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Temperature Sensing Devices and Optimization of Temperature Acquisition Systems

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1.0 Introduction

James Clerk Maxwell defined temperature in the following way, "The temperature of a body is its thermal state, regarded as a measure of its ability to transfer heat to other bodies" [1]. In industry, temperature is of fundamental importance. Whether manufacturing micro-controllers, light bulbs, or batteries, there are stringent temperature extremes that cannot be exceeded in each step of the manufacturing process. Operational temperature ranges are also important for safe and efficient performance.

A processor that overheats can fail, or cause other components to overheat. A light bulb that creates too much heat is both an inefficient light source, and a fire hazard. When molding plastic it is important that it be kept between certain temperatures. Too cool and the material will not pour correctly, too hot and the plastic's properties will change, causing the final product to be deformed or brittle.

Once it is known that temperature plays a critical role in a system, it is imperative to be able to measure and control it. There are many ways in which one can measure temperature, some better suited to specific applications than others. When measuring the temperature of the sun, astronauts cannot fly to the sun and stick and tack on a thermometer. The thermometer will melt before it gets there. In this application non-contact or remote sensing is necessary.

1.1 Background & Scope

This report examines the composition and advantages of the four main thermo-sensing devices used in the manufacturing industry: thermocouples, resistance temperature detectors (RTDs), thermistors, and infrared pyrometers.

The _________________ Plant produces lead-acid automobile batteries. A car battery is composed of a durable plastic case, lead-oxide paste cured onto lead plates, and a sulfuric acid electrolyte. Virtually all of the processes involved in manufacturing a battery must be maintained at a critical temperature: molding the plastic cases, forming the lead paste and plates, fusing the cells of plates together, and charging the batteries. This report focuses on temperature readings taken in the lead smelting furnace where scrap lead is recovered, and the temperature of batteries as they charge on the charge tables.

1.2 Outline

This report is intended for readers who have experience in the manufacturing industry and are aware of the functioning of lead-acid batteries, though an intimate knowledge of either is not required. Section 2 of this report discusses the technology and structure of the temperature sensors individually. Section 3 compares and contrasts the sensors by analyzing their specifications. Section 4 summarizes the advantages and shortcomings of the sensors in different applications. It goes on to propose improvements to the current temperature acquisition system. Background reading on temperature sensors for this report was done at the following websites: the Omega Engineering webpage [2], the Watlow Electric Manufacturing website [3], the GlobalSpec Company website [4], and the Raytek non-contact temperature measurement solutions website [5].

2.0 Temperature Sensors

Common industry temperature sensing devices include thermocouples, resistance temperature detectors (RTDs), thermistors, and infrared pyrometers. These sensors translate the temperature into a reference voltage or a resistance, which is then measured and processed and a numerical temperature value is computed. The benefit of these sensors over regular mercury thermometers is that they can be connected to computers and networked with other sensors and heating elements, enabling continuous, real-time control to maintain, monitor, and record temperatures.

2.1 Thermocouples

Thermocouples are a physically simple sensor, though how they function is more complex. Figure 1 shows the basic wiring of a thermocouple. A thermocouple is comprised of two dissimilar alloys (wires A and B) joined at one end, called the “hot junction” (T_1). The other leads are connected to a voltmeter or other input device that measures the voltage (V_1) across the “cold junction” (T_2).

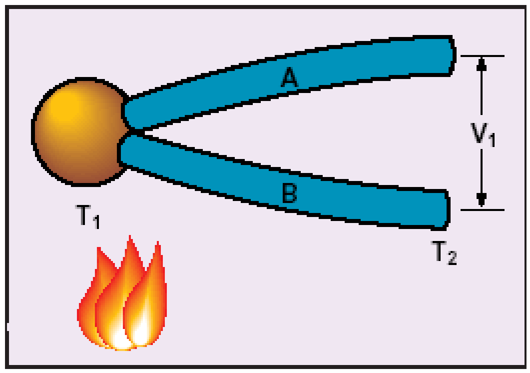

Figure 1: Thermocouple wiring diagram [6].

The hot junction is the sensing element, and the cold junction is kept at a constant reference temperature. A voltage is produced as the hot junction is heated, which is proportional to the temperature difference between the two junctions. This principle, called the thermocouple effect was discovered by Thomas Seebeck in 1821 [7]. And so, the electromotive force (emf) produced when the junctions of dissimilar alloys are maintained at different temperatures is known as the Seebeck emf. The theory behind the thermocouple and thermoelectric effect is based upon the atomic structure of the alloys and is beyond the scope of this report. The voltage is also dependent upon the type of conductors used. Different alloys produce distinct voltages; therefore standards have been established to facilitate reliability and repeatability. There exist eight standardized alloy combinations, each referenced by a letter: B, E, J, K, R, S, T, and N. Refer to the “Thermocouple Identification” and “Sensor Temperature Ranges and Accuracy” charts in Appendix A for their range, insulation colour codes, and alloy combinations [8].

The Seebeck emf produced by a thermocouple is of such small scale that the voltage must be amplified and processed by a specialized thermocouple input module. Figure 2 shows the Seebeck emf response of each thermocouple type to temperature. It also includes the non-standard C type thermocouple, composed of tungsten-rhenium alloys.

