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Energy Savings through Accurate Temperature Measurement

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Abstract

Inaccurate temperature measurement in the process industries wastes energy. If the product does not meet quality specifications because of poor temperature control, the energy used both in producing the feedstock and in processing it is wasted. Often, the energy to recycle the scrap adds to the burden. If the product is overheated but quality is maintained, the energy wasted is that used to raise the temperature of the feedstock and process environment above the ideal. This energy waste is substantial: process overtemperatures of 10% are common. A new type of pyrometer, an expert system multi-wavelength instrument known as the SpectroPyrometer, has greater accuracy and is accurate more often than conventional instruments. Through its increased accuracy, the new pyrometer has been seen to pay for itself in days. Substantial energy savings, more than 4% of the total energy burden, have been generated from productivity increases.

Introduction

A straightforward way to save energy in any process industry is to increase the yield of the process. A one percent increase in yield nets at least a one percent savings in energy. The savings includes the energy burden for the proportionate amount of raw materials in addition to the direct energy usage of the process. There is also the potential savings of waste treatment, since much scrap must be remediated before being discarded or returned to the process. Since the topic of this paper involves the improved measurement of a process variable, temperature, the increase in yield comes from improved process control. The methods of process control are sophisticated; the hardware is robust and reliable. However, process control itself is no better than the measurement of the variables being controlled. Temperature, one of the most important variables with respect to energy usage, is also one of the most difficult to measure accurately.

Process Control

Process control is "the use of instruments and control devices and systems to measure and manipulate one or many variables to assure the safe and efficient operation of machines and equipment required in manufacturing"[1]. For a simple, two-parameter process, a diagram as shown in Figure 1 could be constructed. The shaded surface is the area of good quality, delineated by the oval boundary.

Point A is the centroid of the surface, and corresponds to the ideal value of each parameter. The horizontal and vertical arrows associated with Point A show the natural, unavoidable variation of each parameter stemming from the precision, accuracy, and timing of the measuring devices and the response of the process controller. If the process is operating at Point A, product quality is uniformly good despite these natural variations. If, however, the process is operating at Point B, it is clear that product quality will be compromised. The problem occurs when the measuring device's inaccuracy in Parameter 1 allows the process to slip from Point A to Point B. An aside: if the manufacturer's quality control analyses are sophisticated enough, some of the scrap will be recognized as being caused by Parameter 2 being out of control. But from this diagram, it is clear that the problem lies with Parameter 1; the variation in Parameter 2 is within the unavoidable range. In any event, it's obvious from the diagram that a manufacturer would choose to operate at Point A if possible. However, without accurate measurement devices, this is not possible.

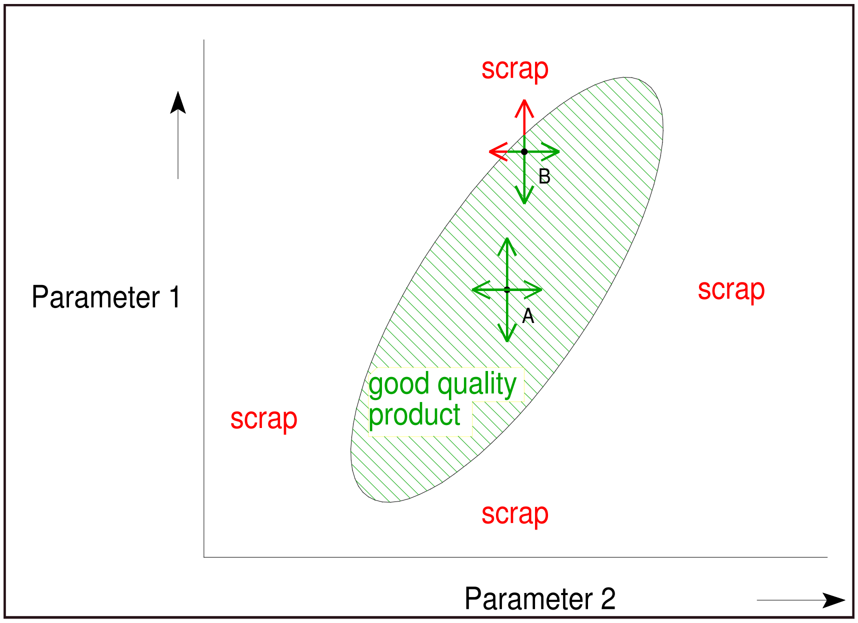

Figure 1: Area of good quality for a 2-parameter process.

