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Successful Pyrometry in Investment Casting

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The FAR Expert System SpectroPyrometer has accurately measured solid and liquid metal temperatures in investment casting. The problems it has solved are significant and explain the skepticism investment casters have toward non-contact temperature measurement. The problems are caused by the nature and behavior of the target: a solid metal charge changes phase into a turbulent liquid. Liquids, especially turbulent liquids, give conventional pyrometry problems because the changing microscopic shape of the surface governs the radiation characteristics, i.e., the emissivity. Metals as a class, whether solid or liquid, are the most difficult for pyrometry due to the behavior of their emissivity: it changes with wavelength (color) in addition to all the other variables that affect it. Put the two together and no instrument that requires emissivity information beforehand or assumes constant emissivity (or constant relative emissivity) has a chance of success. The SpectroPyrometer has shown exact agreement with dip thermocouples for extended periods, confirming accurate temperature measurement in this demanding environment. The improved control resulting from continuous, accurate temperature measurement has effected a 41% decrease in non-fill, a key process variable.

Need for accurate temperature measurement.

It is generally accepted that metal temperature is a critical factor in investment casting. Solidification mechanics depend on metal temperature, which in turn effects many quality characteristics. Uncontrolled variations in temperature can adversely affect the following:

- Fill of Thin Sections (non-fill or misrun)
- Grain Size and Distribution
- Porosity (micro-shrink or sponge shrink)
- Mechanical Properties
- Hot Tearing
- Finished Casting Dimensions

When the metal temperature is higher than desired, a common occurrence with conventional measurement techniques, there is increased potential for inclusion defects due to greater crucible erosion.

Techniques of temperature measurement: contact and non-contact methods.

Contact methods usually mean thermocouples. While these relatively simple devices are ubiquitous in temperature measurement, they have a significant number of disadvantages in foundry application.

- Finite lifetime, therefore replacement costs
- Thermocouples "poison" with use, thus accuracy changes with time
- Thermocouples can fail catastrophically
- They require elaborate delivery hardware with the added disadvantage that the equipment must operate at high temperatures, often in vacuum
- They can be used once per melt (i.e., one reading per melt)
- They require substantial time to equilibrate, on the order of a minute for a thermocouple sheathed in ceramic
- They have a substantial thermal mass which affects the melt temperature and ensures slow or indistinguishable response to changing conditions
- The electrical signal is small, therefore they are subject to noise

Non-contact Technology

Advantages of non-contact techniques are speed, no physical effect on the temperature being measured, robustness (catastrophic failures are rare), and that no consumables are required.

However, most casters know that there are areas of concern related to non-contact temperature measurements. These problems can be divided into three major categories: those related to the target (material being measured), those related to the environment (what lies between the pyrometer and the target), and those related to the instrument itself. Examples of environmental difficulties are :

- Vapor interference – *offgas from the target, furnace, accessories or heat source may absorb or emit radiation, causing temperature errors in either direction.*

- Sight port obstructions – *conventional instruments may be affected by dirt on windows; all instruments are affected by metallic deposition on windows.*

Because vapor interference is not a problem in vacuum work and sight port obstruction is mostly a matter of housekeeping, this paper focuses on the difficulties associated with the instrument that is measuring, the pyrometer, and with the material being measured. The property of the material of interest is the emissivity, the variable that relates the abstract physics of non-contact temperature measurement to the actual target being measured. Emissivity is no more than a material's efficiency as a radiator. As such, it varies between zero and one. The problem results from this efficiency being unknown, or changing with processing. Some of the specific causes of unknown or changing emissivity are multiple alloys, turbulence effects, temperature and wavelength dependence, and composition changes during processing.

To best understand the effects of emissivity, it is necessary to understand the types of pyrometers and how they respond to that variable. The spectral curves of intensity vs. wavelength that are the basis of all pyrometry are the starting point. Figure 1 shows the spectral curves for several temperatures. The curves show the ideal intensity vs. wavelength, or amount of light vs. color, for each temperature.

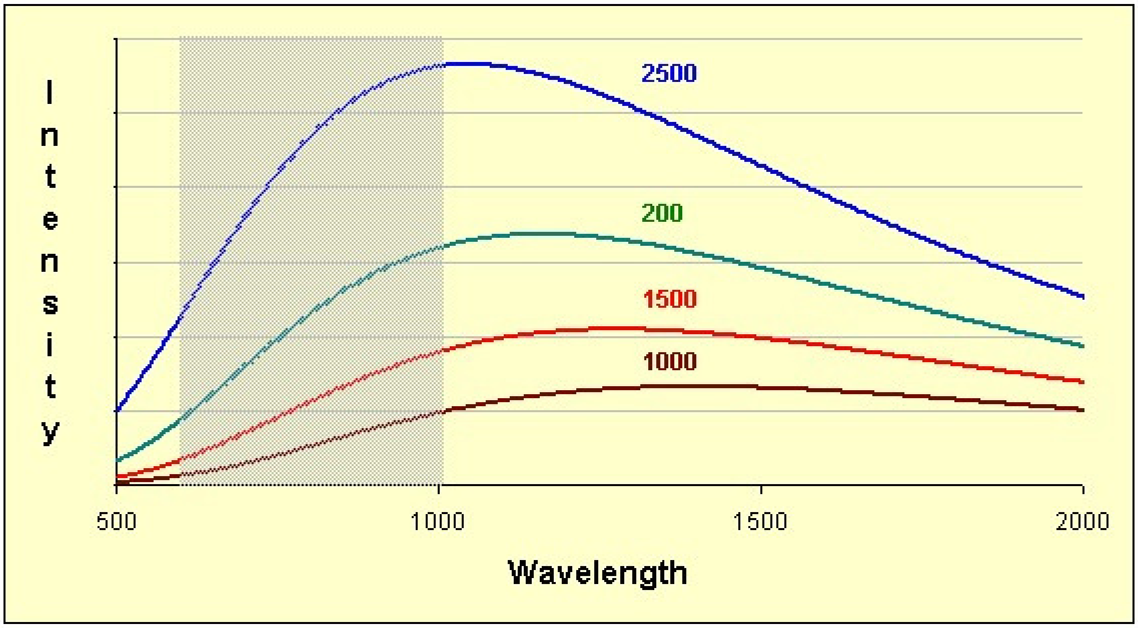

Figure 1. Planck's Law curves for 1000 - 2500°C; grayed spectral area is most commonly used for pyrometry.

