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Real-Time Melt Temperature Measurement in a Vacuum Degasser Using Optical Pyrometry

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I. Subject Categories *(list primary one first)*
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J. Description/Abstract

The objective of the research was the development of a fiber-coupled, optical pyrometer for continuous melt temperature measurement in a vacuum degasser that reduces process time, enhances process control and eliminates manual or robot-operated thermocouples. Through the live testing performed at US Steel's Edgar Thompson Works, the challenges associated with making optical temperature measurements in a vacuum chamber were identified. As a result of these challenges it was determined that continuous temperature monitoring in RH-type degassers was not a viable alternative to standard immersion thermocouples. The project was not successful.

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Title and Subtitle:

AISI/DOE Technology Roadmap Program for the Steel Industry
TRP 0034: Real-Time Temperature Measurement in a Vacuum Degasser Using Optical Pyrometry

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Abstract

The objective of the effort described herein is the development of a fiber-coupled, optical pyrometer for continuous melt temperature measurements in a vacuum degasser that reduces process time, enhances process control, and eliminates manual or robot-operated thermocouples. Such data are crucial for efficient degasser operation and to downstream processing of the heat, especially when a continuous caster is in use. A lance-based sensor that can measure melt temperature automatically before and after oxygen blowing has the potential to significantly reduce process time and consumables cost.

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American Iron and Steel Institute
Technology Roadmap Program

FINAL REPORT

REAL-TIME MELT TEMPERATURE MEASUREMENT IN A VACUUM DEGASSER USING OPTICAL PYROMETRY

by

Process Metrix LLC — Peter Hues, Michel Bonin
US Steel — William Federhoff
Berry Metal Company — Nick Rymarchyk, Todd Smith

February 14, 2007

Work performed under Cooperative Agreement No. DE-FC36-97ID13554

Prepared for
U.S. Department of Energy

Prepared by
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Technology Roadmap Program Office
Pittsburgh, PA 15220

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PROJECT DESCRIPTION AND MOTIVATION

The objective of the effort described herein is the development of a fiber-coupled, optical pyrometer for continuous melt temperature measurements in a vacuum degasser that reduces process time, enhances process control, and eliminates manual or robot-operated thermocouples. Such data are crucial for efficient degasser operation and to downstream processing of the heat, especially when a continuous caster is in use. A lance-based sensor that can measure melt temperature automatically before and after oxygen blowing has the potential to significantly reduce process time and consumables cost.

EXECUTIVE SUMMARY

The degasser is a common ladle treatment process for producing low carbon steel. Melt temperature is a crucial input to the model used to define the heat recipe and to subsequent processing of the heat, especially if a continuous caster is in use. Given this emphasis, a lance-based optical pyrometer for real-time measurement of melt-temperature was developed and tested at US Steel, Edgar Thomson Works.

The pyrometer was fiber-optically coupled to the melt surface through the degasser oxygen lance manufactured by the Berry Metal Company. The sensor has an intrinsic measurement uncertainty of less than 1°F. Melt temperature measurements made under stable conditions in the degasser were within 22° F (absolute difference) and 23° F standard deviation. The average difference is slightly higher than what we had hoped to achieve, though the absolute minimum difference that is theoretically possible, taking into account the uncertainty in measurement of both immersion thermocouple and optical devices, is on the order of 15-20 °F.

Through the testing performed at US Steel's Edgar Thomson Works, we have identified the challenges associated with making optical temperature measurements in the vacuum chamber of an RH-type degasser. These include the following:

- Accurate measurements are not possible during the first 3-5 minutes after the vacuum is established due to the combustion of carbon monoxide (CO).
- All temperature-impacting operations are performed in the vacuum chamber. Due to its relatively small mass, the temperature of the steel in the R-H degasser is more heavily impacted by these operations than is the temperature of steel in the ladle.
    - It can take up to 10 minutes after oxygen is blown for the bath temperature in the vacuum chamber to reach equilibrium with the remainder of the bath.
- Accurate measurements are not possible when the wall mounted burner is on (oxygen is injected).

As a result of these challenges, it was decided that this approach to continuous temperature monitoring in RH-type degassers was not a viable alternative to standard immersion thermocouples. We have therefore terminated the project.