Temperature Measurement

Manufacturers choose non-contact temperature measurement – pyrometry – for a number of reasons: it's fast, it doesn't affect the temperature that's being measured, it isn't prone to catastrophic failure, and it needs no consumables. The non-contact feature itself is an advantage: it will not contaminate or perturb the product. For temperatures above about 1800°C/3300°F there isn't really a practical alternative. Pyrometry is applicable to solids and liquids; it's defining equation is Planck's law:

$$I_0 = \frac{C_1}{\lambda^5}\left(e^{\left(C_2/\lambda T\right)} - 1\right)^{-1} \tag{1}$$

where C_1 and C_2 are constants, λ is the wavelength, I_0 is the intensity of thermal radiation at that wavelength, and T is the absolute temperature. This equation can be solved for the temperature. Planck's law is the statement for an ideal, or blackbody, radiator. It is obvious that anything that affects the value of the intensity affects the temperature calculated; therefore, for real measurements the equation is modified:

$$I = \varepsilon \tau I_0 \tag{2}$$

where I is the radiation actually measured, ε is the emissivity, or the efficiency of the radiator, and τ is the transmission of the medium between radiator and pyrometer. Both numbers normally vary from zero to one; if the process gases are energetic enough to radiate, the transmission can effectively be greater than one. The two factors are inserted with the intention to correct for the behavior of real radiators, which do not radiate at 100% efficiency, in real environments, which do not transmit 100% of the radiation. Emissivity is a particularly ill-behaved variable, changing with composition, surface finish, temperature, wavelength and others. Conventional pyrometers require either outright knowledge of the value of emissivity, or tacit assumption about its behavior. A new class of pyrometer, a multi-wavelength expert-system pyrometer, or SpectroPyrometer, requires neither [2, 3]. Transmission varies with wavelength because of the physics of gases. Conventional pyrometers do not even consider the transmission between instrument and workpiece, despite its being as important as the emissivity; the SpectroPyrometer detects and corrects for non-ideal transmission.

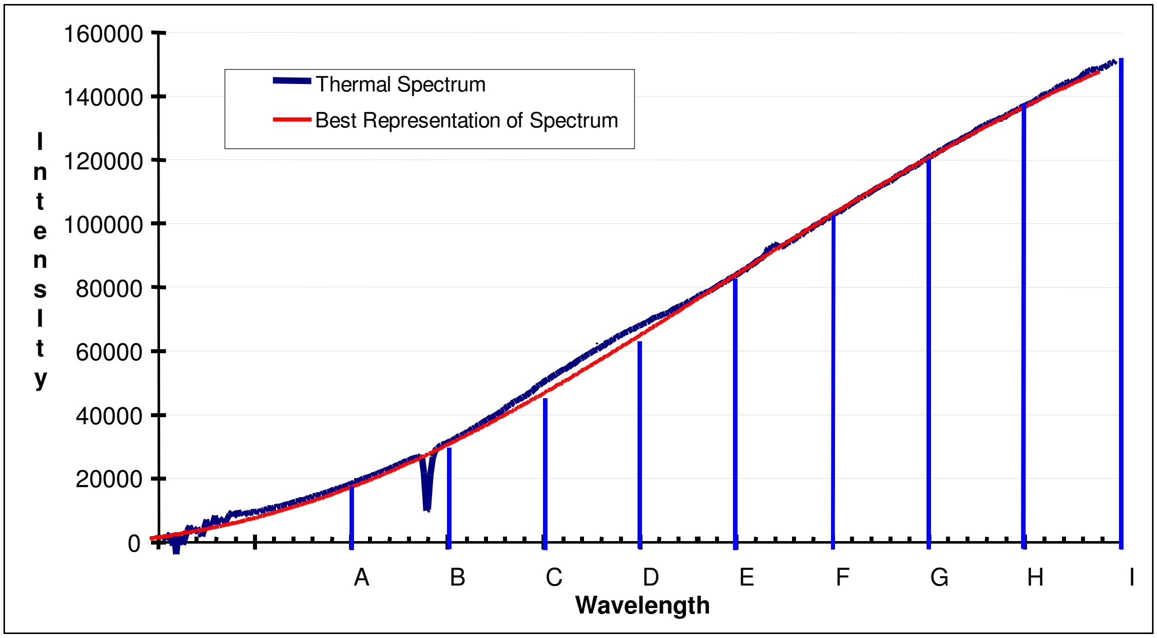

Figure 2: Thermal spectrum, corrected spectrum, and points from which temperature is calculated by the SpectroPyrometer. This thermal spectrum shows absorption ($\tau < 1$) between A and B, and emission ($\tau > 1$) between B and E.