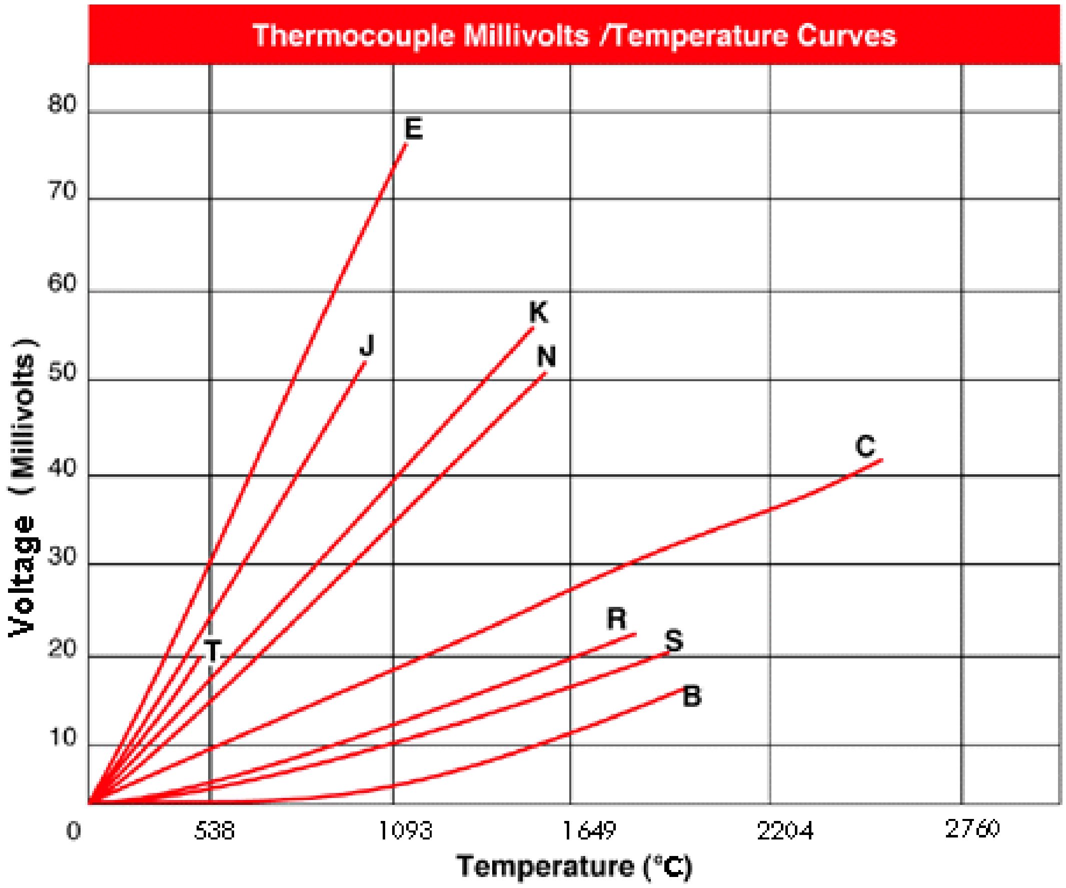

Figure 2: Thermocouple output voltage, by type [9].

Thermocouples are calibrated with a cold junction temperature of zero degrees Celsius. However, two problems arise when connecting thermocouples to their input device: the input terminals, which are constructed with a different type of metal, create their own Seebeck voltage which alters the actual thermocouple voltage; and second, the device has to be recalibrated for an operational cold junction temperature. With the advancements in technology over the past few decades, these input modules have been designed to be self-calibrating and self-compensating and are able to be configured for a variety of thermocouple types.

2.2 RTDs

Resistance temperature devices, known as RTDs, are constructed by winding a fine metal wire around a glass or ceramic cylinder, then a coating of glass or ceramic is applied to insulate the coil. RTDs function on the principle that as the sensing element is heated, the resistance of the metal wire increases proportionally. RTDs are commonly made with copper, nickel, or nickel-iron, but platinum RTDs are the most linear, repeatable, and stable, as can be seen in Figure 3. The resistance is almost a linear function of temperature for very pure platinum, which is the primary reason for this metal's pervasiveness in RTDs.

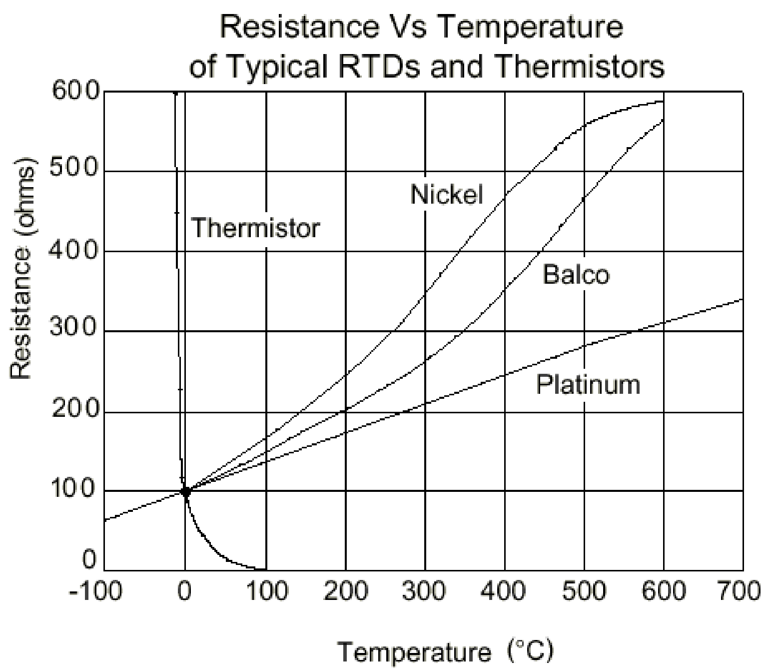

Figure 3: RTD and thermistor resistance versus temperature curve [10].

