\in$ is the emissivity. The emissivity and reflectivity are related and for opaque materials appears simply as

$$\epsilon = 1 - R \qquad (3)$$

The most important relationship in radiative heat transfer is Planck’s equation which appears

$$L_B = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

In Pyrolaser® and Pyrofiber® the quantities (Lt), Lw), and R are measured thus permitting solution for emissivity and background radiation wall shine corrected temperature measurement. For the cases where there are no radiative sources such as hotter walls the temperature measurement is simplified since no average wall radiance need be measured.

It is important to note that selection of the wavelength and bandwidth are very important for these parameters establish the sensitivity (lowest and highest) radiance signals the pyrometers will "see", and the quality of the measurements particularly in combustion furnace environments. The Pyrolaser® bandwidth from (0.850-0.890) microns makes it possible to avoid combustion gas and gas flame interference; it also restricts the lowest temperature to 600°C. For Pyrofiber® fiber optic sensor, the additional waveband (1.52-1.67) microns allows measurement in the 250-750°C region. While quite free of combustion gas disturbance, propane flames will disturb measurement.

The measurement of emissivity is in fact a measurement of reflectivity at the selected wavelength. We rely here on Lambertian or diffuse reflection, thus this technology does not apply to mirror-like or specular surfaces. Fortunately ceramic and metal oxides are diffuse reflectors, and in most cases hot metals exposed to air rapidly become diffuse targets. For diffuse targets the instruments do not have to be perpendicular to the target surface, indeed angles up to 60 degrees off the normal are conveniently handled via a built-in cosine function which corrects for non-perpendicularity. At angles near perpendicular the correction factor is insignificant.

Appendix B - Specifications

• **Selectable Readout:**	°F,°C
• **Standard Temperature Range:**	1100°F - 2730°F (600°C - 1500°C)
• **Optional Extended Temperature Ranges:** See Calibration Lens & Filter Table	1300°F - 3600°F (700°C - 2000°C) 1450°F - 4500°F (790°C - 2500°C) 1550°F - 5400°F (850°C - 3000°C)
• **Calibration Ranges:**	(4) Ranges Available
• **Accuracy:**	± 5°F (3°C)
• **Resolution:**	± 1°F (1°C)
• **Repeatability:**	± 1°F (1°C)
• **Effective Wavelength:**	0.865 mm ±0.015

Bandwidth:	0.055 mm
Automatic Emissivity Measuring Range:	0.01 -1.0 (Increments 0.01)
Aquisition Time:	1ms - 2000ms Selectable
LED Display In Viewfinder:	4 Digit Corrected Temperature (Tt)
LCD Disply	40 Digit Readout of Target Distance Emissivity Value (E), Uncorrected Temperature (Tu), & Corrected Temperature (Tt)
Standard Target Distance: Optional Target Distances Available	2-10 meters
Target Size vs. Distance: **Standard 2 - 10 meter Range** Optional Target Size/Distances Available	**Target Size** **Target Distance** (Target Size = 1/200 of Target Distance) Min Max Min Max 0.39" (5cm) 1.96" (5cm) 6.56' (2m) 32.8' (10m)
Visual Field Of View:	7°
IR Field Of View:	0.333° (1mm @ 20cm; 0.04" @ 8")
Sample Rate	1, 2, 4, 8, 21, 23, 37 Readings/sec Selectable
Maximum Equipment Operating Temperatures:	32°F - 125°F (0°C - 32°C)
Display Output:	LCD 3.5" x 0.75" Target Emissivity Target Uncorrected Temperature Target Emissivity Corrected Temperature
Instrument Enclosure:	Cast Aluminum
Auxiliary Output:	Single Analog Output: 0 -5vdc or 0-20mA Single Digital Output : RS232C
Power Supply:	(3) x 9v Rechargeable Ni Cad Batteries 115v/60Hz or 230v/50Hz Charger 2 Hours Operating Time w/Batteries - Unlimited Operating Time With Charger.
Dimensions:	12.5" x 8.0" x 3.0" (318mm x 211mm x 74mm)
Weight Including Batteries:	7lbs. (3.5kg)