Figure 2 shows how a brightness, or one-color, pyrometer would operate on one of the curves of Figure 1. All the energy in the area of the pyrometer's sensitivity, represented by the black area, is added up and converted to a temperature through either a look-up table or linearizing electronics. The operator must know and enter the emissivity. Anything that affects the amount of light, such as steam, smoke, process offgas, combustion byproducts, or dust, affects the temperature determined by this type of pyrometer.

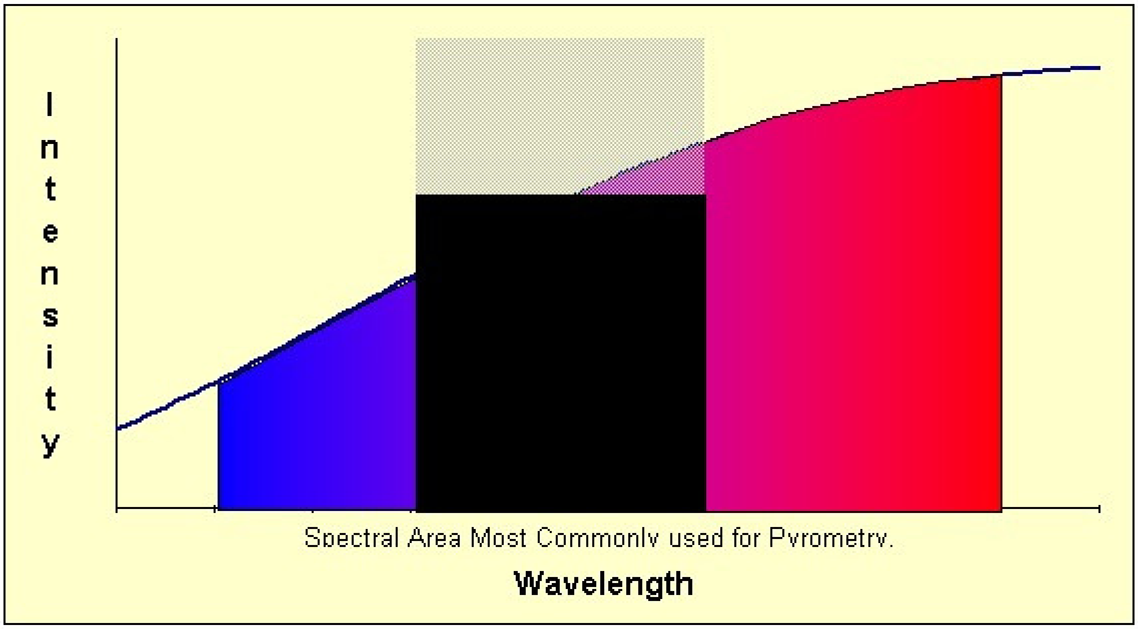

Figure 2. Brightness (one-color) pyrometer.

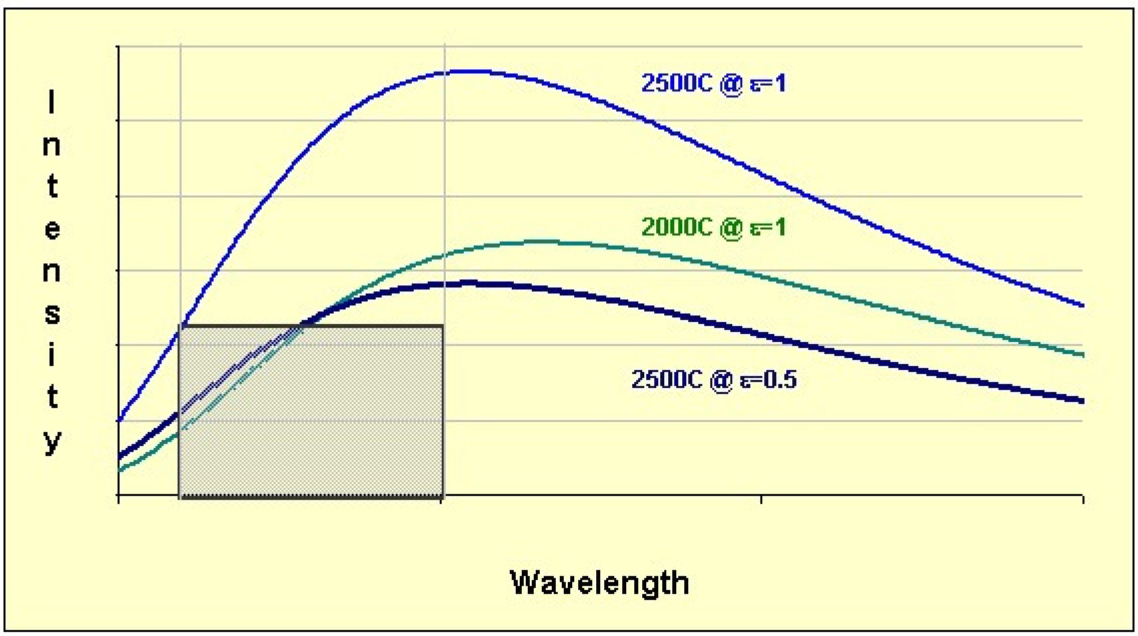

Figure 3. Brightness pyrometer on targets of differing emissivity.

Figure 3 shows the raw input to a brightness, or one-color, pyrometer from materials at two temperatures with different emissivities. The area under the curve is the same for the two different temperature and emissivity combinations. When the emissivity is unknown, as it usually is, a brightness pyrometer cannot distinguish between the two temperatures.

The brightness pyrometer dates from the beginning of the last century, and its shortcomings have been well known for a long time. An effort to improve pyrometry was the ratio, or two-color, pyrometer. The theory shows that if the intensity in two wavelengths (really wavebands, as seen in Figure 4) is divided, the emissivity will cancel if it is the same at both wavelengths.