1. Statement of the Problem

1.1 Background

The vacuum degassing furnace is a practical and efficient means for producing ultra-low carbon steel through ladle treatment. As with all ladle treatment operations, temperature control in the ladle is crucial to downstream processes, especially in plants where a continuous caster is in use. To produce the desired grade of steel, process models based on melt temperature and chemistry are used to determine degassing duration, amount of additive addition (if any) and the amount of oxygen blowing required. Melt chemistry and temperature are typically measured immediately after tapping from the iron conversion vessel (Basic Oxygen Furnace (BOF), modified Basic Oxygen Process Furnace (Q-BOP) or Electric Arc Furnace (EAF)) and often again at the ladle treatment station. Because of the importance of melt temperature monitoring during vacuum degassing, the development of a lance-based, optical pyrometer was proposed for real-time temperature measurements of melt temperature in the degasser before and after oxygen blowing.

In our proposal, we had originally suggested that the development of a two-color pyrometer be based on Thermal Imaging Pyrometer (TIP) sensor technology developed by Sandia National Laboratories, Bethlehem Steel, and Process Metrix (PMC). In actuality, over the course of the project we determined that the measurement accuracy of the original TIP sensor was far below that needed for this application. As a result within the project, completely new electronics were developed, optimized and tested and integrated with the RTSteel software program.

The TIP sensor was developed under a previous DOE/AISI-funded activity as a lance-based sensor for BOF melt temperature measurements [1]. Housed in the center of the oxygen lance, it views the melt through a small diameter, dedicated port in the lance tip or through one of the oxygen nozzles. The TIP sensor incorporates a hybrid optical package that includes a Closed Circuit Digital (CCD) camera for viewing and photodiodes for two-color temperature measurement. A single, coherent fiber bundle collects light for imaging and pyrometry. Within the optical train, the collected light is divided into input signals to the color camera, and to each photodiode. A pinhole in the optical train restricts the temperature measurement to the central 10% of the collected image. A micro-controller in the sensor communicates with the host computer and controls all probe functions. Digital communication (RS-422) eliminates data transmission losses and provides rugged, noise free data transmission to a host computer and customized software package that displays temperature in real time.

The ratio of image intensities (brightness) at each wavelength determines the temperature of the surface or object in the field of view of the camera system according to the following relation:

$$T = \frac{-C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}{\ln\left(\frac{I_{\lambda_1}}{I_{\lambda_2}}\right) - \ln\left(\frac{G_1}{G_2}\right) - \ln\left(\frac{\varepsilon_{\lambda_2}}{\varepsilon_{\lambda_1}}\right)} \quad (1)$$

Equation (1) is the well-known two-color temperature equation [2-4]. λ_1 and λ_2 represent the two wavelengths of spectral filtering, $I_{\lambda 1}$ and $I_{\lambda 2}$ are the intensities measured at each wavelength, C_2 represents the second radiation constant, $I_{\lambda 1}$ and $I_{\lambda 2}$ represent the emissivities of the surface at the two wavelengths λ_1 and λ_2, and G_1 and G_2 are calibration constants. Over the narrow wavelength range between λ_1 and λ_2, the emissivities are assumed to be equal and this term drops out of Eq. (1).

1.2 Degasser Combustion Lance (DCL) Sensor Configuration

The DCL Camera platform that houses the TIP sensor was developed to image the interior of the vacuum degasser during processing. Existing camera systems mounted in the dome of the degasser are frequently occluded by metal splash back into the dome when the vacuum seal is inadvertently lost at the melt-vessel interface. A lance-based system is particularly attractive as the purge gas/oxygen flow prevents contamination of the viewing window.

Two versions of the lance camera are currently in operation in the steel industry. The first incorporates an in-lance camera at the lance tip. The second uses a long-length coherent fiber bundle to convey the image from the lance tip to a camera mounted at the top of the lance. The effort described herein incorporates the latter configuration, as the two-color pyrometer hardware/electronics are too large for an in-lance solution. The sensor views the vessel interior through a window located behind the throat of the single oxygen nozzle. In the event of window fouling, the window can be easily replaced by plant personnel without removing the lance from the carriage.

