A Review of Non-contact Process Temperature Measurements In Steel Manufacturing

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ABSTRACT

Accurate and reliable temperature measurement is necessary for the efficient production of steel and steel mill products. Many steel processing operations such as continuous casting, hot rolling and continuous annealing require the use of non-contact temperature measurement devices because the product moves and cannot be measured by contact means. This paper reviews the requirements for non-contact temperature measurement in several common steel industry processing operations and presents examples of the benefits derived from the introduction of line scanning temperature sensors to these processes.

KEYWORDS: radiation thermometer, Planck, Wein, Raleigh-Jeans, blackbody, temperature, non-contact, measurement, steel industry, process control

1. INTRODUCTION

The production of steel mill products is a series of batch processes in both fully integrated and mini-mill plants. The end results are products that meet the users’ standards for dimensions, mechanical properties, surface quality, shape and corrosion resistance.

Integrated plants make liquid iron and steel from iron ore and coke, whereas mini-mills produce steel from scrap or other cold feed materials. In either case, in the initial iron and steel-making processes contact temperature measurement is the rule and non-contact temperature measurements are mostly related to safety and maintenance rather than process control. Some examples are: blast furnace components, liquid steel transporter vessels and other refractory-lined vessels and containers, which must withstand repeated thermal cycling and mechanical loading.

After the liquid steel is cast into solid form, the remainder of the steel processing depends very much on accurate and reliable temperature measurement by non-contact means to achieve both product properties and manufacturing efficiencies. Figure 1 illustrates the material flow and the many linked processes in steel making. The key parts of solid steel processing are casting, reheating, hot rolling, cold rolling, annealing, temper rolling and coating.

These processes are characterized by a wide span of processing temperatures, ranging from about 1300°C in reheating, down to about 70°C in temper rolling. (Note, while it is customary in most USA steel mills to use the English unit system, the international and scientific nature of the audience for this paper makes SI units the preferred choice).

Steel is typically cast into semi-continuous slabs or bars (750°C - 1000°C). Figure 2 shows a large slab being cut. These are processed in a hot strip mill into hot-rolled products (450°C - 1300°C) as seen in Figure 3, which can be sold as-is or further processed into thinner material by cold rolling (max. ~150°C), with subsequent annealing (500°C - 880°C) and temper rolling (max. ~70°C). Many integrated companies add value by offering tin, zinc and other coated products. Figure 4 is steel exiting a hot-dip galvanizing “pot” (~540°C).
Needless to say, the temperature of the product is critical in all production steps, yet in all of the steps, the material is moving, sometimes at speeds in excess of 15 to 25 meters/second. The use of non-contact temperature sensors is an absolute necessity if processing temperatures are to be controlled within acceptable limits. In some processes these limits are as small as ± 8°C and in others, ± 20°C or more.

The steel industry has been a significant user of spot-measuring radiation thermometers (infrared thermometers, radiation and optical pyrometers) for process measurement and control since the 1950's. Infrared thermal imaging devices, or area measuring radiation thermometers, are used also in many maintenance areas and, now, high accuracy, line-measuring radiation thermometers are being adopted as process tools adjunct to, and possibly replacing, spot-measuring devices.

The higher process temperatures are well within the capabilities of short wavelength, uncooled sensors (down to ~0.9µm). Those used have good stability (about 1 to 3 degrees/year), excellent accuracy (about ±1% of temperature or better) and robust properties, yielding long life (tens of years). Below 450°C, 2.4 µm and 3.9µm thermometers are the types most used. Very few, if any, longer wavelength devices are used in process control for reasons that will become evident from the discussions below. Ratio or two-color radiation thermometers are used primarily in measurements in the open or "Category 2" measurements, as shall be seen below also.

2. RADIATION THERMOMETRY APPLICATION FUNDAMENTALS

The basic physics that underlie radiation thermometry, Planck's law and its various equations, should be almost second nature to most temperature technologists. For those not familiar with these basics, there are several excellent reference works and various manufacturers' literature, which summarize the essentials of the theory. Those details are not covered here.

The application principles for radiation thermometers (RT) are, however, less well understood or appreciated than the basic theory. Yet, the application choices can spell the difference between success and failure in use, especially in steel processing. The concepts and examples of mill process temperature measurements discussed in this paper can be applied to all measurements of opaque object temperature by radiation thermometric means.