PYROLASER® vs PYROFIBER® Infrared Thermometer Temperature Sensor			
CONFIGURATION	**PORTABLE & ON-LINE**	**ON-LINE &**	**SEMI-PORTABLE**
WAVELENGTH:(MICRONS)	0.865	1.550	0.865
EMISSIVITY:	0.10 – 1.00	0.10 – 1.00	0.10 – 1.00
TEMPERATURE:	600 – 1500°C	250 – 800°C	600 – 1500°C
ACCURACY:	± 3°C	± 3°C	± 3°C
OPTIONAL RANGE:	TO: 2500°C	TO: 1100°C	TO: 2500°C
TARGET SIZE (mm)			
STANDARD:	10 – 50	1-2-4-10-20	1-2-4
ADD-ON-LENS:	1.0 (minimum)	-	-
TARGET DISTANCE (cm)		SENSOR HEAD TO TARGET(cm):	
STANDARD:	200 – 1000	20 - 400	20 – 1000
ADD-ON-LENS:	20 – 100	CUSTOMIZED<50	CUSTOMIZED<50
MEASURES IRRADIANCE:	YES	YES	YES
MAX. MEASUREMENT RATE:	700/20 sec.	700/20 sec.	700/20 sec.
DATALOG (700 RECORDS):	YES	YES	YES
ANALOG/DIGITAL OUTPUT:	YES	YES	YES
RS/232 COMMUNICATION:	YES	YES	YES
REMOTE OPERATION:	YES	YES	YES

APPENDIX C - APPLICATIONS DATA

1- Pyrolaser® Temperature Measurement in Hydrogen Furnaces Offers High Economic Incentive

In a hydrogen furnace the coil outlet temperature (COT) declines as the catalyst activity declines. At that time the tube metal temperature (TMT) limitation comes into play. This is normally about 25% of the time, i.e. the latter part of the catalyst life. Obviously some furnace designs with higher design heat flux may have a somewhat higher percentage time.

The following table covers two hydrogen plants, each making 19.2 MSCFD contained hydrogen, with one plant producing 97.0 vol % H_2 (19.7 MSCFD total product) and one producing 95.0 vol % H_2 (20.2 MSCFD total product). The feed type is methane and the plants are the conventional configuration with HTS, LTS, CO_2 removal and Methanation. It should be noted that the incentive at high temperatures is associated with steam savings - not reduced fuel rates in the fired heater. This results because the product hydrogen purity is controlled by both COT and process steam (or S/C ration). Both higher COT and S/C ratio improve conversion of hydrocarbon feed to hydrogen as well as maintain product purity. With fixed conversions and purity as in the table, the process heat requirement is almost constant (less than 0.5% delta heat duty due to increasing steam rates over the full COT range given). Hence, as COT is reduced the S/C ratio has to increase to maintain the feed conversion and product purity bases. In each case the feed rate is constant over the full COT temperature range. The high-pressure process steam was valued at 4 $/k#.

97% vol % H_2				95.0 vol % H_2		
Coil Outlet Temperature (deg.F)	S/C Ratio	Process Steam (k#/hr)	Incentive (M$/yr)	S/C Ratio	Process Steam (k#/hr)	Incentive (M$/yr)
1550	4.71	49.4	Base	3.53	39.8	Base
1525	5.17	54.3	0.16	3.88	43.9	0.14
1500	5.68	59.7	0.34	4.29	48.5	0.29
1475	6.25	65.7	0.54	4.75	53.7	0.46
1450	6.89	72.4	0.76	5.26	59.5	0.66

During the final 'year' of catalyst life when (TMT) is the limitation we can conservatively assume a (1:1) relationship between (TMT) and (COT). Typically errors of (25° - 40°F) due to emissivity and reflected wall radiance occur using conventional infrared and/or optical pyrometers. A 25°F (high) reading equates to <u>$163,678.yr</u>. Even if this occurs only --during the last <u>25%</u> of catalyst life in a furnace on a four-year cycle it more than justifies a PYROLASER®. Moreover, most plants have multiple H2 furnaces, therefore at least one furnace is experiencing declined catalyst life at all times.