A simplified algorithm for temperature determination by the SpectroPyrometer is illustrated in Figure **2**. First, the thermal spectrum is measured; next interference is removed to generate the best possible spectrum. Then points are chosen from the corrected spectrum and temperature calculated for each pair: T_{AB}, T_{BC}, …T_{HI}. The actual temperature is determined from these calculations. Because of the large amount of data it collects and analyzes, in addition to the temperature the SpectroPyrometer also returns two other pieces of information. These are the accuracy of the measurement just made (reported as a tolerance to the value of temperature) and the product of emissivity and transmission ($\varepsilon\tau$ in Equation 2), called the signal strength. As operators become familiar with the instrument, these values become meaningful and can guide them to more efficient operation.

Energy Loss Mechanisms and Examples

The energy loss mechanisms related to temperature for controlled thermal processes are overheating and scrap. Errors in conventionally-measured temperature values caused by the factors that affect the intensity of the radiation, emissivity and transmission, are surprisingly large, often exceeding hundreds of degrees. They are also surprisingly frequent, as illustrated in the examples below.

Graphite Manufacture and Use

Graphite is perhaps the most common refractory material. The process was the manufacture of graphite furnace elements used in the steel industry. Figure 3 shows transmission loss in the thermal spectrum due to absorbing process gas between the pyrometer and the workpiece. The temperature returned for these data by a conventional pyrometer was low by 400°C (720°F), or 15%. The manufacturer, presented with a temperature value much lower than the actual temperature, reacted as expected. Power levels were increased, resulting in parts with built-in thermal stresses from over-temperature processing. These parts were more likely to be early failures in the steelmakers' process. Energy losses resulted from the warranty replacement of the original graphite parts (the re-manufacture of all failed pieces), and the effects of the parts failure on the steelmakers (quality issues and loss of temperature while the offending parts were replaced).

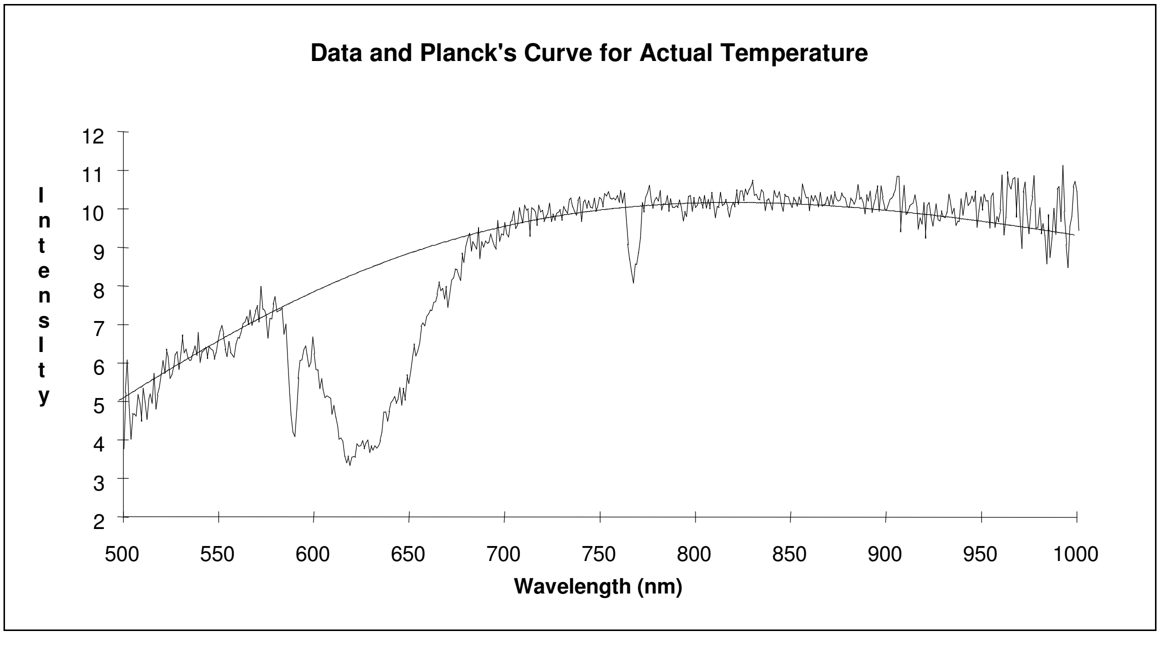

Figure 3: Transmission loss in part of the radiated spectrum; the ideal curve is the smooth one superimposed on the noisier data. The substantial absorption trough around 650 nm is common.