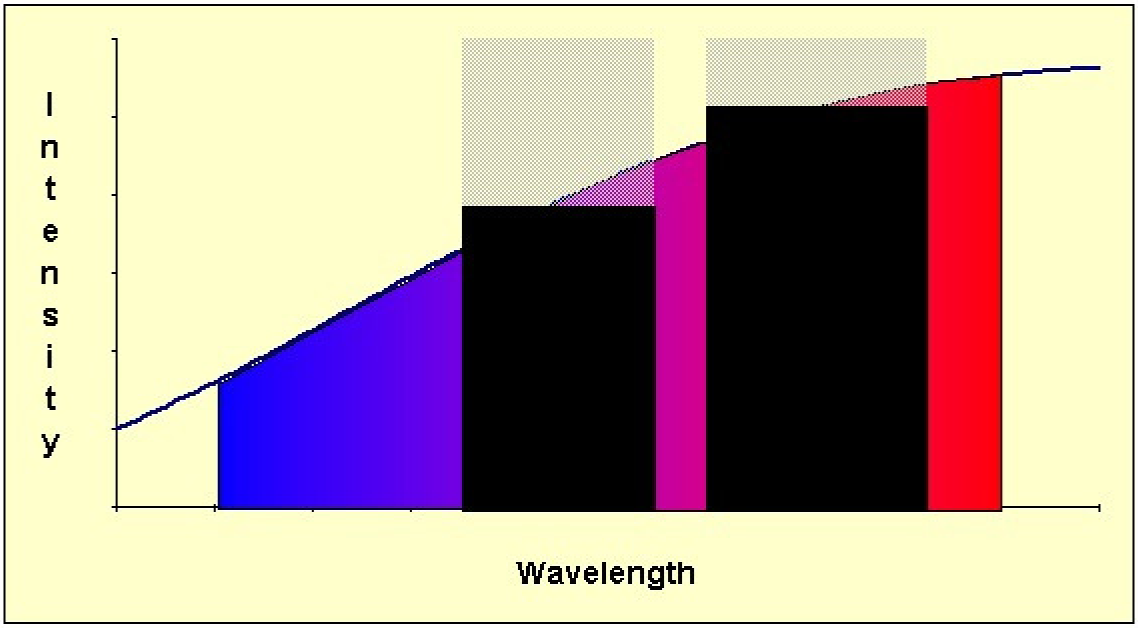

Figure 4. Ratio (two-color) pyrometer.

However, the emissivity of metals is not the same at any two wavelengths. In general, the emissivity of metals is a decreasing function of wavelength. The emissivity of nickel, shown in Figure 5, illustrates the metallic behavior of the emissivity of metals.

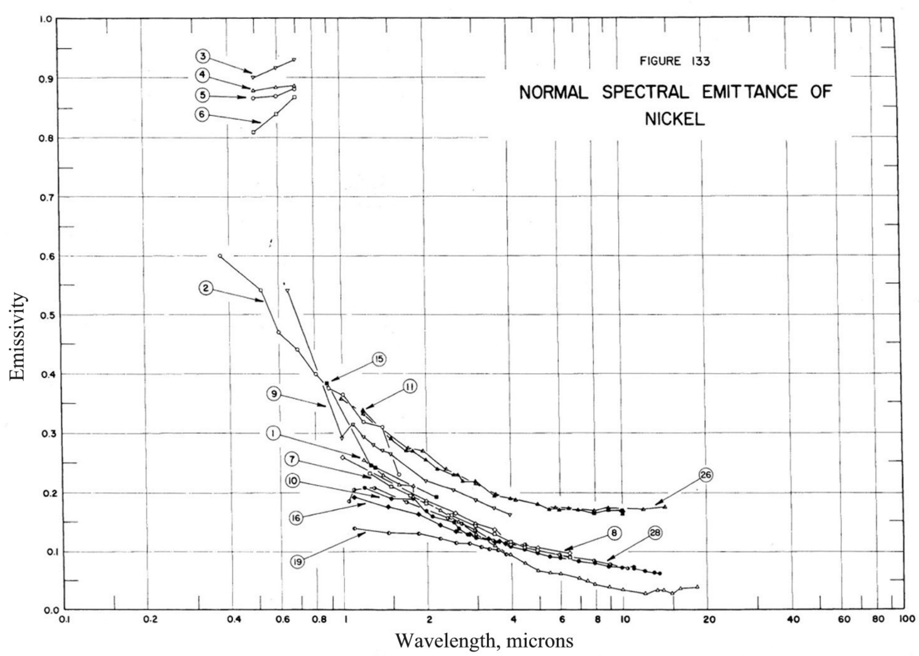

Figure 5. Emissivity of nickel, from the Thermophysical Properties of Matter, Vol. 7[1].

This behavior removes the chief advantage of ratio pyrometers, their ability to measure the temperature without knowledge of the target's emissivity. Now, rather than the emissivity, the operator must know and input the relative emissivity. The graph clearly shows that the samples reported here all had different values of relative emissivity, and their values change with wavelength. For many metals, these values also change with temperature. Finally, they also change with turbulence. Determining and inputting the correct relative emissivity is clearly an impossible task. Figure 6 illustrates the effect of emissivity changing with wavelength. The top and bottom curves have the areas (wavebands) a ratio pyrometers would measure colored in. The shorter wavelengths of the bottom curve are enhanced with respect to the longer wavelengths due to the emissivity changing with wavelength. This enhancement of the shorter wavelengths makes the ratio of the two intensities shown for 2000° (black, emissivity changing with wavelength) equal to the ratio of those at 2500° (gray, emissivity constant at one). Both ratios are 2:1, therefore the ratio pyrometer returns the same value, 2500°, for each measurement.