The uses of radiation thermometry can be organized into three distinct categories of measurement: measurements of objects in surroundings that are at about the same temperature, in cooler surroundings and in hotter surroundings. Each has its own special measurement information requirements, distinct from the others.

A radiation thermometer of any type (spot, line or area) receives radiation from the object of interest. If the object is opaque like steel and, if the medium between the sensor and the object is non-participating (i.e., neither adds to or reduces the radiation leaving the surface of the object), then the received radiation consists of two combined components:

1. The radiation emitted by the surface, the radiance from the object, \( \varepsilon L_B(\lambda, T) \), and,

2. The superimposed radiation from the surroundings which is reflected by the object surface or, the reflected irradiance upon the object surface, \( \rho \Sigma_k \{ F_k L_I(\lambda, T_k) \} \) coming from each of the (k) sources in the surroundings with its own temperature, \( T_k \), and a geometric view factor, \( F_k \), to the surface.

Where:

- \( \varepsilon \) and \( \rho \) are the spectral, in-band emissivity and reflectivity of the surface, respectively;
$L_b(\lambda,T)$, is the spectral radiance at a wavelength, $\lambda$ (the effective wavelength of the thermometer being used or approximately the center wavelength of a narrow spectral waveband thermometer) from a blackbody at temperature $T$;

$L_i(\lambda,T_k)$, is the blackbody radiance from the $k^{th}$ source at the same wavelength having a temperature, $T_k$, which irradiates the object; and,

$\sum_k$ represents the summation over all $k$ sources.

The net result is that the object appears to have some false, or apparent, temperature, $T_a$, instead of the true temperature, $T$. Depending upon the corrections made and the sensitivity of the sensor to errors in the corrections, the apparent temperature can be higher or lower than true.

While these comments pertain directly to single waveband thermometers, they can also be used, in context, to describe the applications conditions for "two-color," ratio radiation thermometers. In the interest of time, comments on ratio thermometers, however, will be restricted to only practical ones. As most know, the principle advantage offered by ratio devices is the ability to measure accurately when the field of view is incompletely filled or when the view of the optimum target size is partially obscured by something which affects both wavebands by the same amount. They are also very sensitive to changes in the ratio of emissivities in the two measuring wavebands.

Mathematically, the combination of the two components of thermal radiation received by a thermometer sighted on the object can be expressed in the equation:

$$L(\lambda,T_a) = cL_b(\lambda,T) + \rho \sum_k (F_k L_i(\lambda,T_k))$$

(1)

Where the object surface is assumed perfectly diffuse and the terms are defined previously, except for:

$L(\lambda,T_a)$, the combined radiance reaching the sensor
$T_a$, the apparent temperature of the object.

Applications can be categorized into three groups:

1. The object is at about the same temperature as the surroundings,
2. It is much hotter than the surroundings, or
3. It is much cooler than the surroundings.

In Category 1, if the surroundings are about the same temperature as the object, they can be easily combined into one source at the same temperature, $T$, and the equation becomes:

$$L(\lambda,T_a) = cL_b(\lambda,T) + \rho \sum_k L_i(\lambda,T)$$

(2)
Since the object is opaque, $\varepsilon = (1 - \rho)$ and,

$$L(\lambda, T_a) = L_b(\lambda, T).$$

Therefore $T_a = T$ without the need for any correction of any kind. This is also called “measuring under blackbody conditions”. If one were to apply an emissivity correction to a measurement in this category, one would produce a false high temperature reading. The error depends upon the specific instrument and its wavelength response, which is readily calculated from the equations.

An obvious question is how far can the surroundings differ from the object in order for this condition to apply? There is no simple answer, since it depends greatly on the temperature domain, the wavelength response of the sensor and the allowed measurement error. One needs to calculate the conditions for each case to arrive at a set of options to consider.

Note: ratio thermometers can be used in the applications described above, but they offer no measuring advantages, yet can cost considerably more than single waveband thermometers.

Category 2 is the measurement situation most familiar to those who deal with temperature measurement where the temperatures are high, often above incandescence. In this category, the steel is the hottest source in the area; its surroundings temperatures produce radiation but their effects are so small as to be negligible. Due to the non-linearity of Planck’s equation, the second term of equation (1) vanishes and a simpler equation is left:

$$L(\lambda, T_a) = \varepsilon L_b(\lambda, T)$$

This relation shows that an emissivity correction is needed. Also, measurements in this application Category often occur where Wein’s approximation $[L_b(\lambda, T) \sim \lambda^{-5}\exp(-c_2/\lambda T)]$ to Planck’s equation can be used (where $c_2/\lambda T<<1$ in Planck’s equation and $c_2$ is the second Planck radiation constant, $1,4387.69 \mu m \text{K}$), i.e. on the short wavelength side of the peak in Planck’s curve.