This phenomenon was first detected by the SpectroPyrometer in 1994 [4]. Since then it has been seen in many applications with graphite as either workpiece or refractory; it is observed more often than not in such cases. A few examples are in the manufacture of ablative and frictional materials, and the manufacture of engineered ceramic powders for either structural or electronics applications. It is interesting to note that the location of the absorption trough is particularly damaging to pyrometry: for historical reasons a large number of conventional pyrometers operate in the 650 nanometer region, near the center of the trough. It is easy to conclude that the yield of the industries mentioned above, and hence their energy usage, is affected by the incorrect processing temperatures this causes. These losses extend beyond the examples cited to any industry which manufactures graphite or uses it as a refractory.

Powder Metallurgy – Tantalum Sintering

Powder metallurgy is an attractive process which yields near-net shape parts and preforms for further processing. Tantalum is a refractory metal with multiple uses in the electronics industry. One significant use is in wire-wound capacitors. A preferred manufacturing method is to sinter, or hot isostatically press, a tantalum powder preform into a metal bar, which is then drawn into wire. The preform is electrically heated during sintering to very high temperatures (tantalum's melting point is 2996°C/5425°F). Product quality was variable and process upsets, wherein the preform melted or slumped, were frequent. If the failed preform then contacted metal fixtures within the furnace they would be flashed to vapor and the furnace would be out of commission for repair and cleaning.

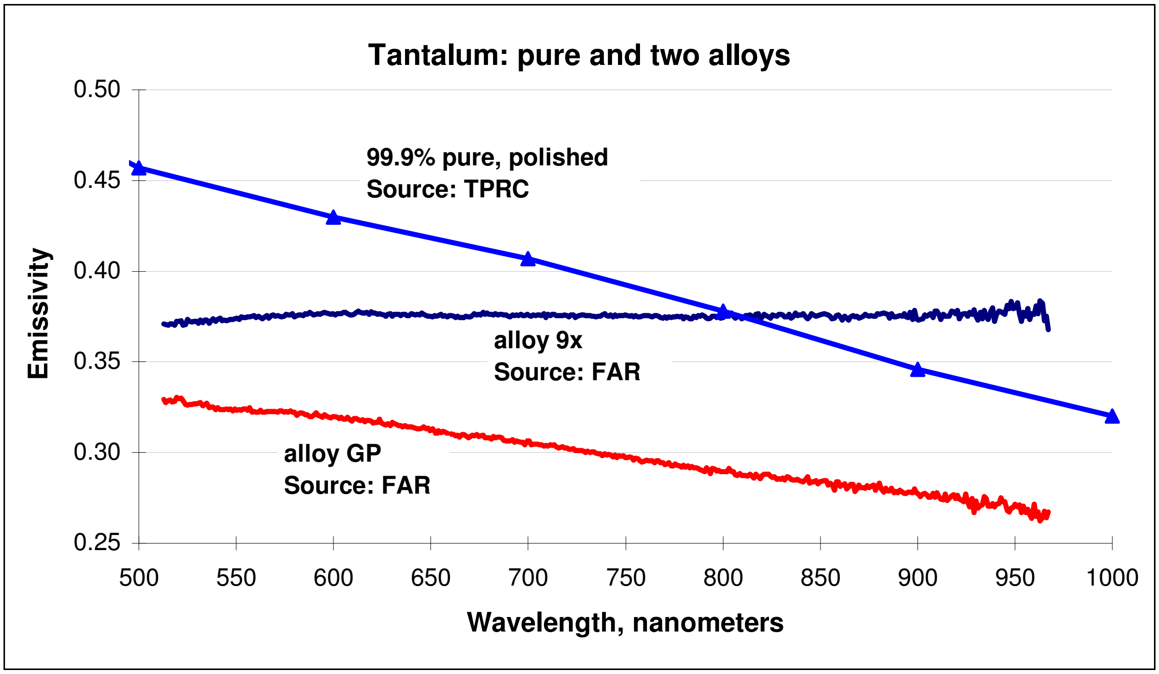

Figure 4: Emissivity of tantalum published by the Thermophysical Properties Research Center [5] and measured by FAR.