RTDs are calibrated to exhibit a resistance of 100 ohms at zero degrees Celsius. The resistance at other temperatures depends on the value of the mean slope of the metal's resistance-temperature plot, known as the constant alpha. The standard alpha values for platinum RTDs, their resistances, and accuracy are in Appendix B [11]. Alpha is dependant upon the platinum's purity. Although RTDs are fairly linear, advanced RTD input devices use software with curve fitting and software processing to increase their accuracy at higher temperatures.

2.3 Thermistors

Thermistors, like RTDs, vary their resistance as the ambient temperature is changed. Unlike RTDs, the resistance of a thermistor decreases as the temperature rises — and not in a linear fashion either. Comprised of a metal oxide ceramic semiconductor sensing element, thermistors are notorious for their non-linearity, which engineers often dampen by implementing pairs of offsetting thermistors, providing a more linear output. These temperature dependant resistors are highly sensitive to temperature change. Thermistors vary their resistance about -4.4 percent at 25ºC when heated by one degree Celsius [8]. Since thermistors are resistive devices, in operation an electrical current is passed through the sensor. Some of this electricity is converted into heat, which may cause slightly higher than ambient temperature readings. Thermistors can operate without significant error with long lead wires, because of their high base resistance. Thus they can be installed at long distances, upwards of one hundred metres, from the input module. Thermistor resistances are non-standardized and vary from 100 to 1,000,000 ohms at 25°C [8]. Figure 4 shows the resistance response of a Davis Industries precision platinum wire thermistor calibrated to 10,000 ohms at 25ºC

°F	°C	kΩ
-40	-40	328.400
-31	-35	237.700
-22	-30	173.900
-13	-25	128.500
-4	-20	95.890
5	-15	72.230
14	-10	54.890
23	-5	42.070
32	0	32.510
41	5	25.310
50	10	19.860
59	15	15.690
68	20	12.490
77	25	10.000
86	30	8.060
95	35	6.536
104	40	5.331
113	45	4.373
122	50	3.606
131	55	2.989
140	60	2.490

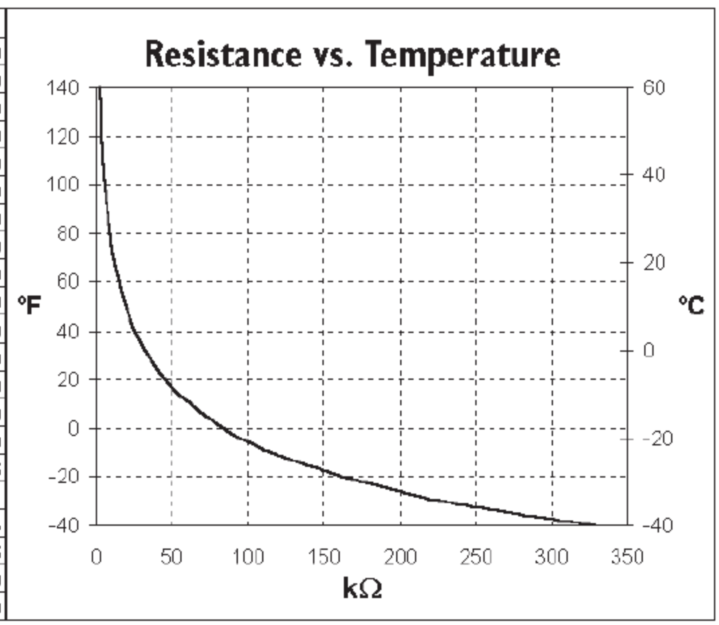

Figure 4: Thermistor resistance versus temperature response [12].

2.4 Infrared Pyrometers

A pyrometer is a device that measures high temperatures, meaning above the mercurial thermometer. These optical sensors measure the blackbody radiation emitted by the surface of an object with a photosensitive cell. The efficiency of a thermal emitter is measured by its emissivity; a perfect or blackbody radiator is given the value of one, and a perfect reflector is given a value of zero, though these perfect objects exist only in theory. The sensor converts the rate at which the object emits heat energy (thermal radiation) into a voltage or current, and built-in processing assigns it a temperature value in one of the common temperature scales. These sensors are calibrated using a radiator with an emissivity value approaching one and of known temperature. Therefore it is imperative to account for the emissivity of the object that is being measured. Compare for instance the emissivity of highly polished copper and asphalt, 0.03 and 0.9 respectively, from the emissivity chart in Appendix C [13]. In general metals are less emissive than non-metals, and shiny objects are less emissive than matte ones.
Another factor affecting infrared pyrometers is their field of view (FOV). Since these sensors are non-contact, the sensing element must be aimed directly at the object. If the FOV of the sensor encompasses more than the specimen being measured at a given distance, and if the other surface that happens to be in the FOV is of a different emissivity or temperature, the reading will be skewed. For proper operation, the target area should be at least one and a half to two times larger than the FOV. Figure 5 shows the correct placement of Object 2, but the sensor is positioned too far away from Object 1 to read accurately.