The familiar application “rule” of using the shortest wavelength possible for best accuracy applies to this measurement category. The measured, or apparent, temperature is very sensitive to changes in temperature since the radiance is very non-linear in temperature and is only linearly dependent to changes or inaccurate estimates of the emissivity.

Ratio thermometers can also be used in Category 2 applications and they excel in steel mills for several reasons. One, the product is inherently gray*, or very close to it. Two, the mill staff never needs to change the emissivity ratio setting (also called the non-grayness, slope control and other names by instrument suppliers). Three, the lenses can withstand more dirt accumulation than single waveband thermometers before measuring accuracy is impaired. Four, the ratio thermometer tends to selectively measure the highest temperature within its field of view or spatially peak-pick temperatures.

* Gray here means that the spectral emissivity is essentially constant over the wavebands of importance.
Category 3 measurements are the main problem measurements in steel processing because equation (1) applies in full. The object to be measured is cooler than its surroundings. The second term in the equation, the reflected component, is larger than the first, sometimes very much larger due to the non-linearity of the Planck equation.

Three corrections are needed, under the simplest modeling assumption. They are corrections for emissivity, reflectivity and the surroundings' temperature. Also, in this case, the non-linearity of Planck’s equation works against a short wavelength sensor solution because the hotter source radiation can easily overwhelm the emitted radiation signal. A more-nearly-linear relationship between radiation and temperature, such as the Raleigh-Jeans approximation \((\lambda T \gg c_2)\), is required. That approximation applies when the radiation thermometer waveband lies on the long wavelength side of the peak in Planck’s curve, and it is: \(L_b(\lambda, T) \sim \lambda^{-4}(c_1 T / c_2)\), where \(c_1\) is the first Planck radiation constant, \(1.191044 \times 10^8 \text{ W m}^{-4} \text{ m}^{-2} \text{ sr}^{-1}\). The peak in Planck’s curve occurs at about \(\lambda = 3000/T\), for \(T\) in Kelvin and \(\lambda\) in \(\mu\text{m}\).

In large furnaces with uniform temperature regions\(^3\) one simplification that has worked is modeling the reflected irradiances as originating from only one source temperature. Then, equation (1) has only a single second term. In practice, the irradiance source temperature is measurable with a thermocouple (or a wide-angle radiation thermometer) and that value, combined with an assumed emissivity, can be used to correct a thermometer reading an object’s apparent temperature. This is the two-thermometer method described in Section 4.

3. CATEGORY 1 MEASUREMENTS IN STEEL PROCESSING

There are several Category 1 measurements in steel plant applications. Some are quite novel uses of spot radiation thermometers.

A. The Wedge and Gold Cup methods

Sighting a radiation thermometer into the wedge\(^4\) formed by strip turning under (or over) a roll having the same temperature eliminates both emissivity and reflectivity corrections and the effects of any background radiation because of the multiple reflections that occur within the wedge.

A sketch of the geometry involved is shown in Figure 5a. In essence, the wedge formed by strip passing around a roll yields an effective emissivity of close to 1.0, if the roll and strip are at about the same temperature. It also means that since \(e \sim 1\), then \(p \sim 0\), and little to no radiation can be reflected, even from nearby brighter sources.

The wedge or "multiflex" method has been applied to a number of continuous strip annealing furnaces with a great deal of success. It simplifies the measurement of strip temperature under very demanding conditions and is in use in many plants worldwide, including one at LTV Steel in Cleveland, Ohio

A very similar method was developed many years ago using a highly reflective, hemispherical mirror\(^5\) or "Gold Cup", sketched in Figure 5b. When it is placed near a surface it blocks out any
reflecting sources and creates multiple reflections of the surface, thereby enhancing the emissivity and causing it to appear closer to 1.0 to a thermometer sighted into the enclosure formed by the mirror and the surface. Until recently, its use had been limited to portable, reality-check types of measurements.

An interesting variant on the original Gold Cup method was reported at Thermosense XIV, in 1992 by Stelco (Steel Company of Canada) and NRC (The National Research Council of Canada). The method involved the use of a conical gold-plated reflector placed in a strip annealing furnace close to the strip with a radiation thermometer sighted onto the steel through a small hole in the reflector.