Figure 4 shows the cause of both the variability in product quality and the frequent upsets. The emissivity reported for pure tantalum metal is considerably higher than that measured for the alloys being used; this means a conventional pyrometer would return a temperature lower than actual. Further, the alloys show variation among themselves, so attempting to reproduce the measurement value from one alloy to another would not be a useful means of process control. (Manufacturers know that conventional pyrometers often return incorrect values; they rely on learning what the value should be by trial and error, equating a number with good quality. Then they reproduce that number to maintain quality.)

A process upset occurred while a SpectroPyrometer was monitoring a sintering run. Control was being maintained by a conventional pyrometer. The temperatures vs. time are shown in Table I. The shaded data from 13:32 to 14:09 show the upset. The tantalum preform slumped against water-cooled copper fixtures, flashing the copper to vapor and depositing it on all surfaces, including the sight port window through which the two pyrometers were measuring. The increased tolerance returned by the SpectroPyrometer reflects the new transmission of the window, which varied with wavelength in a manner not usually observed for natural emitters. This increased tolerance was the first sign that a process upset had occurred. The window was replaced before the 14:13 measurement, and the instrument's accuracy returned to earlier levels. Note that the 'temperatures' returned by the conventional pyrometer are about 500°C/900°F low at the peak values.

Table I: Temperature for sintering run with a process upset; temperature was monitored by a SpectroPyrometer and controlled by a conventional pyrometer. The upset occurred during the times shaded; note that the increase in the SpectroPyrometer's tolerance announces the process upset.

Time	**SpectroPyrometer, Temperature °C**	**SpectroPyrometer Tolerance, °C**	**Conventional Pyrometer, Temperature, °C**
10:57	2096	15	1925
11:04	2203	15	2000
11:09	2303	17	2075
11:13	2402	17	2160
11:47	2464	22	2150
13:32	2786	45	2300
13:39	2777	71	
14:09	2657	103	
14:13	2837	19	2340
14:21	2793	19	2300
15:03	2771	23	2290
15:11	2752	24	2290
15:28	2742	26	2287
15:58	2736	25	2310

Energy losses for this process are from overheating product during sintering, and include all the energy used in the production of any poor quality tantalum bar, including that to make the powder. Once sintered, the material is not easily recoverable.

Metal Casting – Investment Casting

The investment casting process rapidly melts high tech alloys and casts many parts at once. High value parts for the aerospace industry are manufactured by this technique. Metal temperature is a key variable, and affects the product quality in many ways [6]. Process times are brief, and energy losses are mainly from the energy used to produce the material that becomes scrap. Once scrapped, recovery of the raw feedstock is again energy intensive. And once more, errors are much larger and more prevalent than manufacturers believe. A test was arranged where both a conventional and SpectroPyrometer measured a nickel-based casting alloy. The alloy was heated rapidly at several different power settings, and then allowed to cool naturally. The emissivity was seen to vary from 0.22 to 0.60, a fact not previously recognized. Figure 5 shows the result: conventional pyrometers, set to an emissivity of 0.30, returned errors that ranged from about –200 to +200°F, a total of 400°F/222°C. The reason for the large setpoint (static) error in emissivity is that many alloys are used. These alloys have emissivities that range from 0.16 to 0.34 as measured by the SpectroPyrometer, so errors in emissivity of 15 to 50% are seen.

