THERMAL PROTECTION OF AN INDUCTIVE PROXIMITY SENSOR UTILIZING LOW-DENSITY CERAMIC COMPOSITION TILE

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by

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ABSTRACT

This thesis presents the results of a unique method for protecting inductive proximity (IP) sensors from extreme thermal exposure. The method presented in this study employs a barrier of ceramic tile material developed for the space shuttle program. While it may be intuitive that the ceramic tile material will provide adequate protection for extreme temperatures, what is not clear is the adaptability of this material to commercial use in a steel mill environment.

One of the potential problems associated with using any thermal barrier is a partial or complete attenuation of the magnetic field generated by the sensor. To effectively utilize the shielding material in an application such as this it is necessary to understand the effect of the ceramic material on the magnetic field generated by the proximity sensor.

In order to test the effectiveness of the ceramic tile to provide the level of thermal protection required and to discover if the tile will allow adequate magnetic field penetration for sensor detection, a series of two separate tests will be run. The first test will verify that the thermal shielding properties maintain the cool side temperature within the operational threshold of the sensor; the second test will establish the maximum sensing distance with the ceramic tile interposed between the sensor and the detectable object. This study determines if it is possible to consistently detect piping of 4” nominal diameter carbon steel pipe at a minimum specified distance from the shielding assembly.

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CHAPTER 1

INTRODUCTION

The manufacture of pipe generates thermal energy in excess of 1200° F and ambient temperatures in the manufacturing facility can range up to 100° F on a continual basis. The purpose of this project will be to test a system that will protect the proximity sensors from direct radiant exposure shock. Protection of the sensor will yield a longer mean time before failure, and reduce replacement costs significantly!

As is common with most industrial manufacturing, steel mill operation relies heavily upon automated systems to control essential processes. In the manufacture of steel piping, automated systems also perform in a hazardous environment.

Statement of the Problem

Pipes manufactured by U.S. Steel are produced by an electric resistance welding (ERW) method. Two welders are coupled with two hot reduction systems to produce various sizes and grades of piping. The production method for ERW pipe produces a pipe equal in performance characteristics to seamless pipe for most applications. A thermal treating facility ensures the consistent production of high strength grades for American Petroleum Institute (API) products.

When a piping order is to be fulfilled, piping is moved from the stocking area onto a conveyor system that takes the piping through a reheat furnace to bring the metal temperature up to a level that will allow the pipe to be straightened before shipment. Piping on the conveyor system can reach temperatures in excess of 1100° F. To cool the pipe prior to straightening, and to further cool the pipe after straightening, a series of four cooling tables are utilized. The cooling tables are fed from a conveyor system; a set of mechanical lifting arms moves the piping off the conveyor and on to the table. A series of proximity sensors detects the presence of piping and activates the lift arms. Entry and exit temperatures at the cooling tables calculated by Lone Star Steel engineers are depicted below.

Table 1 Expected Thermal Conditions.

	By-passing Straightener Assembly				Through Straightener Assembly		
	Table Entry	Table Exit	Time on Table		Table Entry	Table Exit	Time on Table
Table #1	1100 F	386 F	00:53		0 F	0 F	00:00
Table #2	386 F	184 F	00:53		945 F	404 F	00:29
Table #3	184 F	134 F	00:53		404 F	253 F	00:24
Table #4	134 F	114 F	00:53		253 F	182 F	00:24

Proximity sensors are utilized to control conveyor speed (timing pipe movement) and to activate the mechanical arms used to lift the pipe from the conveyor. Continued exposure from direct radiant energy (up to 1100° F) from the piping causes incremental damage to the sensors, creating a constant maintenance issue. The sensors are placed directly under the conveyor, and replacing them requires the system to be shut down.