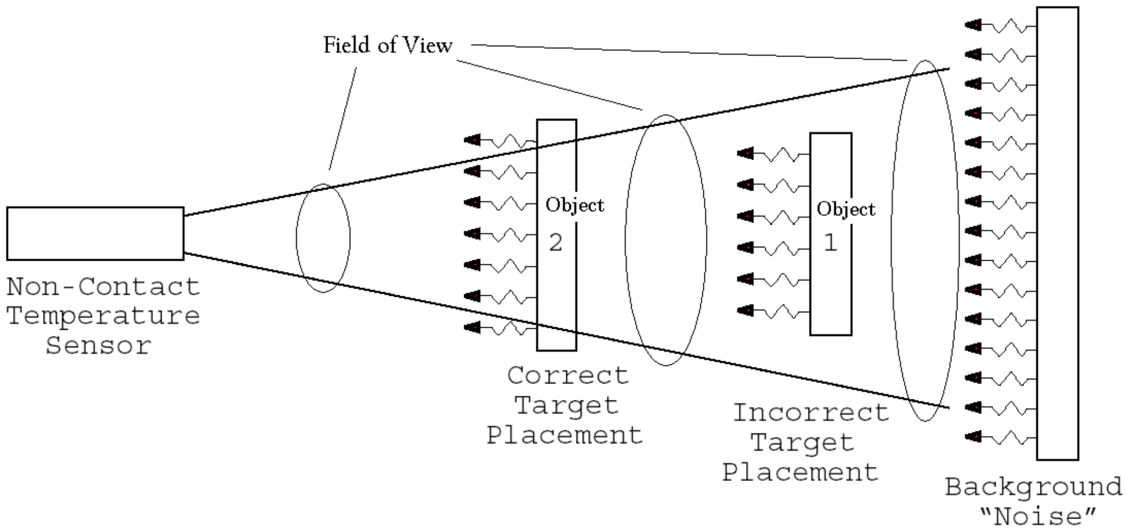

Figure 5: Infrared pyrometer placement and field of view [14].

Reflected heat energy is another source of error. Low emissivity surfaces, under certain conditions, tend to reflect more energy then they actually radiate causing misleading temperature readings.

While handheld infrared pyrometers are commonly available, data acquisition systems require a fixed sensor to achieve a consistent reading. Infrared sensors with fiber optic extensions are available where line-of-sight metering is not available. Infrared thermocouples are available with output power ratings analogous with the thermocouple standards. They are connected to regular thermocouple input modules, without the need of a power source.

3.0 Analysis & Comparison

A set of criteria is needed to compare various types of sensors and to ascertain the benefits and disadvantages of each. Based on the results, it will be shown which type of sensor is most suitable for specific applications. Many sensor properties are interrelated, so there are tradeoffs involved when determining the sensor's specifications. Refer to Table 1 for a side by side comparison of sensor specifications.

Table 1: Sensor Specification Guide [15].

Characteristic	Platinum RTD	Thermistor	Thermocouple	Infrared
Active Material	Platinum Wire	Metal Oxide Ceramic	Two Dissimilar Metals	Photosensitive Cell
Changing Parameter	Resistance	Resistance	Voltage	Voltage or Current
Temperature Range	-200°C to 500°C	-40°C to 260°C	-270°C to 1750°C	-50ºC to 3000ºC
Sensitivity	2 mV/ °C	40 mV/ºC	0.05 mV/ °C	1 mV/ ºC
Accuracy	-45 to 100°C: ±0.5°C; 100 to 500°C: ±1.5°C; 500 to 1200°C: ±3°C	-45 to 100°C: ±0.5°C degrades rapidly over 100°C	0 to 275°C: ±1.5 °C to ±4°C; 275 to 1260°C: ±0.5 to ±0.75%	± 1 to 3% of reading
Linearity	Excellent	Logarithmic, Poor	Moderate	
Response time	2-5 s	1-2 s	2-5 s	1 ms
Stability	Excellent	Moderate	Poor	Moderate
Base Value	100 Ω to 2 kΩ	1 kΩ to 1 MΩ	<10 mV at 25°C	
Noise Susceptibility	Low	Low	High	Low
Lead Resistance Errors	Low	Low	High	Low
Drift	±0.01% for 5 Years	±0.2 to 0.5°F per year	1 to 2°F per year	
Ruggedness	Good	Good	Excellent	
Special Requirements	Lead compensation	Linearization	Reference junction	Emissivity Calibration
Relative Sensor Cost	Moderate	Low	Low	High
Sensor Cost	$60-$215	$10-$350	$20-$235	$150-$450
Relative System Cost	Moderate	Low to Moderate	Moderate	Moderate to High

3.1 Temperature Range

Looking first at the measurable temperature ranges of these devices, note that no one sensing element will have the ability to span the entire range for which that family of sensor is rated. Infrared sensors have the largest range, followed by thermocouples. Although infrared sensors are able to measure extreme temperatures, the sensors themselves are not so resilient: the maximum ambient operating temperature is often less than 100ºC. Thermocouples have the largest range for a contact sensor, while thermistors have the narrowest measurable temperature band.