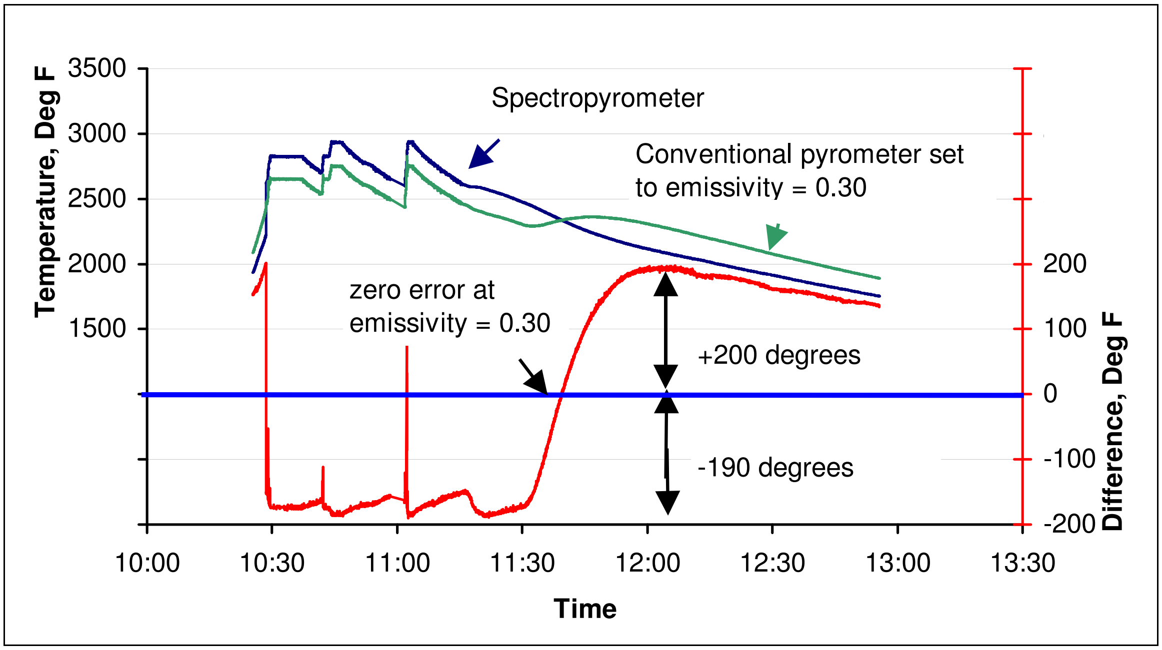

Figure 5 Temperature for an investment casting test; temperatures measured by conventional and Spectro- pyrometers (marked traces, values on left-hand y-axis). The bottom trace is the difference between the readings of the two pyrometers (values on right-hand y-axis): the error of the conventional pyrometer.

The next step was to observe the casting process while it was controlled by the conventional pyrometer; this is shown in Figure 6. The peak temperature is seen to be well above 2900°F (2700°F was the setpoint) and the repeatability is seen to be poor. The spikiness of the emissivity is caused by the turbulence of the melt, which is in turn caused by the power supply turning on and off. Turbulence enhances emissivity, which results in the conventional pyrometer sensing that the temperature is above the setpoint. Power is turned off by the controller, the melt quiets down, and the conventional pyrometer senses a temperature lower than the setpoint. The controller acts and the resulting spike in power electromagnetically stirs the melt, and the cycle continues.

Contrast this with the data shown in Figure 7. The ultimate temperature is well-controlled and reproducible at 2700°F. There is some turbulence early in the power cycle, but the magnitude is much smaller than that shown during the control of the conventional pyrometers. Also, the turbulence stops completely when the melt reaches and is controlled around the setpoint. This reduction in turbulence is a highly desirable result; turbulence erodes the refractory walls and one of the failure mechanisms is inclusion of the eroded refractory in the castings.