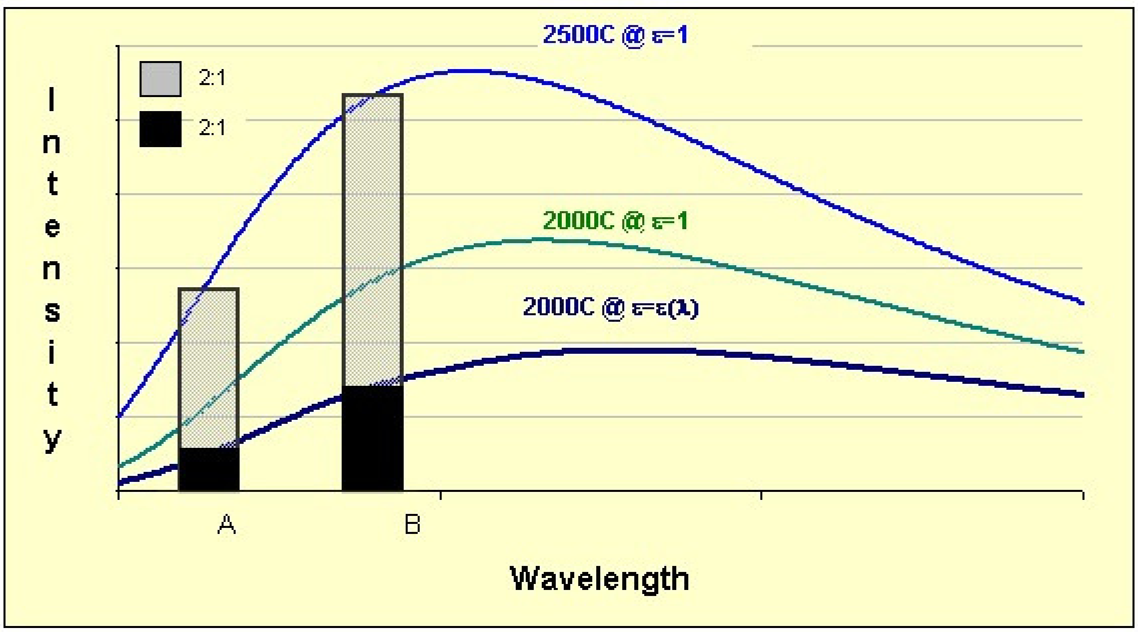

Figure 6. Ratios of gray areas B:A and black areas B:A are the same; 2500 and 2000° are therefore indistinguishable to this ratio pyrometer.

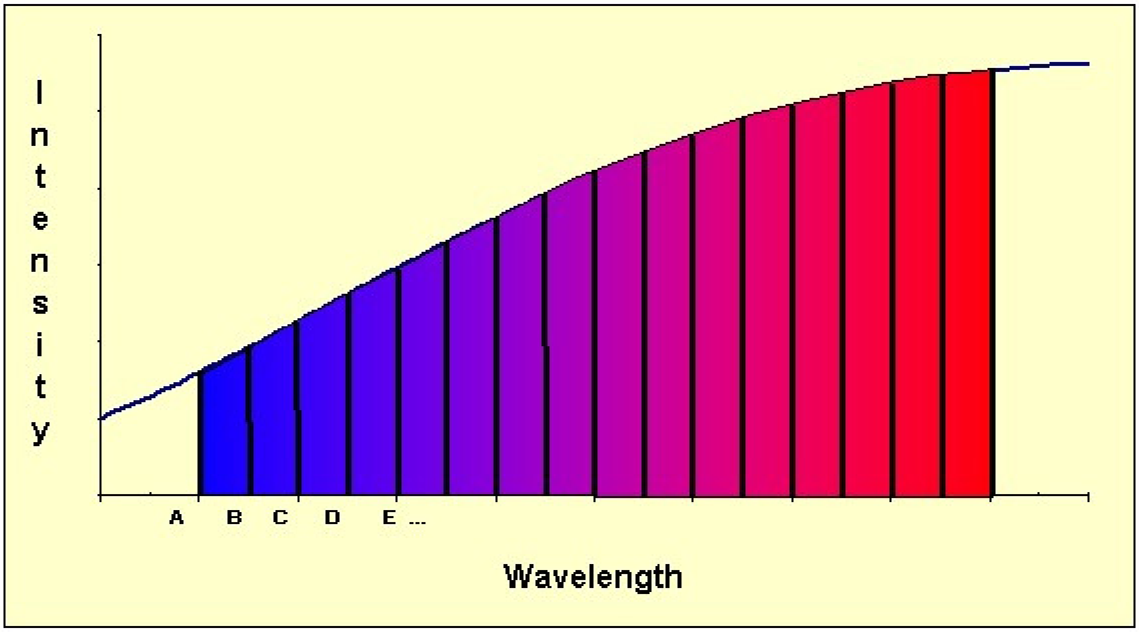

Figure 7. FAR SpectroPyrometer uses hundreds of wavelengths and statistical analysis of data to determine emissivity behavior.

The next step beyond one and two-wavelength pyrometers is the multi-wavelength pyrometer. The FAR expert-system multi-wavelength SpectroPyrometer uses hundreds of wavelengths of exceedingly narrow bandwidth. From this wealth of data much has been learned[2,3] and it becomes possible to determine and correct for metallic behavior, the change of emissivity with wavelength. The SpectroPyrometer approaches each measurement without preconceptions and uses the data to determine the behavior of emissivity. As is shown below, this is key for turbulent liquid metals.

Real World Results

Figure 8 shows data collected at the initial installation of a SpectroPyrometer on a vacuum investment casting application. Temperatures were collected by both the conventional pyrometer historically in use and the new SpectroPyrometer. A cold charge was heated under manual power control.