2. TECHNICAL APPROACH

2.1 Sensor Electronics Development

2.1.1 Evaluation of Existing System

The project began with an assessment of the existing two-color pyrometer system, constructed previously under the American Iron and Steel Institutes' (AISI) Advanced Process Control program. Our primary concern was system stability, more specifically system noise as pertaining to the accuracy and repeatability of the temperature measurement. To this end, we evaluated the probe noise level in the absence of any input signal and found it to be unacceptably high; temperature measurement uncertainties of 4-8°F were predicted using these electronics due to this effect alone.

This unacceptable result necessitated the construction of new electronics, a possibility that was noted at the project kick-off meeting. A new chip set was selected for minimum noise generation and optimized two-color pyrometer performance. The chip set incorporates a dual trans-impedance amplifier. Since we already had all necessary firmware required to communicate with this device, the same micro-controller used in the original design was initially retained in the revised implementation. However, new firmware was necessary to operate the new analog to digital converter (A/D) selected for the input configuration.

As part of the reconfigured electronics, new Able code was developed for the Programmable Logic Device (PLD) that controls data acquisition from the two-channel integrating A/D. Fundamentally, the high clock rates of the PLD are required for precise timing control of the A/D. In addition, the PLD is the core electronics controller, and is responsible for the following:

- Setting the integration timing for the A/D,
- Controlling the integration capacitance of the A/D,
- Synchronous data acquisition from the A/D,
- Buffering the 40-bit serial data stream to the micro controller.

PLD mode control is accomplished with a Basic Stamp, a simple microprocessor that was used on prior versions of the TIP sensor. In parallel with PLD code development, Basic code was written to:

- Communicate and receive data from the PLD,
- Read board temperature,
- Convert the bit-stream to two sixteen-bit values,
- Communicate the two sixteen-bit values to the RTSteel program over an RS-485 interface.

The data from the Stamp is received at a standard PC operating RTSteel, a Windows-based software program written by PMC. This code calculates a two-color temperature based on the sixteen-bit values obtained from the Stamp. The program also reports board temperature, and is capable of reading various process signals (such as oxygen flow rate, lance height, etc.) over a National Instruments interface.

2.1.2 Signal-to-Noise Determination

The first TIP sensors tested in a BOF used 8-bit camera systems to calculate temperature. Best performance of an 8-bit system (256 counts) in a 1-count noise environment has a corresponding error of ~16 °F. Since a zero-noise environment is not likely, these early systems had little chance of achieving the required accuracy. We subsequently migrated to a 16-bit system, which had a theoretical (1-count) limit of less than 0.1 °F. In practice, we could not achieve this level of uncertainty because of high input noise to the A/D's and because of inherent A/D noise. Consequently, the prior-generation systems exhibited approximately 150 noise counts, which equates to a measured temperature uncertainty of ~8 °F; marginal uncertainty in comparison with immersion thermocouples.

With both the PLD and Basic Stamp systems functional, we determined that the noise level on the input channels was ±50 counts out of 65,535. Some reduction in noise was realized by adding capacitance to the power supply, and by reconstructing the reference voltage circuit used by the A/D. However, even after completing these modifications, the noise level was as high as ±40 counts out of 65,535. While this equates to only ~4.6 °F uncertainty, improved performance could be realized by averaging. Assuming the noise is normally distributed, noise levels should fall as the inverse square root of the number of samples averaged.

Unfortunately, the Basic Stamp micro-controller is limited to 16-bit arithmetic. While an accumulator could have been developed using the Basic Stamp by manually accounting for the carry-over bits, a decision was made to replace the Basic Stamp with an updated micro-controller that has become a standard at PMC. This new micro-controller offers full 32-bit arithmetic, is programmed in C, and has full support libraries for communications. PMC's long term plan included migrating to the new micro-controller once proof-of-principle had been established at the research level. So, we undertook this activity in advance of demonstrating feasibility. We believed that the need to reduce noise warranted the change at that point in the project. A board revision was implemented, and the new boards populated with the 32-bit micro-controller.