B. Other Category 1 Applications

1. Some reheat and batch heating furnace soak zones have temperature differences between furnace and product that are less than the required measuring tolerance. Common practice, however, is to use thermocouples which require less maintenance than radiation thermometers. The deciding issue is life cycle cost.

2. Closed-ended sight tubes are often inserted into furnace environments and radiation thermometers are sighted down into them. They are often used as a lower life cycle cost alternative to a platinum alloy thermocouple. The thermometers, if properly maintained and periodically cleaned and checked, perform well and provide measurements for many years.

4. CATEGORY 2 MEASUREMENTS IN STEEL PROCESSING

There are perhaps more measurements of this type in steel processing than all other radiation thermometer measurements combined. In all cases, the steel is the hottest material in the region of measurement and reflections from cold surroundings can be neglected. However an approximately correct, though not necessarily perfect, emissivity correction is necessary. Without the correction the thermometer will read an incorrect, systematically low temperature. The use of short wavelength thermometers minimizes the error, but using both the emissivity correction with a short wavelength thermometer produces the best measurement.

A. Hot Rolling

There are many locations on a hot rolling mill where temperature is measured as part of the overall mill control system. Hot strip mills are one of the more complex operations. In Integrated Steel Mills, strip is reduced in thickness from 220 to 250 mm to about 2 to 12 mm, depending on product need. The slabs are processed one at a time, proceeding from furnace discharge to a roughing operation, with 4 to 6 individual reducing operations, to a finishing reduction in a tandem, multi-stand operation comprised of 4 to 7 individual reducing stations. It then proceeds down a long cooling table where water is applied and then the strip is collected into a coil. A slab about 10 meters in length and 220 mm thick, processed into a strip 2.5 mm thick is more than 880 meters long at the end of the operation. The whole process takes less than 6 minutes, typically, and three to four slabs are in the mill at any one time during peak production. Controlling the speeds and forces on each mill stand, applying the required cooling and operating all the associated controls to monitor and adjust thickness requires fast acting, precision temperature measurement to provide inputs for fast responding, real-time computer control systems. Modern thermometer response times are 10 milliseconds or less.
Typical process temperatures range from about 450° to 1300°C, well within the capabilities of short wavelength (1.6μm units below 600°C and ~ 0.9 μm above) spot-measuring radiation thermometers. The thermometers used on a hot rolling mill are almost universally single waveband or ratio types operating at narrow wavebands near these two wavelengths. They are applied with rugged, cooled mounting jackets, air purges and resemble something more like a plumber's nightmare than the precision measuring sensors they are. Figure 6 shows a sketch of a typical installed unit. The actual measurement sensor is inside a cooled, cast metal housing.

The emissivity setting on a single waveband thermometer for steel rolling is not critical as long as it is in the correct domain for iron oxide (Fe₂O₃), the material on the surface. The spectral emissivity of iron oxide, over a rather wide wavelength range (0.8μm to 5.0 μm), lies in about the 0.78 to 0.88 region. Picking a mid-point value of 0.82 means that the maximum radiometric measuring error will be about 5% if the actual emissivity lies nearer the extreme values rather than the mid-point. As pointed out by Nutter in Reference 2, the temperature error, (dT/T), for a radiation thermometer operating at a wavelength, λ, can be related to the radiance error, (dL/L), by the relation:

$$\frac{dT}{T} = \left[\frac{\lambda T}{14388} \right] \frac{dL}{L}$$

Where λT has the units micrometer-Kelvin.

At a λ of 0.9μm and a temperature of 1000°C, the error due to emissivity being at the extreme rather than the mid-point setting is approximately ±5°C. If a wavelength of 3 micrometers was used, it is easy to appreciate from the linear relation shown in equation 5 that the likely range of errors would be about ±15°C. Mill tolerances today are about ±12°C and likely to become less.

B. Other Category 2 Applications.

1. Continuous Caster: within the strand and exiting product after cut-off. Measurement conditions on a large slab caster are similar to those on a hot strip mill. There are, in addition, challenges of physical access, equipment survival, need for regular maintenance and on-site calibration verification means.

2. Induction-heated tubes, bars, slabs and plates, during heating. Usually very straightforward except for radio frequency (RF) shielding of any measuring electronics from RF interference. Good grounding technique and the use of fiber optics to help keep the electronics far away from the RF sources are some practical measures used to reduce the interference.