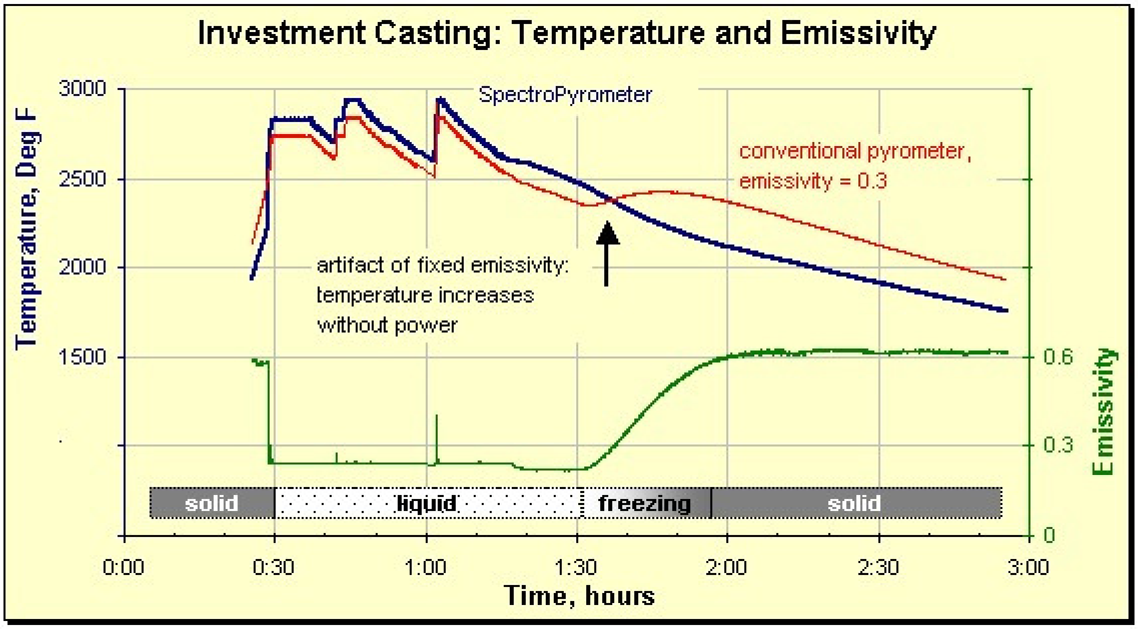

Figure 8. Contrast of conventional pyrometer and SpectroPyrometer results on a nickel superalloy.

The operator's first comment indicated his belief that the newly-installed SpectroPyrometer was reading several hundred degrees high. Power was adjusted up and down, and both pyrometers tracked the change. The SpectroPyrometer recorded and displayed emissivity values, which are also plotted in Figure 8. Note the spike of increasing emissivity every time the power is changed. This is a result of the turbulation of the melt by the power surge, the same phenomenon as electromagnetic stirring. (The mechanism is that the surface is roughened by the turbulence and a rough surface has a higher emissivity due to the small blackbody cavities formed. Another way of looking at it: reflectivity and emissivity add up to equal 1; when reflectivity is lowered, as by a rough or matte surface, emissivity is increased.) Eventually the melt was allowed to cool naturally. The artifact at 1:35 PM, an indicated temperature increase without power being added, was a clear sign to the operator that the conventional instrument was reading incorrectly.

The next step was to compare results in production. Figure 9 shows several molds cast; these were controlled by the conventional pyrometer and monitored by the SpectroPyrometer. The target temperature was 2700°F, but the achieved temperature was a more than 200°F higher. It is also clear that during the time supposedly devoted to holding temperature that temperature could increase, decrease, or hold. Note the extreme spikiness of the emissivity tracks during the heat-up portion of the cycle. This is due to excessive turbulation of the melt due to on-off cycling of the power source. As has been seen in Figure 8, turbulence enhances emissivity, and the enhanced emissivity is interpreted as an over-temperature by the conventional instrument. Power is shut off in response to this false over-temperature and the melt quiets. The resulting return to lower emissivity with removal of the turbulence is perceived by the conventional instrument as an under-temperature indication, and power is reapplied. The power surge turbulates the melt and the cycle is repeated again and again.

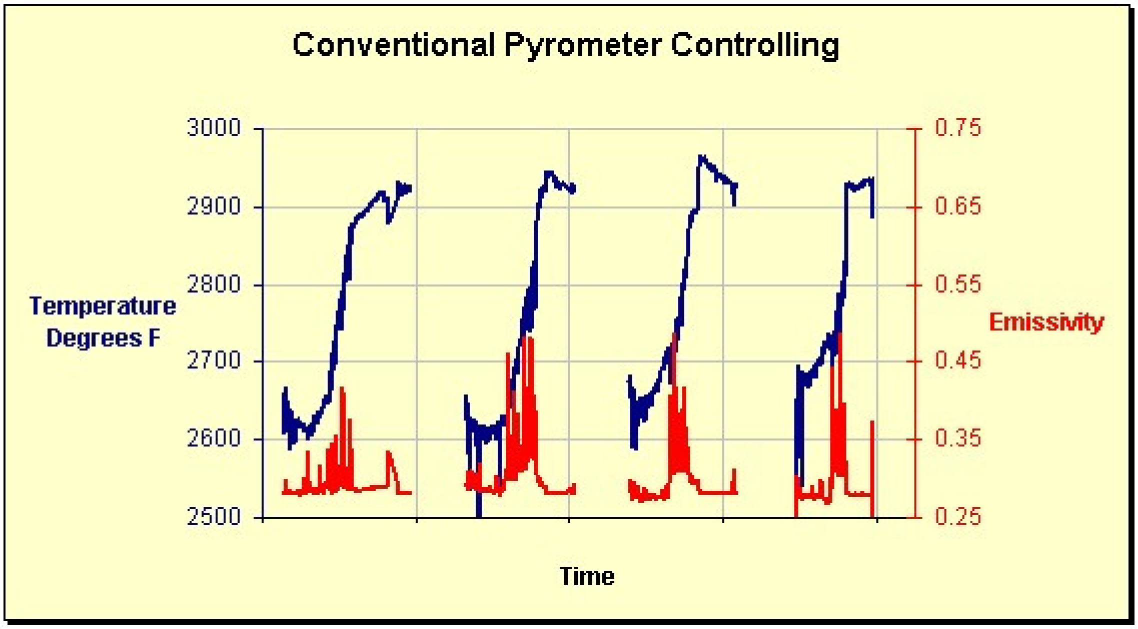

Figure 9. Several investment casting cycles: conventional pyrometer controlling, SpectroPyrometer monitoring temperature, emissivity. Spiky behavior of emissivity trace indicates extreme turbulence.