1 - Molten Aluminum

The Pyrolaser® was configured to take continuous temperature readings every minute while the furnace was operated in a normal manner. These readings were compared to thermocouple temperatures measured in the pump well.

"The Pyrolaser® followed the changes in the metal film temperature as shown in Figure C1. When the burner was shut off at one point, the film layer was observed to drop over 400°F in 10 minutes time. The level of repeatability seems to be good. During one twenty-minute period where the temperature was fairly constant, the standard deviation in the temperature was 18°F while the average temperature was 1838°F. This yields a coefficient of variation of less than 1 %. Some of this variation may have been caused by either the furnace itself or by small amounts of motion in the mount. A more rigid mount would have worked better. A better indication of the metal film temperature can be obtained by averaging the incoming temperatures over a several minute period as is shown by the second line in Figure C1.

The Pyrolaser® instrument is not a perfect measurement tool. However, it has given us the ability to make a number of measurements we would not be able to make before. I believe it can be a very useful process characterization and evaluation tool when used under the correct conditions. With some further investigation it might also become a useful process control instrument."

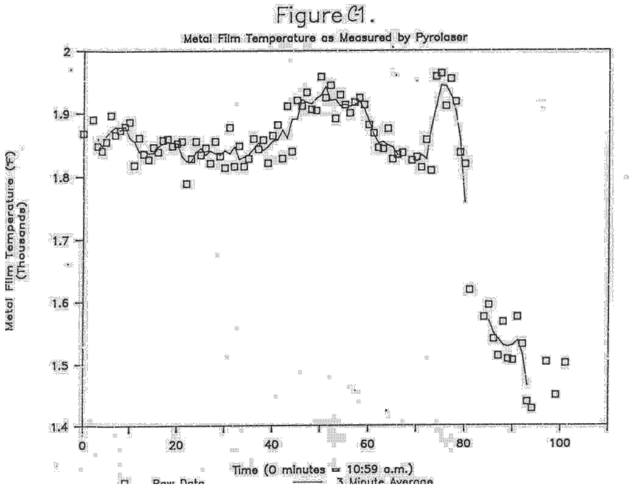
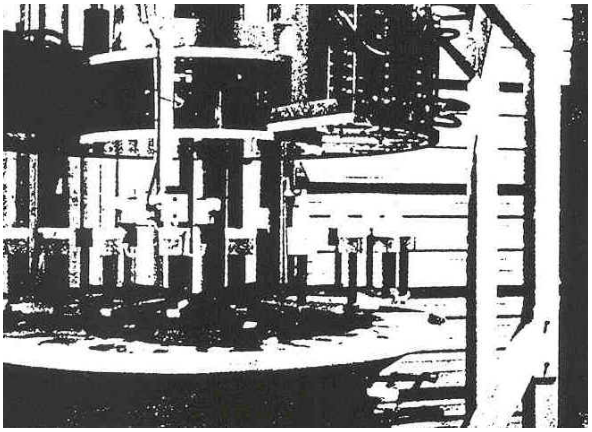
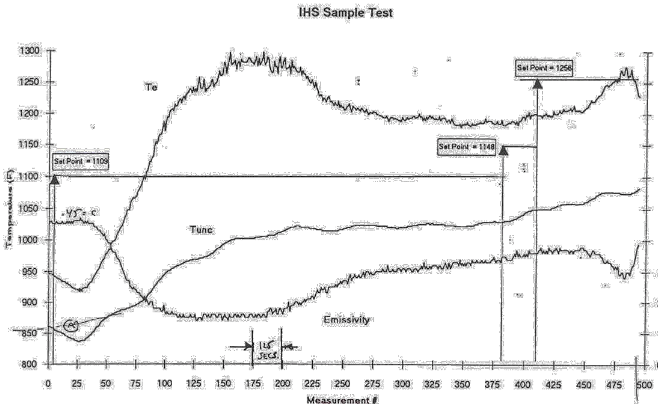