3.2 Sensitivity, Accuracy, and Repeatability

Sensitivity is the measure of the rate of change in output as the input is varied. In the case of temperature sensors it is the change in resistance or output voltage as the temperature is increased by one degree Celsius at a given temperature. Accuracy is the tolerance or proximity of the sensor's reading to the actual temperature. Thermocouples and infrared sensors have large ranges, but tend to have less sensitivity and accuracy. On the other hand, thermistors are very sensitive in a small temperature range. They are ten times more sensitive than RTDs and over 500 times more sensitive than thermocouples. With sensitivity comes accuracy and repeatability. Repeatability is the consistency with which the sensor gives the same output for a given temperature under the same conditions. The tight tolerance of thermistors exceeds that of other types of sensors, though RTDs can be calibrated to account for their slight nonlinear response to improve accuracy. Thermistor accuracy decreases as the temperature reaches its rated limit, while thermocouples are most accurate at higher temperatures. Platinum RTDs are, in theory, able to operate accurately at higher temperatures, but the price for higher purity and uniformity is often too costly to be worthwhile.

3.3 Response Time & Stability

Response time is the period of time it takes for the sensor output to adjust to a percentage (usually 63.2 percent) of its end value as the ambient temperature is increased instantaneously. Response time is predominantly a function of insulation and surface area to volume ratio. Smaller thermistors have a very quick response time, though unsheathed thermocouples also exhibit speedy response times. Stability describes the ability of a sensor to maintain a fixed output under a constant temperature. The larger and more insulated the sensor, the slower it will absorb heat, and more time will elapse before its output stabilizes. Conversely, self-heating of thermistors and RTDs is more significant in smaller packages than larger devices because of the difference in heat capacities. More energy is needed to raise the temperature of a larger device than is required to effect the same change in temperature of a smaller sensor. Self-heating is further reduced by limiting the current that passes through the sensor, which in turn will limit the sensor's resolution.

3.4 Base Values, Noise Susceptibility, and Lead Length

An advantage of thermistors over RTDs, because of their heightened sensitivity and relatively high base resistance, is that thermistor extension wires are able to be much longer than is possible for RTDs. Thermocouple extension wire is also available, but it must be composed of the same alloys as the thermocouple sensing element. Thermocouples are more vulnerable to noise and electromagnetic interference than other types of sensors, as their low base voltage and inferior sensitivity allows transient signals to permeate into the sensor's output signal causing erroneous or unstable readings.

3.5 Drift, Ruggedness, and Longevity

Unfortunately, the accuracy of a sensor is not maintained over extended periods of time under demanding conditions. Extreme temperatures may require a recalibration of the sensor, shorten the sensor's lifespan, or cause the sensor to fail immediately. Sensor drift is the tendency for a sensor to lose repeatability over long periods of time. Thermistors have a high chance of failing or outputting erroneous readings after being exposed to heat in excess of their rated temperatures. Thermocouples can drift significantly if installed directly in contact with a metal casing or thermowell, over time contaminating the thermocouple wire alloys. The longevity of a sensor is dependant on the amount of deterioration due to physical manipulation and temperature extremes that it endures, as well as how well it is protected from these stresses. Sensors are often guarded from extreme heat, corrosion, and other physical damage by means of metal thermowells, plastic sheathes, rubberized coatings, or ceramic insulation. The sensor and the lead wires are also shielded to reduce their vulnerability to noise being injected into the signal path.

3.6 Cost

Among the many factors that differentiate the sensors from one another, there are two overriding attributes that may mean the difference between the optimal temperature acquisition system and an ineffective system: temperature range and cost. The former is not so much a function of the latter, as is accuracy and ruggedness. In general, the more accurate and reliable the sensor, the more expensive it becomes. When calculating the total cost of a temperature acquisition system, it is important to account for the cost of the input and processing module in addition to the sensors themselves. Fortunately, many commercially available input modules are configured to accept various types of thermocouples and RTDs. Infrared thermocouples are interchangeable with standard alloy thermocouples, and as such, require only regular thermocouple input modules to operate correctly. As shown in Table 1, every type of sensor is available in a specialized, more costly package. These high priced items include well-insulated thermocouples for high temperature furnaces, miniaturized thermistors for medical use, and tight tolerance RTDs for laboratory use. At the other end of the spectrum, thermistors are the least expensive sensor, followed by thermocouples. RTDs are moderately priced, and can be purchased in quantity for well under $100 each, while the price of infrared pyrometers is consistently above the $100 threshold.

4.0 Applications

Before one can determine which type of sensor is best, the application for which it will be used must be established. In general, thermistors are suitable for applications that require high accuracy and quick response time from a small package. RTDs present a more costly system that is very stable over a larger temperature range than thermistors, while sacrificing accuracy only slightly. Thermocouples are implemented in applications where a robust sensor that offers a large temperature range is vital to the process, while the accuracy is not as critical. Thermocouples are also used in situations where the temperature of stagnant fluids is being measured, as it is in these circumstances that self-heating of resistive devices is most significant due to the lack of heat removal from the system. The temperature of large surfaces, which are either chemically or electro-magnetically volatile, is most appropriately measured by infrared pyrometers, though a larger budget is required. Non-contact infrared sensors are also employed when measurements are taken of extremely high temperature surfaces, or objects that will be ruined by making contact with the sensor, such as the surface of a freshly painted or easily scuffed product.

4.1 Applications in the Battery Plant

At the ________________ Plant, there are many processes that necessitate the control of temperature. Every closed-loop heating or cooling system — that is to say, a process where the output (the addition or extraction of heat) is dependant on some input (the current temperature value) — requires some form of sensor to gauge the needs of the system. Therefore, at the ________________ Plant, there are many processes that necessitate the use of temperature sensors. This section deals with only the lead smelting furnace, and the charge table battery temperatures, as sensors in these systems fail much more frequently than others.