Contrast this behavior with that shown in Figure 10. The temperature rapidly approaches and holds the target value, in this case 2700°F.

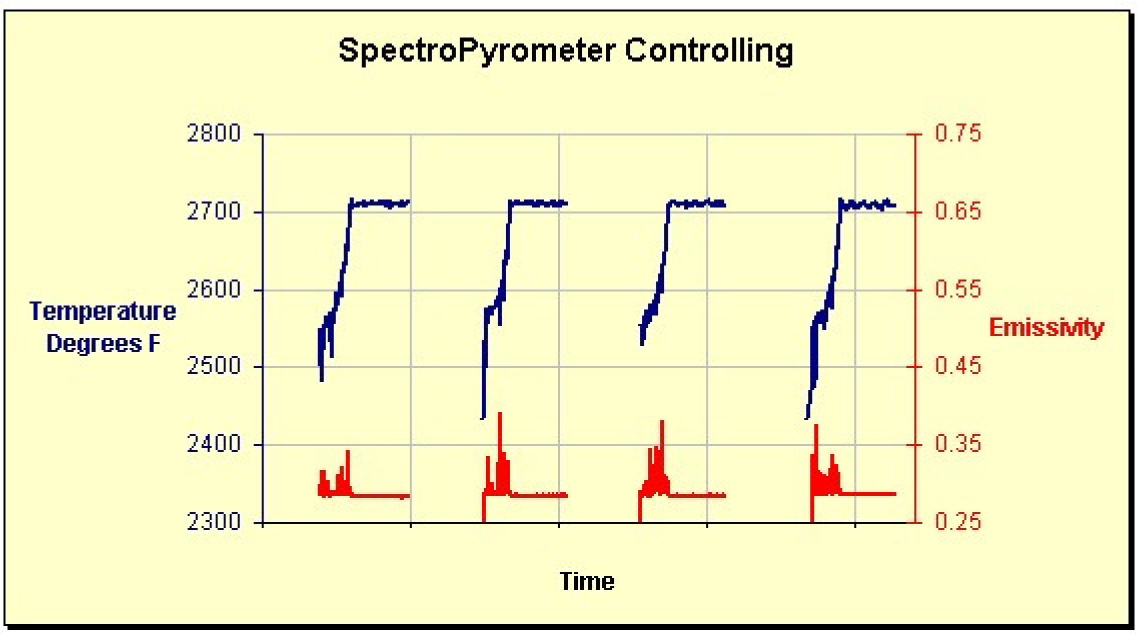

Figure 10. Spectropyrometer controlling and monitoring investment casting cycles.

There is much less turbulence as shown by the drastically-decreased spikiness of the emissivity trace. The decrease in turbulence is a major advantage: turbulence causes erosion of the crucible wall with the eroded material then becoming inclusions in the melt. Figure 10 also shows the errant transfer function entered in the control electronics. While the setpoint is 2700°F the controller is driving the process to about 2710°F. This small error was completely masked by the variability of the conventional instrument.

ESCO Installation

In November of 2006 a FAR SpectroPyrometer was installed on B-furnace in ESCO Turbine Technologies – Cleveland. The reasons to apply spectropyrometry to investment casting are to implement or improve process control, and to thereby generate cost savings and boost productivity. Process control is the driver that allows automation of production and from which the cost and productivity benefits flow. Originally, the protocol called for a ratio pyrometer to control this furnace, checked by an immersion thermocouple every three melts or at part change. It actual operation it became apparent that the ratio pyrometer was not reproducible and showed no correlation with the thermocouple. The immersion thermocouple was then used almost 100% of the time. Thus the SpectroPyrometer was installed to replace the unusable ratio pyrometer.

It quickly became apparent that the SpectroPyrometer was delivering accurate, reproducible temperatures. Indicated values showed excellent agreement with immersion thermocouples from the beginning.

Some early emissivity results are shown in Figure 11.

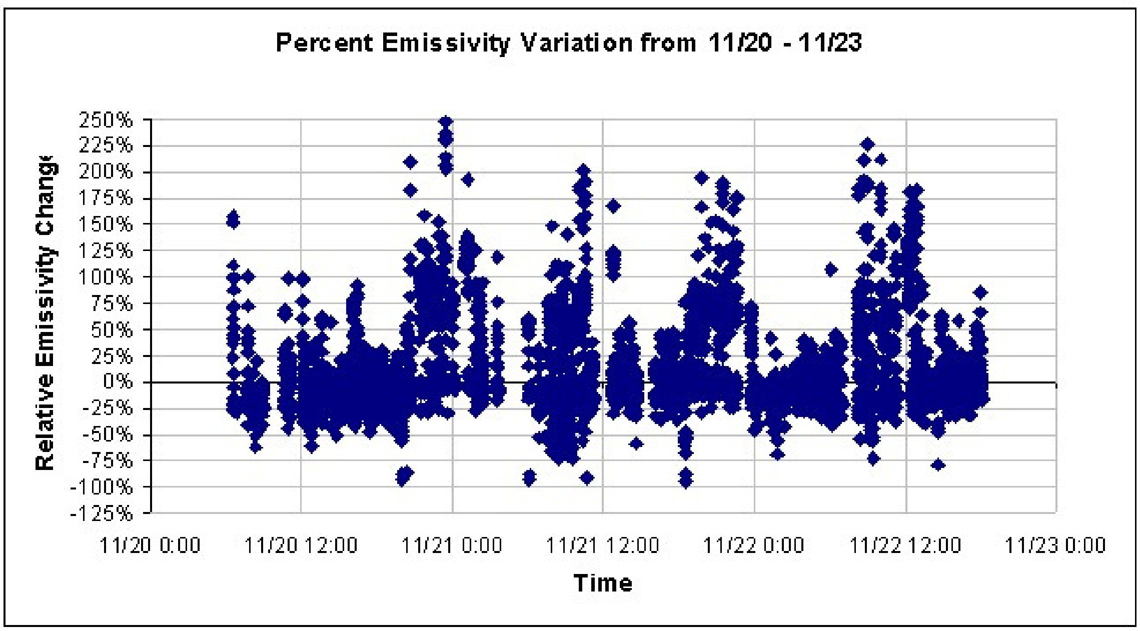

Figure 11. Emissivity variation for early results at ESCO Cleveland. At 2700°F, a 5% variation in emissivity results in a 15°F change in the output of a conventional pyrometer.