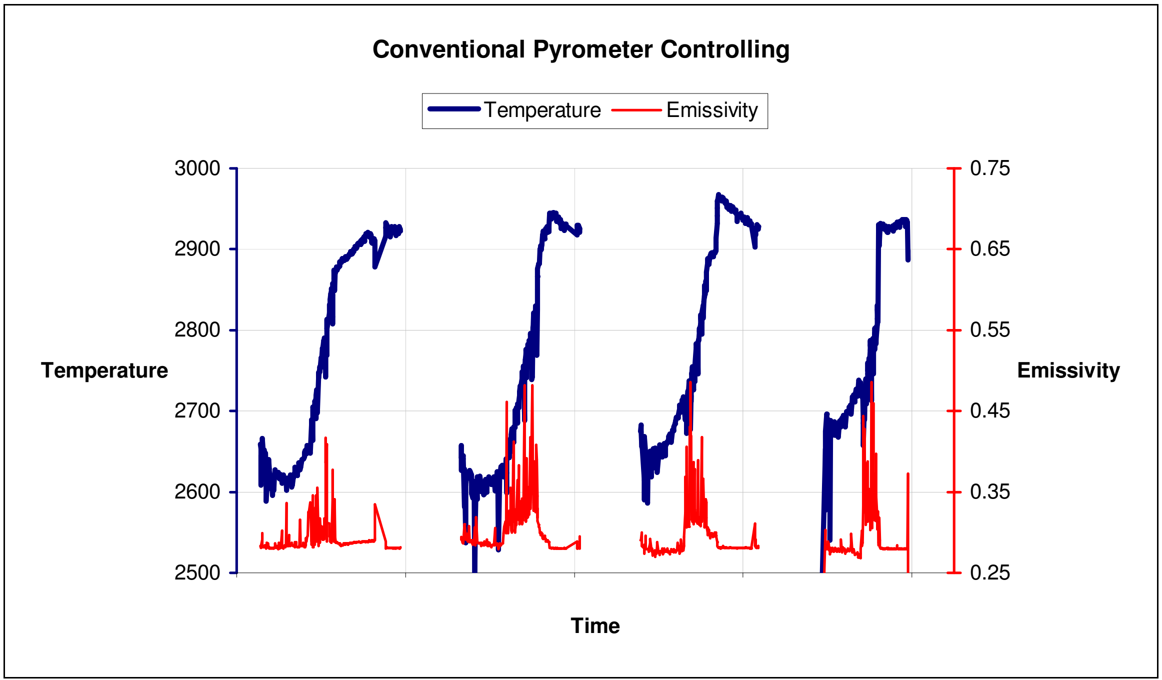

Figure 6: Casting process under conventional pyrometer control, SpectroPyrometer monitoring. Data presented is from SpectroPyrometer. Emissivity, the lower curve, is graphed against the right axis.

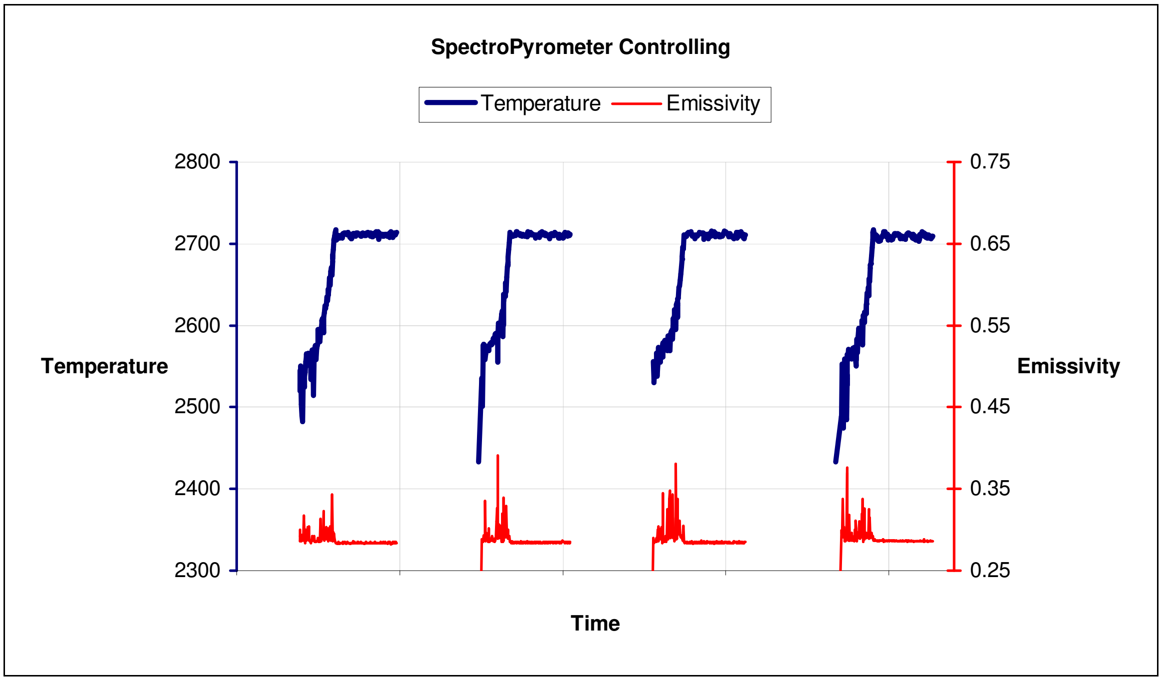

Figure 7: Casting process under SpectroPyrometer control. Temperature is about 250°F less than with conventional pyrometer controlling, and turbulence, as indicated by spikiness of emissivity, is substantially reduced. Emissivity, the lower curve, is graphed against the right axis.