4.2 Reverb Furnace

The reverberatory or reverb furnace is a natural gas fired furnace that deflects and diverts heat onto scrap lead, which is melted down and reused in the production of battery plates. The lead is heated to a temperature of about 590ºC, though the furnace itself is maintained between 980ºC and 1090ºC. Currently, two K-type thermocouples are installed in the ceiling of the furnace. They are encased in ceramic thermowells which protrude slightly from the ceiling and into the airflow of the furnace. The furnace has two safety systems in place: a high limit of 1150ºC, and a failed sensor mode. If the temperature measured by a sensor exceeds the high limit, the furnace will shutdown. If a thermocouple fails and opens the circuit, the furnace is automatically set to a low flame. In either case the temperature drops causing the lead to cool rapidly. Not only is time lost during reheating the lead, but the lead becomes re-crystallized and sulfated; problems that lead to shortened battery life down the road. However these problems are less catastrophic than the furnace temperature rising to such a degree that its contents pour onto the plant floor, or worse melt the furnace itself.

It is expected that the thermocouples fail after several months, but some thermocouples are failing after just three weeks; and at around $800 per thermocouple, it is not a cheap replacement. It has been found that the thermocouples currently in use, rated for 1370ºC, fail because they are exposed to higher temperatures than those specified by the manufacturer. As well, the ceramic thermowells which protected the failed thermocouples were found to be sagging or cracked due to extreme temperatures. After discussion with technical experts from the furnace manufacturer, it was revealed that the flame can reach temperatures of 1650ºC, more than either the thermowell or thermocouple can withstand.

These problems could be solved by substituting an R or S-type thermocouple, and reinforcing the thermowells with higher-temperature resistant ceramic. The Omron DRT1-TS04T thermocouple input module implemented in the furnace temperature system is easily adjusted to accommodate these types of thermocouples. The downside to using these platinum-rhenium devices is that the alloy is easily contaminated by metal fumes.

Another solution is to implement infrared pyrometers, as they can measure the extremely high temperatures found in the furnace. A line-of-sight path would have to be established between the sensing element and the target, fixing the sensor at a distance where it would not overheat. There is a definite uncertainty with this system as the emissivity of the target lead or furnace wall is unknown and possibly not uniform. In addition, steam and smoke can impede the accuracy of the temperature readings.

4.3 Charge Tables

The charge tables are the part of the battery production process where the assembled batteries, filled with sulfuric acid, are loaded for their initial charging. The purpose of the charging is to increase the batteries' capacity to a specified number of ampere-hours, and raise their open circuit voltage (or OCV, the voltage across the positive and negative terminals without the battery being attached to an electrical load) to 12.6 volts. The main factors that affect this voltage are the plates, specific gravity of the electrolyte (or battery acid strength), the amount of time for which the battery is charged, and the current at which the battery is charged. For each battery model, these variables are optimized to increase efficiency. Efficiency, in this case, is the ability to completely charge the batteries in the least amount of time. The number of ampere-hours is just that: the product of the current and duration for which a battery is charged. For any one battery model this ampere-hour rating must be maintained. This value is the battery's capacity, or the amount of time the consumer will be able to run his or her 500 watt stereo with the ignition off before the battery is drained beyond the point where the engine will be unable to start. So far, temperature hasn't been mentioned as a factor, but indeed it is. As the batteries are charged, they dissipate much of the energy as heat. If for instance a batch of batteries, which need 300 ampere-hours of charging, were charged at one hundred amperes for three hours, the heat inside the batteries would be such that the acid would boil, causing them to have an unacceptably high OCV. The batteries would be ruined beyond repair, and after many value-added hours of manufacturing, would be profits would not be. Take the same 300 ampere-hour battery, and charge it at three amperes for one hundred hours. This would take more than four days to reach the required OCV, much too long for this to be a feasible manufacturing process. Thus, the charging time and the charging current are optimized for each battery model to achieve the shortest charge time while maintaining a temperature never in excess of 70ºC.

Battery temperature is measured by inserting a thermocouple into the battery. The sensor sends its output signal to a specialized temperature input module connected to a programmable logic controller (PLC). A PLC is a microcomputer used to control electro-mechanical processes in a manufacturing environment. From the PLC, the data is sent to the charge table operator's console, enabling the operator to adjust charging parameters if the temperature is rising too quickly, and to data-logging computers, where temperature data is recorded for quality assurance and process control documentation. PLCs provide the possibility of automatically adjusting or shutting down charging if the battery temperature exceeds a set threshold.

The acid used in automobile batteries is quite corrosive, which presents several problems to implementing a temperature acquisition system. In addition the high voltage used to charge the batteries imparts another degree of danger onto the system. The sensors used on the charge tables are stainless steel encased J-type thermocouples. They have a thin layer of clear plastic over top of the metal casing, and are further protected by PVC (polyvinyl chloride) heat-shrink tubing. This application doesn't call for an extremely high accuracy sensor, but rather the most robust package available at a reasonable cost. Even with the aforementioned protection, acid is still able to leak under the plastic sheath, eroding the stainless steel casing. In addition, sensors fail due to electricity arcing across the metal jacket, which not only causes the sensor to fail but can overload the input module and cause internal components to malfunction. The plastic shrink-wrap does impede the acid, as a protected thermocouple can last several months while an unsheathed device can fail in a matter of days. Since the thermocouples are subject to mechanical stress due to their insertion and removal from the batteries on a daily basis, the outer layer can be nicked allowing the acid to seep under the protective layers. Figure 6 shows a photograph of a failed thermocouple (on the right). It is corroded and shows signs of arcing; the insulation (on the left) is cracked.