With the new micro-controller in place, the system is capable of averaging 100 samples in approximately 300 milliseconds. Noise levels dropped to ~±2 counts out of 65,535, which equates to ~0.2 °F. At this level of uncertainty, electronic noise is no longer a significant fraction of the overall uncertainty, and PMC has accomplished the original objective that initially motivated the electronics re-design. The final revision also facilitated an Ethernet interface that simplifies field installation.

2.2 Opto-Mechanical

In parallel with the electronics development, a coherent fiber optic bundle was purchased to conduct radiation emitted by the melt through the lance body to the two-color pyrometer. New mechanical hardware was required to integrate the fiber and upgraded camera system. The design includes a pellicle beam splitter. This element replaces a conventional glass element used previously, whose two-sided reflection resulted in a secondary ghost image observed at the camera.

All hardware was fabricated and tested in our facilities prior to installation at US Steel's Edgar Thomson Works. Drawings, schematics and firmware source code have been provided to AISI in CD-ROM format.

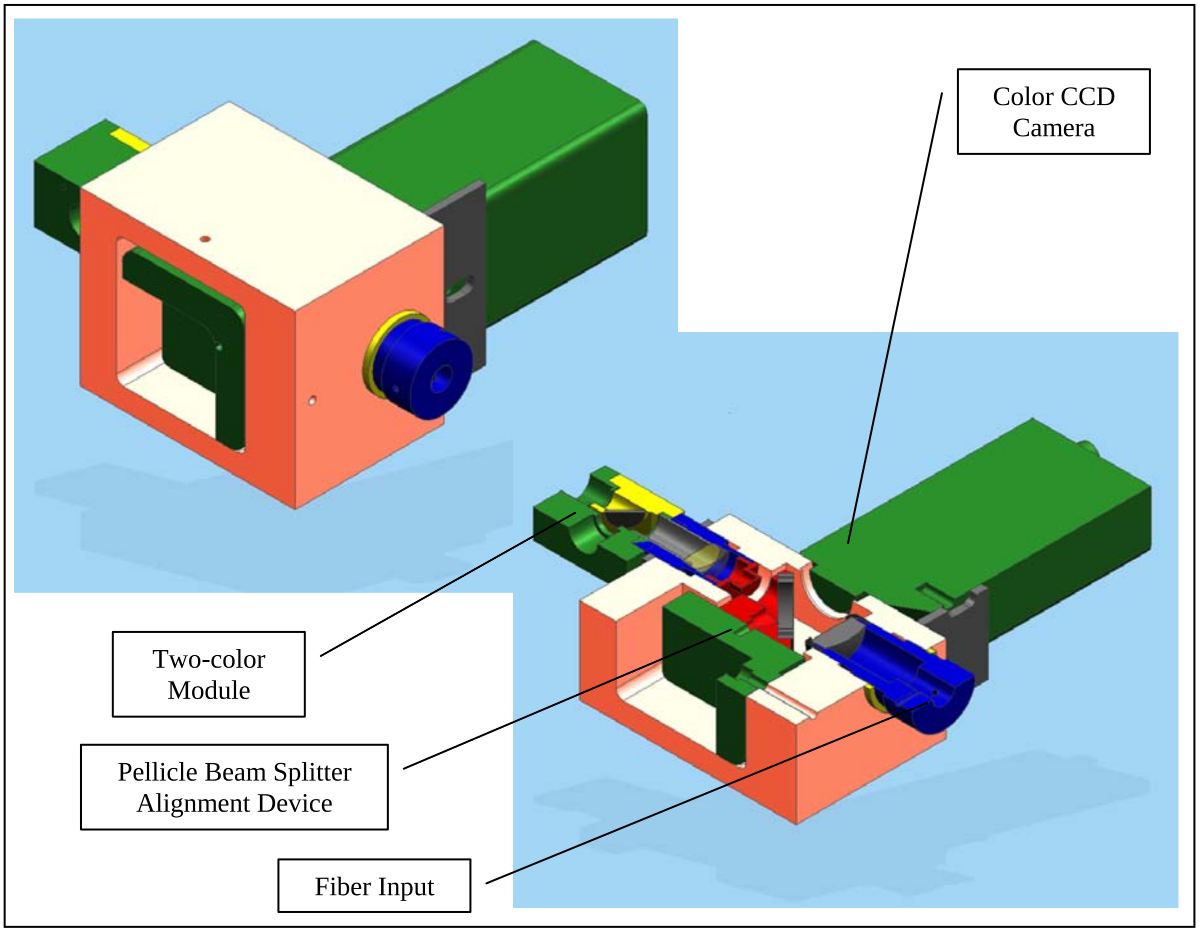

Figure 1. Opto-mechanical design illustrated in 3-D CAD. System integrates fiber input, two-color pyrometer and color camera for imaging.