3. Galvannealing. One of the most difficult Category 2 applications in recent years has been galvannealed strip because of the large emissivity changes (from 0.15 to 0.85) that occur during the formation of an iron-zinc alloy phase from a pure zinc coating. This has been solved by no less than four radiation thermometric techniques in the last 10 years and produced one novel application of a fluorescent powder measurement application. This is one of the few, special Category 2 applications requiring extra effort to solve.

Hot slabs exiting a reheat furnace still need a reliable sensor. Loose oxide or scale that partially obscures the hot, tightly adherent oxide complicates this measurement, as do patches of thicker,
adherent, scale. Most mills rely on a downstream measurement with back calculation from a thermal model to estimate the exit temperature.

4. CATEGORY 3 MEASUREMENTS IN STEEL PROCESSING

These are the applications which have proven the most difficult to solve, and all measurement solutions have not been satisfactorily sound. Most workable solutions revolve around converting the measurement to a Category 1 or 2 measurement, with a few exceptions.

A. Strip temperatures in Continuous Anneal Furnaces

The most demanding steel mill applications from a measurement perspective are in the continuous annealing of strip products. In these applications, the strip is contained in a series of connected furnaces and cooling sections, all, or nearly all, of which contain a reducing gas, usually a hydrogen-nitrogen mixture. Typical strip speeds are about 1 to 9 meters/second and the strip temperature ranges from about 480°C to about 870°C. Measurement difficulties arise from two facts: 1. In most of the furnace the steel is cooler than its surroundings, and, 2. The steel normally has a reduced surface with a low and very wavelength-sensitive spectral emissivity. (This is in sharp contrast to most other applications where the strip is oxidized and has a relatively high and non-wavelength dependent spectral emissivity).

A plot of the spectral emissivity of some typical reduced steel strip is shown in Figure 7.

These problems were studied in great depth and several measurement solutions proposed by T. Iuchi at Nippon Steel Company in the 1970's. He principally proposed shielding a small portion of the strip from reflection with a large, cooled, low-reflectivity shield and thus converting the measurement to a Category 2 measurement by eliminating the reflections.

This method assumes the emissivity is always at a nominal 0.25 or 0.30 value at 2.1 or 1.6 μm, respectively. But that is not always the measuring condition. Unremoved oxide, dirt, stain and several other complications can and do arise to change emissivity. The change is unpredictable. The end result of such complications can be a sudden shift of emissivity from 0.3 to 0.8 or 0.95, depending upon the source of the emissivity change.

The result of an increase in emissivity is that the strip will measure hotter than true. The control system will subsequently reduce the heating input, which often makes matters worse, in terms of annealing.

The wedge method, described in Section 2, eliminates the varying emissivity limitations of the cooled-reflector technique in those cases where the strip goes around a roll. But that cannot be applied everywhere. There are numerous locations in existing furnaces where the wedge method is inadequate and the cooled reflector is not a satisfactory solution.

There are still some needs for process temperature measurements in continuous anneal furnaces especially at the exit of heating and cooling zones in horizontal furnaces which have not been met.

B. Other Category 3 Measurements

The relatively high background reflections of the entry and middle zones of billet and slab reheat furnaces have been solved by the two-thermometer method (since the emissivity is reasonably stable). In this approach, as mentioned above in Section 2, the assumed single reflection source temperature is measured with a thermocouple. The atmosphere, usually a participating one (i.e.,
one that either adds to or reduces the radiation leaving the surface of the object and reaching the sensor), is rendered non-participating through use of a 3.95 μm measuring waveband, which just also happens to meet the Raleigh-Jeans criteria for typical furnace temperatures. Equipment for this application is offered by several vendors in the USA, but today most US steel mills instead use computer-modeling to predict product surface, as well as bulk, temperature inside reheat furnaces. More work has been done in Europe where upwards of 4% energy savings have been reported using the method\(^\text{14}\). Perhaps additional fuel savings or higher furnace yield demonstrations like this will produce more interest in direct steel temperature measurement elsewhere.

6. LINE-MEASURING IR THERMOMETER IMPROVEMENTS

In both hot rolling and continuous annealing of strip, it is important to maintain product uniformity across the strip width to the very strip edges, in addition to along the length. Since spot radiation thermometers have historically been used to measure only on the centerline of the strip, it stands to reason that either multiple sensors or some transverse measuring technique is needed to achieve measurements across the width. The use of line-measuring thermometers has developed rapidly in the past few years as several high quality devices have come onto the market.