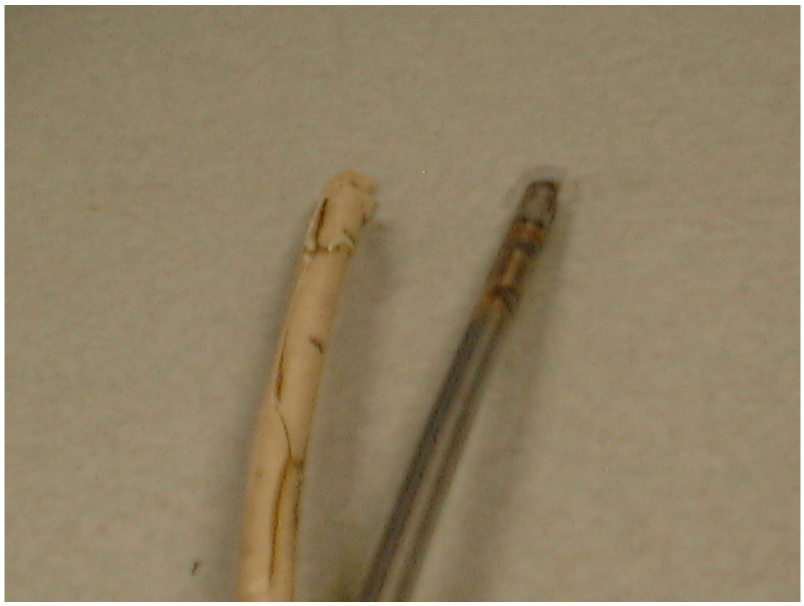

Figure 6: Photograph of failed thermocouple and PVC sheath.

Several ideas have arisen to improve the longevity of the sensors: dipping them in an acid resistant rubber to seal the sensors, encasing them in a ceramic shell, using non-contact infrared thermocouples, covering the sensors in a fiberglass and epoxy resin, and developing an ergonomic thermowell which would ease mechanical stress as well as sheltering the sensors behind another layer of protection. After discussion with technical representatives from the Loctite Corporation it was concluded that their rubberized acid-resistant coatings would not withstand the highly corrosive battery acid, and there was a concern that the coating would be scraped off the thermocouples as they are inserted and withdrawn from the batteries. The fragile ceramic shell would be too easily broken, even if it could stand up to the acid bath. Infrared thermocouples were rejected because the sensors are used to measure the temperature of the acid inside the battery, and the emissivity of the liquid surface is continually changing. Design and construction is underway for the fiberglass encapsulation and the battery-fitted thermowells.

To reduce costs, inexpensive thermistors could be implemented, as they are available in temperature ranges between 0ºC and 150ºC. They would need to be packaged in a similar protective casing as the thermocouples mentioned above. As well a feasibility study should be performed to investigate the cost of implementing a new thermistor interface system, as well as the sensors' longevity in the harsh operating environment.

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Appendix A: Thermocouple Input Specifications

Appendix A shows the thermocouple type, alloy composition, and the respective colour codes specified under the ANSI standards [8]. As well it details the operational temperature range and accuracy by thermocouple type. It also includes the range and accuracy of a 100 ohm platinum RTD for comparison.

THERMOCOUPLE IDENTIFICATION

ANSI Code	Alloy Composition		COLOR OF INSULATION American: ISA-RP1 (ASA-C96-1)		
	+ Wire	- Wire	Outer Sheath	+ Wire	- Wire
J	Iron Fe	Constantan Cu-Ni	BLACK	WHITE	RED
K	Chromel Ni-Cr	Alumel Ni-Al	BROWN	YELLOW	RED
T	Copper Cu	Constantan Cu-Ni	BROWN	BLUE	RED
E	Chromel Ni-Cr	Constantan Cu-Ni	BROWN	PURPLE	RED
B	Platinum-30% Rhodium Pt-30%Rh	Platinum-6% Rhodium Pt-13%Rh	GREY	GREY	RED
R	Platinum-13% Rhodium Pt-13%Rh	Platinum Pt	GREEN	BLACK	RED
S	Platinum-10% Rhodium Pt-10%Rh	Platinum Pt	GREEN	BLACK	RED
N	Nicrosil Ni-Cr-Si	Nisil Ni-Si-Mg	BROWN	ORANGE	RED

Sensor Temperature Ranges and Accuracy

Sensor	Input Type	Max. Range °C	Accuracy °C
J	Iron-Constantan	-50 to 999°C	±2°C
K	Chromel-Alumel	-50 to 1370°C	±2°C
T	Copper-Constantan	-270 to 400°C	±2°C
E	Chromel-Constantan	-50 to 750°C	±2°C
B	Pt 30% RH/Pt 6% RH	300 to 1800°C	±3°C
R	Pt 10% RH/Pt	0 to 1750°C	±2°C
S	Pt 10% RH/Pt	0 to 1750°C	±2°C
N	Nicrosil-Nisil	-50 to 1300°C	±2°C
RTD	PT 100 ohms	-200 to 500°C	±0.4°C

Appendix B: RTD Input Specifications

Appendix B shows the specifications of 1000 ohm and 100 ohm wire wound and thin film platinum RTDs [11]. The ice points, alpha values, and resistance values as a function of temperature are included, as well as their accuracy as a function of temperature.