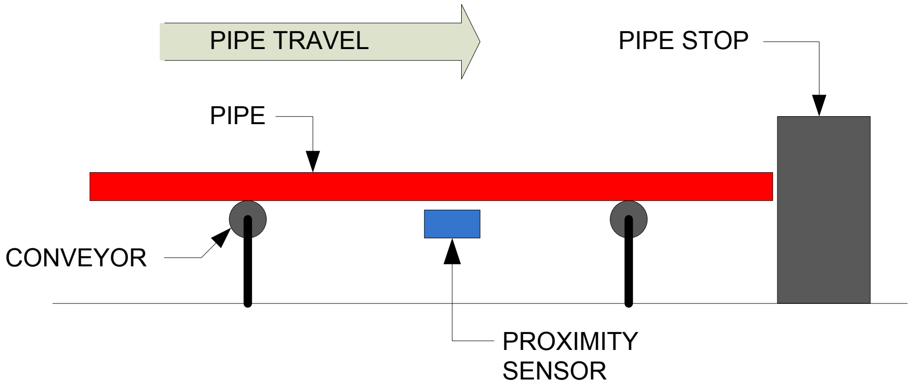

Figure 1. Proximity Sensor Placement

Technology for Research

The NASA space shuttle program utilizes a complex thermal protection system comprised of various light-weight materials applied to the external structural skin of the orbiter craft. The main purpose of the thermal protection system is to protect the shuttle during reentry. The materials applied to the shuttle operate over an extreme range of temperatures, from -250º F in space, to over 3000º F generated during re-entry into the atmosphere. The main types of insulation used are:

- Reinforced Carbon-Carbon (RCC): used on the wing leading edges, nose cap, and immediate area around the forward orbiter/external tank structural attachment, where temperatures can exceed 2300º F.
- High-temperature reusable surface insulation (HRSI) tiles: used in areas on the upper forward fuselage, including around the forward fuselage windows; the entire underside of the vehicle where RCC is not used, temperature ranges below .
- Fibrous refractory composite insulation (FRCI) tiles: developed later in the shuttle program, replacing some of the HRSI tiles.

- Low-temperature reusable surface insulation white tiles are used in selected areas of the shuttle where temperatures are below 1,200 F.
- In 1996 NASA added a fourth tile material, AETB-8 (alumina-enhanced thermal barrier) which is based on the FRCI tile, but includes alumina ($Al2O3$) fiber into the composition.

Purpose of the Study

The purpose of this study was intended to answer research questions concerning whether the ceramic tile material AETB-8 developed for the space shuttle program can be utilized in a steel mill application, with the intent to protect an IP sensor from radiant energy, while allowing the sensor to function in an adequate fashion. As such there were be two separate research questions, and two separate hypotheses.

Statement of Hypotheses

In order to address the two research questions the statement of the hypotheses of the study may be summarized as follows:

i. H1 – A ceramic tile material barrier will protect the proximity sensor at a temperature of less than or equal to 150^{o} F.

ii. $H1_0$ (null) – A ceramic tile material barrier will not protect the proximity sensor at a temperature of less than or equal to 150^{o}F.

iii. H2– A ceramic tile material barrier will not prevent the sensor from detecting the presence of piping at a minimum distance of greater than, or equal to 30 mm.

iv. $H2_0$ (null) – A ceramic tile material barrier will prevent the sensor from detecting the presence of piping at a minimum distance of greater than, or equal to 30 mm.

Set Alpha (Type 1 error)

Alpha is the probability of making a Type 1 error: rejecting the null hypothesis when it is actually true. The greatest risk of making a Type 1 error in this case, is accepting the ceramic tile will not adequately shield the sensor, when in fact it does. A similar mistake could be made by accepting that the shielding material does not allow the sensor to function, when in fact it does. Such mistakes could cause the pipe manufacturing plant to reject a low-cost solution to an existing high maintenance issue.

Setting the alpha at 0.05 is a customary practice; this will allow a confidence level of 95% that the right decision has been made (Spiegel, 2008). An alpha of 0.05 means that 1.645% of one tail of the population distribution could be attributed to chance and we would still be able to reasonably reject the null hypotheses (Glass, 1996).

Statistical Method

The statistical method to be utilized for this research will be the t-test. The t-test distribution is called for when the sample size is small, and when the sample value is ≥ 30 the distribution curve closely approximates the standardized normal curve (Spiegel, 2008). This statistical method has been selected because it is expected that the data recorded will closely approximate a normal distribution. For the temperature portion of the thesis it is important that the ceramic material provides a consistent thermal barrier for the duration of the exposure to the kiln. Since there is only one sample, utilizing the t-test will identify whether the mean of the population has a value specified in the hypothesis. Additionally, since the hypothesis is essentially one-tailed (a thermal value greater than the stated value in the hypothesis would compromise the sensor) the t-test will provide a direct indication as to whether the barrier is sufficient.

The dependent variable in hypothesis H1(i) and null hypothesis $H1_0$ (ii) is the temperature on the cool side of the shielding assembly being tested. The independent variable is the thermal exposure time. For hypothesis H2 (iii) and null hypothesis $H2_0$ (iv), which is concerned with sensor functionality, the dependent variable is the sensor detecting the pipe (discrete function), and the independent variable is the distance between the pipe and the sensor face.