3. RESULTS

In our original proposal, initial field trials were to occur at LTV Steel, Cleveland Works, where a lance-based camera system was already in operation at the degasser. Once the pyrometer had demonstrated good agreement with immersion thermocouple data, a beta-site installation was to be completed at US Steel, Edgar Thomson Works. This approach was envisioned to enable a more thorough evaluation of the pyrometer under a broader range of degasser operating conditions. Unfortunately, LTV Steel operations ceased during the project, and all field trials were conducted at US Steel's facility.

After test and evaluation of the system at Process Metrix, the unit was installed in the degasser lance at US Steel's Edgar Thomson facility. Two field trials were performed at the degasser to assess measurement accuracy at various points in the degassing process. All optical temperature measurements were made in comparison with immersion thermocouple measurements also made at the degasser measurement station.

A typical time-history of the data recorded during degassing is illustrated in Figure 2. In these figures, the green and blue traces represent the 750 and 950nm intensity signals, respectively. The bold red line represents a ten-second moving average of the measured temperature.

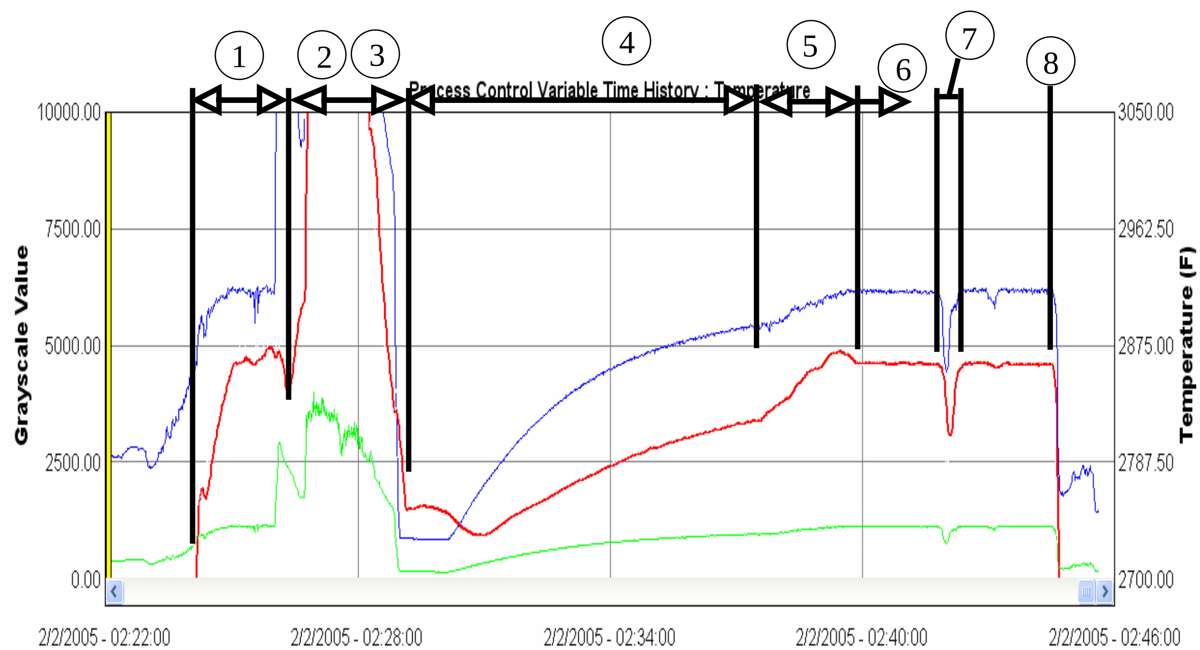

Figure 2. Typical intensity and temperature traces for a complete heat in which oxygen was added near the beginning of the heat.