It is clear from this that the turbulent metal melts show extreme variations in emissivity. It can also be seen from Figure 12 that the emissivity shows the metallic behavior, that is, its value changing with wavelength. The combination of these two effects renders all conventional pyrometers inaccurate in this application. These data explained the failure of the earlier attempt at automated temperature control with ratio pyrometry.

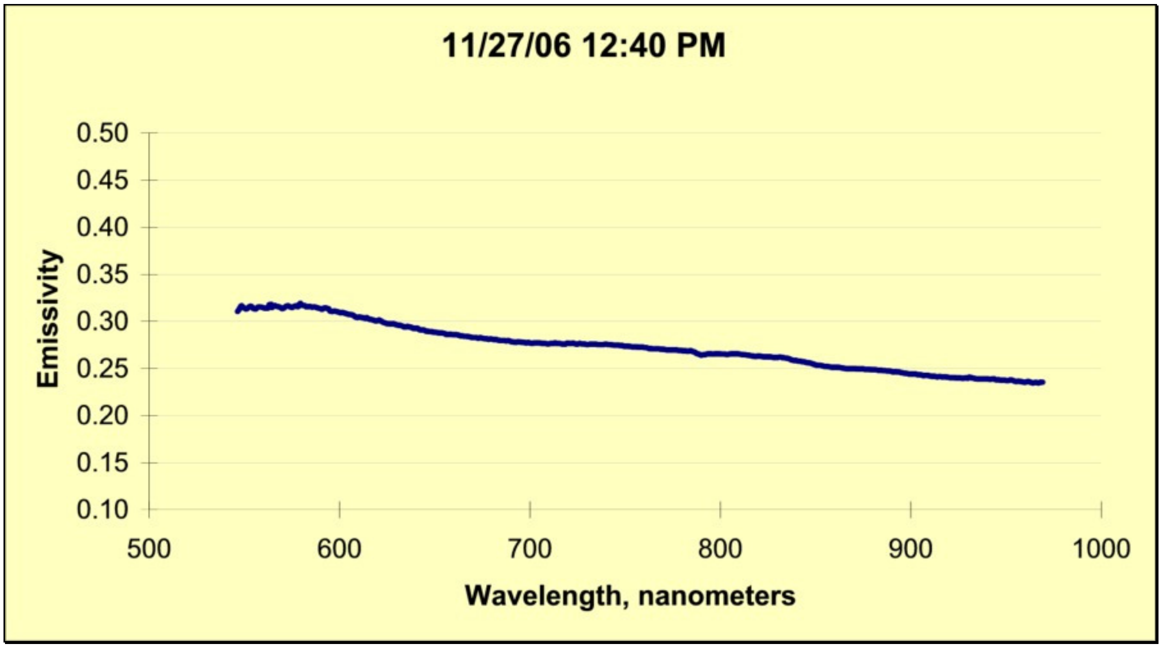

Figure 12. Emissivity is seen to change 30% with wavelength for an ESCO melt.

The situation changed with the SpectroPyrometer. Now non-contact measurements were extremely reproducible and there was excellent correlation with the immersion thermocouple. Today, thermocouples are used only at each change of part number. This is already an improvement on the original protocol, which called for use on part number change and every third part. Plans are to dispense with routine use of the thermocouples completely. Figure 13, Figure 14, and Figure 15 are operator's data sheets showing the agreement between immersion thermocouple and SpectroPyrometer over the period 11/18 – 11/29/2006.

ESCO Turbine Technologies

Cleveland

B-Furnace Infrared to Immersion TC comparison

Thank you for helping us to work to reduce process variation!

DATE	OPERATOR	SHIFT	INFRARED TEMP	IMMERSION TC TEMP	DIFFERENCE
11-18-06	L.P.S.	1st	2760	2762	2
↓	↓	↓	2759	2761	2
			2761	2760	1
11-20-06	SD		2760	2745	15
			2760	2755	5
			2752	2750	2
			2760	2760	0
			2760	2760	0
			2760	2755	5
			2760	2753	7
11-21-06	SD		2775	2765	10
			2780	2776	4
			2775	2775	0

533 ↓

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Figure 13

ESCO
Turbine Technologies
Cleveland

B-Furnace Infrared to Immersion TC comparison

Thank you for helping us to work to reduce process variation!

DATE	OPERATOR	SHIFT	INFRARED TEMP	IMMERSION TC TEMP	DIFFERENCE
11-21-06	SD	1st	2700	2688	12
			2760	2752	8
			2760	2755	5
			2760	2755	5
			2760	2755	5
			2760	2753	7
11-22-06	SD		2700	2680	20
			2760	2741	19
			2550	2550	0
			2602	2602	0
			2603	2603	0
			2604	2605	1
			2760	2759	1

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Figure 14

ESCO® Turbine Technologies — Cleveland

B-Furnace Infrared to Immersion TC comparison

Thank you for helping us to work to reduce process variation!

DATE	OPERATOR	SHIFT	INFRARED TEMP	IMMERSION TC TEMP	DIFFERENCE
11/22/06	BobM	2ND	2756	2755	1
			2762	2760	2
			2755	2759	4
11-28-06	SD	1ST	2720	2713	7
11-28-06	SD		2710	2701	9
			2760	2751	9
			2760	2762	2
11-29-06	SD	1ST	2760	2751	9
			2760	2760	0
			2760	2757	3
			2760	2755	5
	Bn		2760	2745	15

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Figure 15

To date, the efforts to improve process control have resulted in significant savings. Since installation of the SpectroPyrometer, thermocouple use has been reduced from in more than 90% of melts to only in 33% of melts. Thermocouple sheath material has been changed due to the decreased load; from Metamic™ to quartz. This realizes a 97% cost savings. Total thermocouple cost savings to date are 35%. This figure includes the learning curve: the early time when thermocouples were being used routinely for comparison. It is fully expected that the percentage of these savings will grow.