One very specific need, important with advanced finishing mill control, is high-speed thickness measurement across the width. This measurement can only be achieved with required accuracy if all temperature variations across the width are also taken into account.

A well-defined measurement spot size (or line thickness) and accurate calibration are key product features required for accurate temperature measurement with a line-measuring thermometer. Both features are best achieved when the minimum required measurement spot size meet radiometric collection efficiency of 98% or better. This is quite different than the definition of the familiar instantaneous field of view (IFOV) of thermal imaging that is based on the 50% criteria following visual contrast requirements.

The measurements of the line-measuring IR thermometer pose no significant problem in Category 2 measurements and a method to verify on-line measurement accuracy has already been demonstrated.\(^\text{15}\) An example of a high accuracy 2-D thermal image of hot strip, created by accumulating multiple scans from a line-measuring thermometer, is shown in Figure 8. The vertical axis represents the width of the steel while the horizontal axis represents the length. In this thermal image, the strip temperature has been measured with the same uncertainty as the centerline temperature measurement made with a spot thermometer.

Line temperature measurements in Category 3 applications, such as continuous anneal furnaces have yet to adopt the wedge method and thus far have had to accept relative temperature gradients or estimated absolute values based on assumed emissivity values.

7. DISCUSSION

Steel mill processing requires accurate and reliable temperature measurements under not only demanding environmental conditions but also under all three categories of measurements possible. Only rugged, high-quality, non-contact temperature sensors meet such requirements.
It should be obvious that the use of non-contact temperature sensors in steel processing is quite a mature technology. Yet, in spite of accumulated know-how and years of experience there are still several places, where improvements in spot temperature measurement technology are needed. Prime examples are slab temperature exiting reheat furnaces and some continuous strip anneal furnaces where Category 3 measuring conditions prevail.

Now, too, line-measuring thermometers capable of producing temperature maps of a product surface are beginning to be adopted since they produce measurements that are as accurate and reliable as the spot sensors. It is likely that they will become more widely used. For example, measurement of actual transverse temperature profile in continuous strip annealing and galvannealing of strip are two uses where new measurement capabilities could prove beneficial. Additional equipment improvements will need to perform as well, if not better than, these early devices. Yet they must have traceable calibration which can be easily verified. They will also need to remain maintenance free for long periods and still be easy to swap out or repair when the need arises.

It is also likely that area temperature measuring devices will soon be used to provide inputs for steel processing control systems. Some applications such as reheat furnace exit temperatures may well be achievable by combining area temperature measurement with vision system processing. Then, too, the new measurement capabilities of thermal wave imaging to locate sub-surface defects should have some process and/or quality monitoring uses in steel. Any new use will mean some radical improvements in equipment design and its long-term reliability. The building blocks for these improvements, i.e. uncooled short, mid and long wavelength detector arrays, are starting to appear in new designs. But the new units will still face the same physical and measurement requirements as line-measuring devices. This should offer new opportunities and challenges in temperature measurement equipment design well into the next millennium.

8. REFERENCES


10. Private communication, LTV Steel Co.


Figure 1. Chart of Steel Processing

Simplified Sketch of Integrated Steel Operations From Raw Materials To Shipping
Figure 3. Slab Exiting Hot Strip Mill
Reheat Furnace
Figure 4. Freshly Zinc-Coated Steel Strip Exiting Zinc “Pot”
Figure 5. a) Wedge Geometry, b) Gold Cup Sketch—Both Methods Depend Upon Multiple Reflections

a) Wedge Method:
RT Sights Into Roll-Strip Wedge.
Side View.

b) Gold Cup Method: Gold-Plated, Hemispherical Mirror That Creates Multiply Reflected Beams, Enhances the Emissivity of Surface As Viewed Through a Small Hole in Mirror.
Figure 6. Sketch of Ruggedized RT Installation With Cooled Enclosure and Purged Sight Tube
Figure 7. Spectral Emissivity Of Reduced Steel

Emissivity Of Clean, Cold-Rolled Carbon Steel Vs. Wavelength
After T. Iuchi: ASTM STP 895 (1985)
Figure 8. Precision Thermal Image Generated by Line-Measuring RT In A Steel Mill
Note Temperature in Deg. F, Steel Moved Right to Left (Time Axis), Line Temperature Scans From Top To Bottom Are Plotted with False Colors From Scale Yielding 2-D Temperature Map