During degassing, specific steps in the degassing process are reflected in the data collected by the instrument. These are described in the order they occurred, as follows (refer to the numbered balloons above the strip-chart output of Figure 2):

1) Snorkels are plunged into the bath and vacuum is established – CO comes out of solution and combustion reaction results – no optical measurement possible
2) Oxygen is blown – no optical measurement possible.
3) Oxygen blow ceases – bath temperature in the vacuum chamber falls sharply.
4) Bath temp starts to rise.
5) Aluminum is added – Temperature rises as aluminum bonds with oxygen in the bath.
6) Bath temperature reaches thermal equilibrium between vacuum chamber and ladle.
7) Alloy batch is added – Temperature drops sharply as light intensity decreases momentarily.
8) Vacuum is turned off and the ladle is removed.

A similar plot of sensor output versus time is illustrated in Figure3, though this time without oxygen blowing.

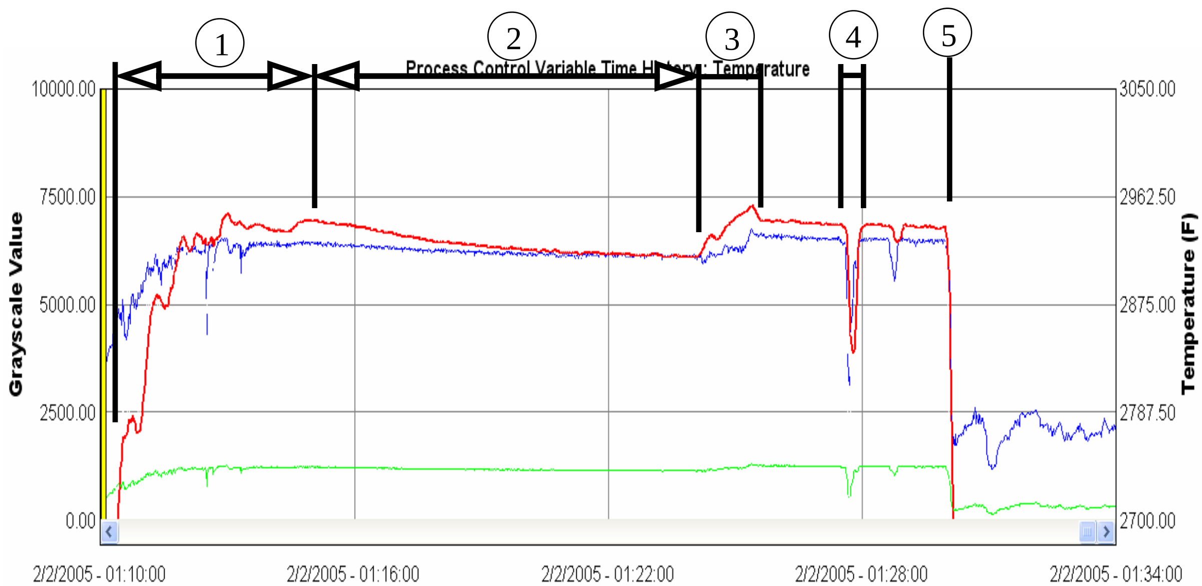

Figure 3. Typical intensity and temperature traces for a complete heat in which no oxygen was added early in heat.

The following describes the order of events associated with Figure 3:

1) Snorkels are plunged into the bath and vacuum is established – CO comes out of solution and combustion reaction results – no optical measurement possible.
2) Combustion ceases and temperature begins to drop, approaching thermal equilibrium with steel in the ladle. It is suspected that the temperature decay is due to radiant emissions from the walls of the vacuum chamber that relax over time.
3) Aluminum is added – Temperature rises as aluminum bonds with oxygen in the bath.
4) Alloy batch is added – Temperature drops sharply as light intensity decreases momentarily.
5) Vacuum is turned off and the ladle is removed.

Finally, Figure 4 represents the intensity- and temperature-time history for a heat in which multiple alloy additions were made.