PLATINUM RTD RESISTANCE-VS-TEMPERATURE				
Ice Point, Alpha Value & RTD Type	1000Ω 0.00375 Pt Thin Film	100Ω 0.00385 Pt Thin Film	100Ω 0.00385 Pt WW	100Ω 0.003902 Pt WW
Temperature °C	Resistance (Ω)			
-200	199.49	18.10	18.10	19.76
-180	284.87	26.81	26.81	28.01
-160	368.57	35.35	35.35	36.17
-140	450.83	43.75	43.75	44.27
-120	531.83	52.04	52.04	52.31
-100	611.76	60.21	60.21	60.31
-80	690.78	68.30	68.30	68.27
-60	769.01	76.32	76.32	76.22
-40	846.58	84.27	84.27	84.15
-20	923.55	92.16	92.16	92.08
0	1000.00	100.00	100.00	100.00
20	1075.96	107.79	107.79	107.92
40	1151.44	115.54	115.54	115.84
60	1226.44	123.24	123.24	123.76
80	1300.96	130.89	130.89	131.69
100	1375.00	138.50	138.50	139.61
120	1448.56	146.06	146.06	147.53
140	1521.63	153.57	153.57	155.45
160	1594.22	161.04	161.04	163.37
180	1666.33	168.46	168.46	171.29
200	1737.96	175.83	175.83	179.21
220	1809.11	183.16	183.16	187.14
240	1879.78	190.43	190.43	195.06
260	1949.96	197.67	197.67	202.98
280	2019.67	204.85	204.85	210.90
300	2088.89	211.99	211.99	218.82
320	2157.63	219.08	219.08	226.74
340	2225.89	226.12	226.12	234.66
360	2293.66	233.12	233.12	242.59
380	2360.96	240.07	240.07	250.51
400	2427.78	246.98	246.98	258.43
420	2494.11	253.83	253.83	266.35
440	2559.96	260.65	260.65	274.27
460	2625.33	267.41	267.41	282.19
480	2690.22	274.13	274.13	290.11
500	2754.63	280.80	280.80	298.04
520	2818.55	287.42	287.42	305.96
540	2881.99	294.00	294.00	313.88
560	2944.96	300.53	300.53	321.80
580	3007.44	307.01		
600	3069.44	313.44		
620	3130.96	319.83		
640	3191.99	326.18		
660	3252.55	332.47		
680	3312.62	338.72		
700	3372.21	344.92		
720	3431.32	351.08		
740	3489.95	357.18		
750	3519.09	360.22		

ACCURACY VS TEMPERATURE			
Ice Point, Alpha Value	1000Ω 0.00375	100Ω 0.00385	100Ω 0.003902
Temperature °C	±ΔResistance (Ω)		
-200	5.1	0.5	0.5
-100	2.4	0.3	0.3
0	1.0	0.1	0.1
100	2.2	0.2	0.2
200	4.3	0.4	0.4
300	6.2	0.6	0.6
400	8.3	0.8	0.8
500	9.6	1.0	1.0
600	10.4	1.2	1.2
Temperature °C	±ΔTemperature (°C)		
-200	1.2	1.2	1.2
-100	0.6	0.6	0.6
0	0.3	0.3	0.3
100	0.6	0.6	0.6
200	1.2	1.2	1.2
300	1.8	1.8	1.8
400	2.5	2.5	2.5
500	3.0	3.0	3.0
600	3.3	3.6	3.6

Appendix C: Table of Total Emissivity

Appendix C provides the emissivity values for common metals and non-metals in alphabetical order [13]. Materials with varying grades are shown with separate emissivity values.

Emissivity Table for Non-Metals

Material	Emissivity
Asbestos	0.9
Asphalt	0.9
Basalt	0.7
Carbon	
Unoxidized	0.8-0.9
Graphite	0.7-0.9
Carborundum	0.9
Ceramic	0.85-0.95
Clay	0.85-0.95
Concrete	0.9
Cloth	0.95
Glass	
Plate	0.98
Gob	0.9
Gravel	0.95
Gypsum	0.4-0.97
Ice	0.98
Limestone	0.4-0.98
Paint (non-Al.)	0.9-0.95
Paper (any color)	0.95
Plastic	
Qpaque	0.95
Over 20 mils	
Rubber	0.9
Sand	0.9
Snow	0.9
Soil	0.9-0.98
Water	0.93
Wood, (natural)	0.9-0.95

Emissivity Table for Metals

Material	Emissivity
Aluminum	
Unoxidized	0.02-0.2
Oxidized	0.4
Alloy A3003	
Oxidized	0.4
Roughened	0.2-0.6
Polished	0.02-0.1
Brass	
Polished	0.01-0.05
Burnished	0.3
Oxidized	0.6
Chromium	0.4
Copper	
Polished	0.03
Roughened	0.05-0.2
Oxidized	0.2-0.9
Electrical Terminal Blocks	0.6
Gold	0.01-0.1
Haynes	
Alloy	0.6-0.9
Inconel	
Oxidized	0.6-0.9
Sandblasted	0.3-0.6
Electoropolished	0.25
Iron	
Oxidized	0.5-0.9
Unoxidized	0.1-0.3
Rusted	0.6-0.9
Molten	0.4-0.6
Iron, Cast	
Oxidized	0.7-0.9
Unoxidized	0.3
Molten	0.3-0.4
Iron, Wrought	
Dull	0.9
Lead	
Polished	0.05-0.2
Rough	0.6
Oxidized	0.3-0.7
Magnesium	0.05-0.3