Quantified Savings

Return on investment calculations have been done for investment casting that show the dollar value of improved temperature measurement from productivity increases. These calculations can be adapted to show the savings in energy and raw materials for any casting process. Energy savings from reducing over-temperature processing can also be calculated.

Table II. Investment Casting Return on Investment Calculation, Optimistic Case. Uses $30K as installed SpectroPyrometer cost.

Inputs	
Parts per mold	16
Cycle time, minutes per mold	8
Overall yield	85%
Production time, hours per week	80
Production time, weeks per year	50
Equipment utilization	45%
Sell price of part	$100
Average part value at inspection areas	$75
Scrap due to metal temperature (% total)	50%
Improvement due to SpectroPyrometer	50%
Return	
Days to pay back, order limited	18
Days to pay back, production limited	14
Average weight of casting, lbs.	0.5
Lbs/year raw mat'l saved	4050
Per cent savings in raw mat'ls energy cost	4.4%

Table II shows a typical calculation with assumptions that are perhaps optimistic with respect to the savings achieved. As can be seen, the savings in raw materials is a substantial 4.4%. Most entries are self-explanatory. “Equipment utilization” is the fraction of production time actually used for manufacture of parts. “Average part value at inspection areas” sets the value of scrap according to the amount of resources already invested. “Improvement due to SpectroPyrometer” means that this percentage of the total temperature-related scrap will now be good product. “Days to pay back, order limited” and “days to pay back, production limited” show how long it takes to recoup the investment assuming a $30K installed cost for the SpectroPyrometer. The difference between the two is the assumption that anything that can be made can be sold in the production-limited case.

To generate a more pessimistic view of the savings, the process yield is increased and scrap due to the temperature process variable and the improvement due to better measurement of temperature are both decreased. This yields Table III, which develops a respectable savings of raw materials equal to 1%. The savings shown in the tables do not include any energy burden to recycle the failed parts. To achieve the final step, turning the raw material savings into energy savings, requires the actual mix of alloys and the energy burden of each, and is beyond the scope of this calculation. Both scenarios use a conservative half-pound weight for a casting. Weights greater or less that this will affect the amount of energy saved but not the percentages.

Table III. Investment Casting Return on Investment Calculation, Pessimistic Case. Uses $30K as installed SpectroPyrometer cost.

Inputs	
Parts per mold	16
Cycle time, minutes per mold	8
Overall yield	90%
Production time, hours per week	80
Production time, weeks per year	50
Equipment utilization	45%
Sell price of part	$100
Average part value at inspection areas	$75
Scrap due to metal temperature (% total)	35%
Improvement due to SpectroPyrometer	25%
Return	
Days to pay back, order limited	77
Days to pay back, production limited	58
Average weight of casting, lbs.	0.5
Lbs/year raw mat'l saved	945
Per cent savings in raw mat'ls energy cost	1.0%

The energy savings for overtemperatures can be estimated fairly accurately. Considering the overtemperatures of Figure 6 relative to Figure 7 as about average for that process (an estimate borne out by the emissivity variations seen), then an ultimate temperature of 2950°F is being reached instead of the setpoint 2700°F. If the thermal capacity is assumed to be constant with temperature (a conservative assumption) then the excess energy is (2950 – 2700)/(2700 - RT) or about 10%.

Conclusions

An immediately achievable way to save energy is to improve process yield by improving the measurement quality of process control variables, and specifically that of temperature. Case studies were shown from the manufacture of ceramic and metal refractories, powder metallurgy, and metal casting. Savings of from one to more than four percent are easily achieved with only the change of the instrument measuring the variable, in this case replacing conventional pyrometers with a SpectroPyrometer. Losses from over-temperature processing were also identified; errors in temperature are larger and more frequent than manufacturers suppose, leading to substantial energy losses shown to commonly reach 10%. The new pyrometer is more accurate more often, and this results in substantial energy savings.

The energy savings quantified are the obvious ones that can be calculated easily. Concomitant savings also include those from decreases in refractory manufacture, scrap recycling, raw material mining, etc. Improvement in process control variable measurement, especially temperature, is a fruitful field for energy savings.

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