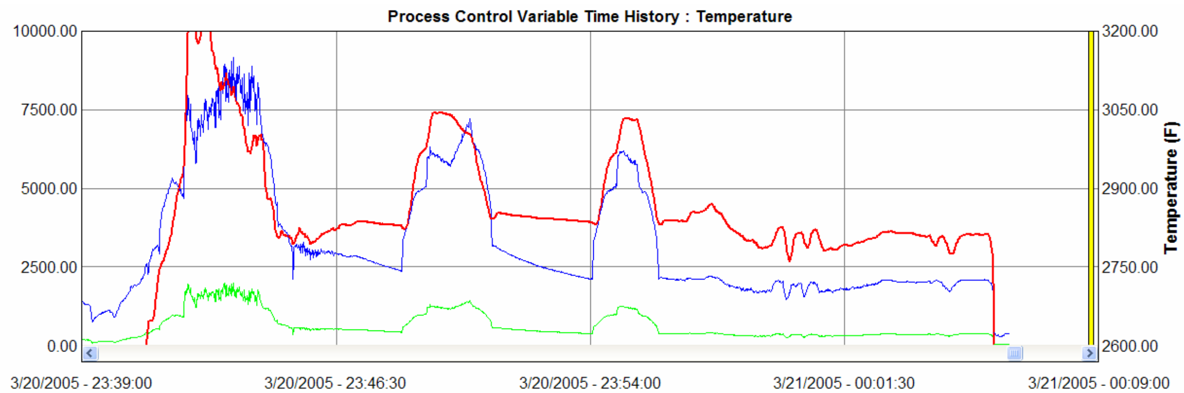

Figure 4. Typical intensity and temperature traces for a complete heat in which multiple additions were made.

4. Discussion of Temperature Measurement Results

In total, 72 temperature measurements were made over 13 heats. Temperature measurements made during material or oxygen addition are known to be inaccurate, and were therefore eliminated from the data set. Due to combustion reactions that take place during the first 3-5 minutes of each heat, optical measurements taken during this time frame were also culled from the data set. In addition, potential outliers were removed, leaving a refined sample set of 52 measurements.

The refined data set shown in Figure 5 suggests good agreement between the two-color pyrometer measurements and those made with immersion thermocouples. The standard deviation of the difference between two-color pyrometer temperatures and those made with the thermocouple is 23°F. The average difference between the two is 22°F. We believe that the discrepancies are caused primarily by steel bath temperature gradients between the vacuum chamber and the ladle.