Perhaps more interesting are the process parameter improvements. Key input and output variables have been seen to improve substantially. The standard deviation of the key input variable pour temperature has fallen from 3.5 to 1.5°F. Figure 16 shows this improvement graphically.

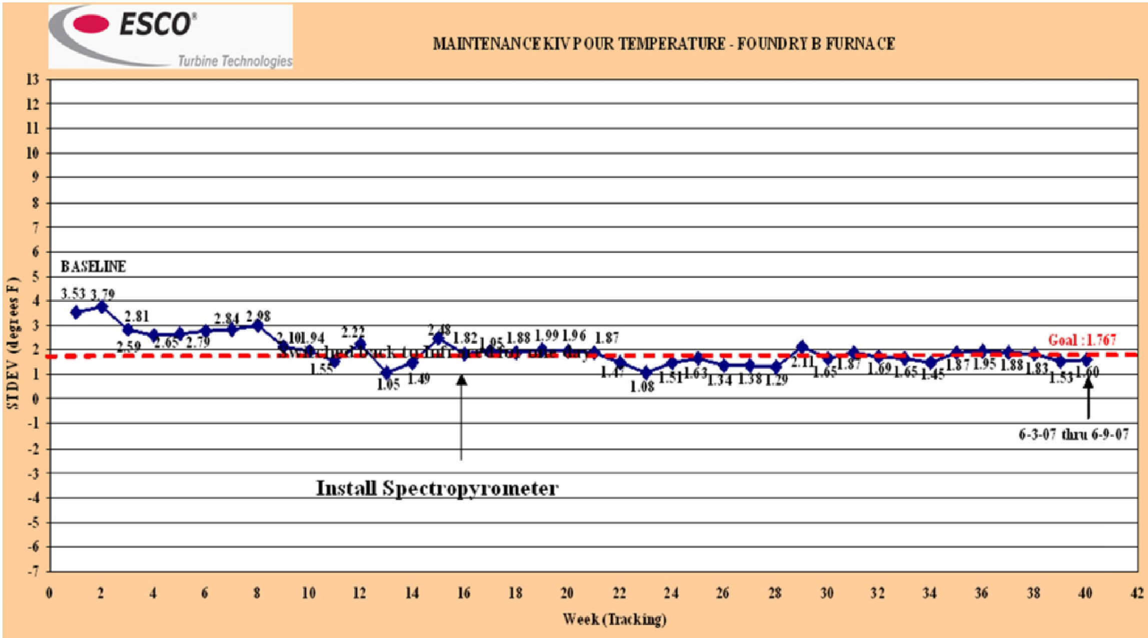

Figure 16. Pour Temperature before and after installation of SpectroPyrometer.

The key output variable non-fill (fill of thin sections) has improved also. An improvement of 41% reduction in scrap from this variable has been observed that is attributable to the SpectroPyrometer.

The variability of emissivity with turbulence can be seen with the naked eye. Figure 17 and Figure 18 are taken from a video of a melt that has been synchronized with the data from the SpectroPyrometer controlling this melt.

Figure 17. Thermocouple immersed in melt.

Inspection of these figures shows bright lines that are locations of either higher temperature or higher emissivity. The several thousand values measured by the SpectroPyrometer do not show any anomalous high temperatures, but emissivity is seen to vary. The conclusion is that the bright lines seen on these stills are areas of enhanced emissivity due to the turbulence of the melt. This was always the suspicion, since the lines follow the structure of the melt.

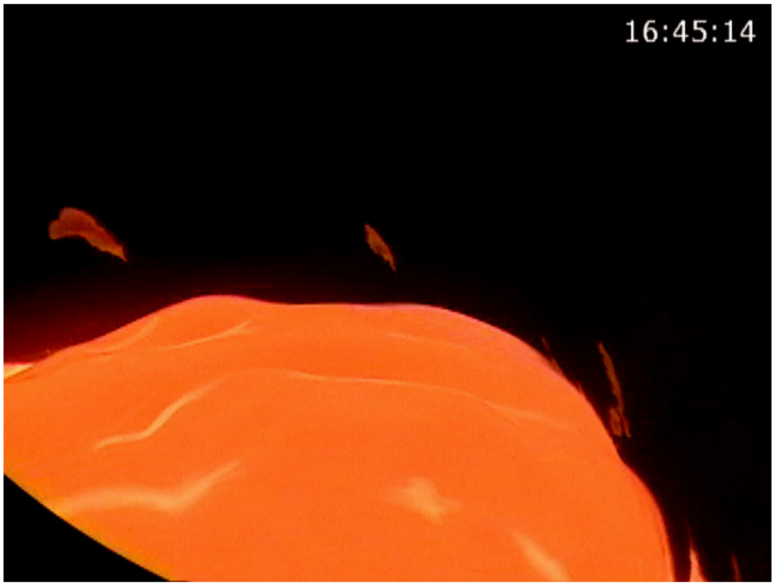

Figure 18. Melt coned up.

Conclusion

It has been shown here that the emissivity of the liquid metal melt for investment casting provides daunting challenges to both one and two-color conventional pyrometers. Among these are emissivity changing with both wavelength and turbulence. Previous work has shown emissivity also changes with alloy and temperature[4]. Nevertheless, FAR SpectroPyrometers installed in this application have been seen to provide accurate, consistent, and reproducible temperatures. To date, these have resulted in:

- 41% Reduction in Scrap due to Non-Fill
- 35% Reduction in Thermocouple / Sheath Costs.
- 57% Improvement in Metal Temperature Variation

[1] Thermophysical Properties of Matter, Vol. 7 – Thermal Radiative Properties, Metallic Elements and Alloys, Ed. Y. S. Touloukian and D. P. Dewitt, IFI/Plenum, New York, 1970
[2] R.A. Felice, US Patent 5772323
[3] R.A Felice, US Patent 6379038 B1
[4] R.A. Felice, Investment Casting Temperature Measurement, Foundry Management and Technology, Sept. 2006