Figure C-1

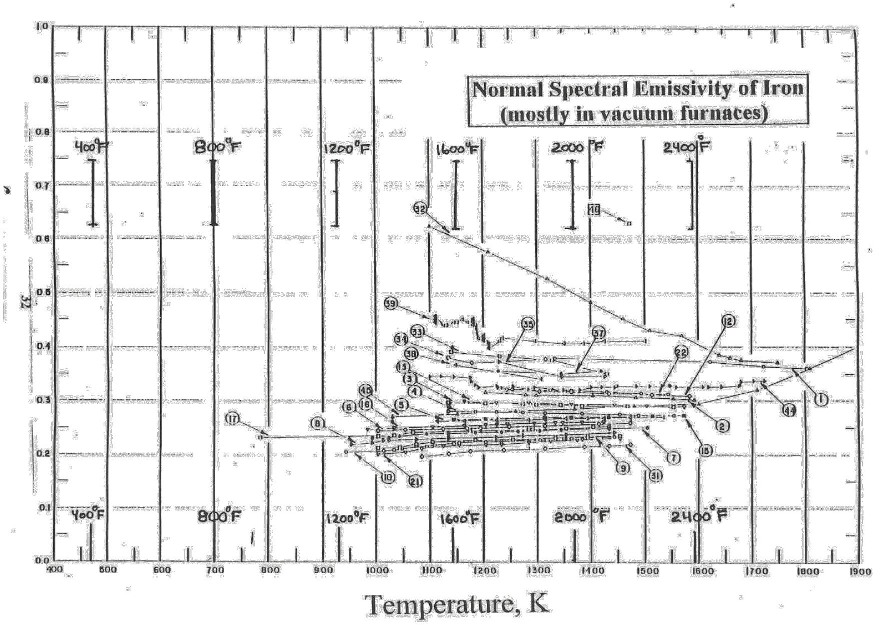


Induction Heating of Aluminum Cylinders

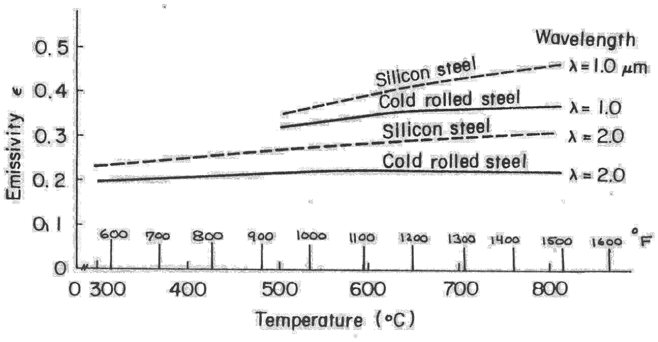


IHS Sample Test

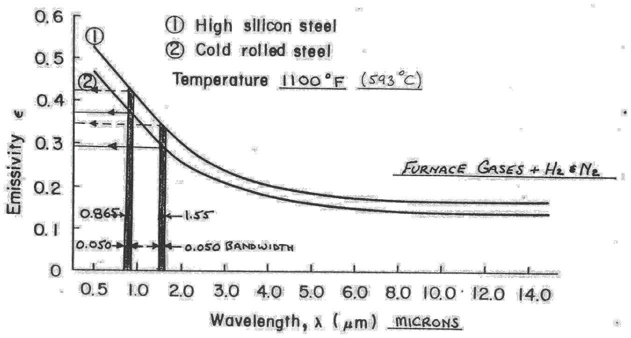
Appendix D - Emissivity Data



Normal Spectral Emissivity of Iron (mostly in vacuum furnaces)



Emissivity of Steel vs. Temperature



Emissivity of Steel vs. Wavelength