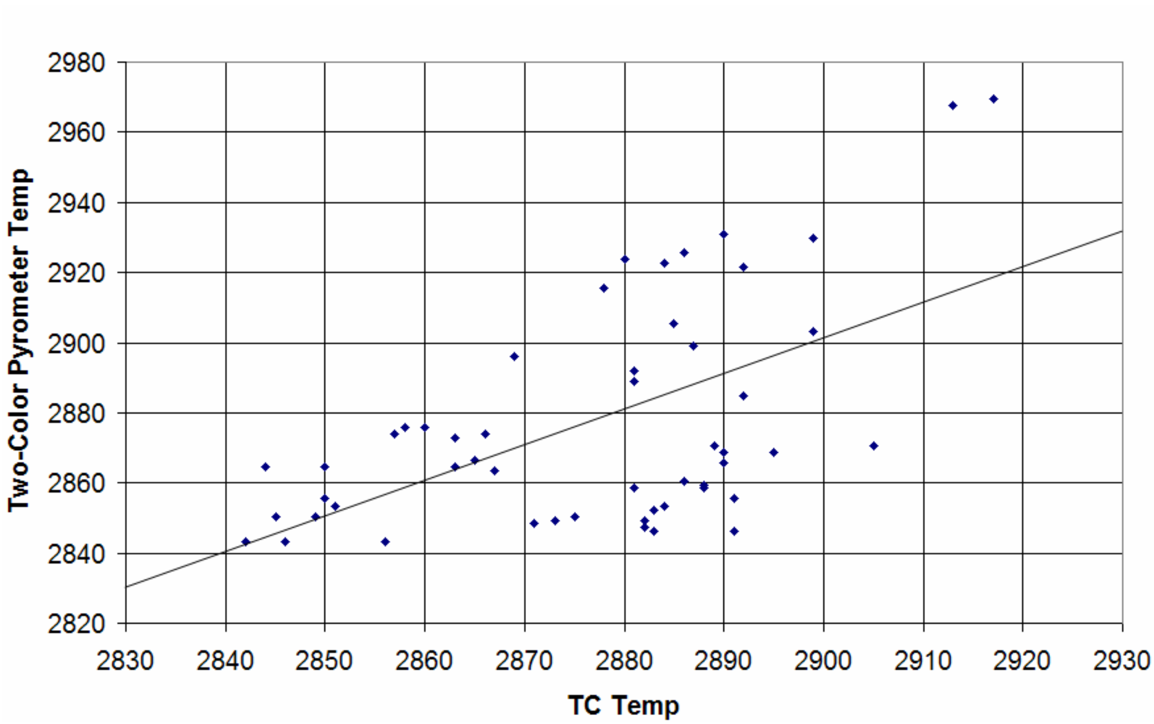

Figure 5. Thermocouple temperature plotted against the temperature observed with the two-color pyrometer for the same heat.

The data suggests that it is possible to use two-color pyrometry to accurately measure the temperature of steel in the vacuum chamber of an R-H type degasser. The average difference of 22 °F is slightly above what had hoped to achieve, though the absolute minimum difference that is theoretically possible, taking into account the uncertainty in measurement of both immersion thermocouple and optical devices, is on the order of 15-20 °F. That said, there are some limitations that we discovered during field trials that reduce the viability of the technique as applied to the degasser.

These include the following:

- Accurate measurements are not possible during the first 3-5 min after vacuum is established due to the combustion of CO. Measurements early in the degassing process are crucial, as they are used to determine whether or not oxygen blowing will be required to raise the temperature of the heat prior to casting. Failing to achieve this measurement early in the process severely limits the utility of the device.

  Clearly, we could not foresee the impact that the CO combustion reaction would have on the accuracy of the measurement early in the degassing process.
  We considered various methods of mitigating the impact of combustion on the temperature measurement. Spatial filtering is not possible as CO emission can occur at any location on the melt surface. Longer wavelength selection might be possible, but this complicates the optics, particularly for fiber-based systems.

- Accurate measurements are not possible when the wall mounted burner is on (oxygen is injected).

- Material additions always create smoke and flame; both bias the temperature measurements making them unusable during and after material addition.

- During degassing less than 10% of the molten steel in the ladle circulates into the degasser. Because of the limited thermal mass of molten steel in the degasser, its' temperature is severely affected by alloy addition. Temperature changes occur through both combustion-related heating, and cooling due to phase-change of the alloying elements. In heats where a large number of alloy additions are made sequentially (e.g. the data of Figure 4) it may be difficult if not impossible to accurately measure temperature.

- Depending on process variables, it can take up to 10 minutes after vacuum is established and combustion reactions cease for the bath temperature in the snorkels to reach equilibrium with the remainder of the bath. An example of this, which has been evident in multiple heats, can be seen in Figure 2. We believe that this relaxation is the result of the inner degasser wall temperature slowly reaching equilibrium with that of the melt. In our proposal, we identified a procedure for correcting the measurements against the "wall effect." This procedure is predicated on accurate measurements early in the heat, prior to oxygen blowing, that would yield an emissivity that could be used to correct the temperature measurements using a single color technique. Unfortunately, as noted above, accurate measurements early in the heat are not possible due to CO combustion, thus eliminating the possibility for mathematical correction of the measured temperature in the presence of radiant emission from the inner degasser wall.

5. CONCLUSION

On Thursday, May 12th 2005, during a meeting between US Steel and Process Metrix LLC at the Edgar Thompson Works, it was decided that this approach to continuous temperature monitoring in RH-type degassers was not a viable alternative to standard immersion thermocouples. This conclusion was communicated to the other project participants and AISI who agreed to discontinue further testing in this application.

REFERENCES

1. Bonin, M. et al. "Optical Sensors and Controls for Improved Basic Oxygen Furnace Operations." AISI Advanced Process Control Program quarterly report, May 1st – June 30th, 1998, contract DE-FC07-93ID13205.