For the first test (H1 hypothesis) the dependent variable will be measured over a period of 45 – 60 seconds to simulate the exposure period of the sensor in a steel mill application. The method is described in detail in the Testing Method – Thermal Shielding section of this document. The measured data will be recorded and then analyzed to determine the temperature range recorded during each exposure period. Particular attention will be paid to determine if there is a thermal “creep” as the result of repeated exposure.

For the second test (H2 hypothesis) the independent variable will be measured to determine if a consistent sensing distance can be established. The detection distance must be sufficient to provide clearance for the pipe traveling above it in the steel mill. In order to clear the ceramic tile the distance must be in excess of 30 mm.

CHAPTER 2

REVIEW OF RELATED LITERATURE

As with any manufacturing entity the costs associated with downtime at a steel mill must be kept at a minimum. Repeated sensor replacement due to environmental damage caused by extreme temperature exposure can contribute to plant downtime. Advanced ceramics have many characteristics that make them suitable for thermal shielding in an industrial environment such as found in a steel mill: they are lightweight, wear and corrosion resistant, and thermodynamically stable (McGuire, 2002).

Environmental Considerations

Environmental conditions can have an impact on the performance of any sensor, IP sensor included. Guerrino Suffi, product marketing specialist for Omron Electronics, indicates that "higher temperature extremes can reduce the operating life, or cause permanent failure. Additionally, the IP sensors' internal semiconductors may begin to behave erratically under extreme temperatures, either producing unexpected outputs or not responding at all" (Suffi, 2001).

In a presentation highlighting the emerging use of frequency modulated guided wave radar, Chuckpaiwong (2002) notes that there are many non-contact methods currently used for measuring displacement: capacitive, inductive, hall effect, and laser. To help make the point for the benefits of using radar technology he points to the limitations of other technologies, one of them being unsuited to ‘hostile environments’, (which can be equated to the environment you would find at a steel mill, due to the elevated temperatures required to form and process products.)

Economic Considerations

The economic costs of sensor replacement are broad as pointed out by Ron Cunningham, Cutler-Hammer product manager, “In today’s industrial automation applications, downtime can cost anywhere from $5,000 to $25,000 per hour.” He goes on to state, “However, the cost equation has a broader scope. While the cost of replacing a damaged sensor is the factor that gains attention, the true cost goes beyond that. It is the sum of procuring a new sensor, downtime, reduced machine efficiency, the sensor itself, plus installation and adjusting time” (Wayne Labs, 1999).

Material Development and Mastery

In a white paper produced for the Department Of Energy (DOE) the author(s) state: “From the Bronze Age to the silicon-driven Information Age, civilization has defined itself – and advanced itself – by mastering new materials.” Advances in materials at the core of our everyday lives, and drive our economical, scientific and social progress. The federal government has supported numerous studies that document the huge economic and strategic importance of material research and development, particularly focused on industrial research and development.

Our current standard of living has been determined in a large part by the past discovery of “new” materials and their fast adoption into our society. Seemingly simple discoveries can yield huge economic impact. The white paper from Ames Laboratories gives us a good example: “Finding new cost effective ceramics that would allow the operating temperature of power plants to increase by just 100° C would raise their efficiency by two percent and reduce the amount of CO_2 emitted by 10 million metric tons" (U.S. DOE, 1999).

Researchers Susan White and Daniel Rasky of Ames Research indicate, in a white paper describing an advanced fibrous-ceramic composite, "Tiles made of ceramic fibers are known for mechanical strength, toughness, and machinability" (White, n.d.). This durability and workability will be important to any steel mill applications.

Lance Caspersen, manager of market development for Thermal Ceramics, Inc., indicates that "because of their low density, micro-porous insulation materials, such as Thermal Ceramics BTU-Block, are particularly useful in areas in which thickness or weight is an issue." He continues, "For example, 1-in. (25 mm) thick BTU-Block delivers the same thermal efficiency as three to four inches of standard ceramic fiber blanket or board" (Caspersen, 2001).

Researchers at NASA's Ames Research Center have discovered that thermal-protection panels made by impregnating fibrous ceramic substrates with organic polymers can temporarily protect against temperatures up to 3500° C, or heat fluxes up to 16 megawatts (MW) m^2. At a heat flux of approximately 4.3 – 16 MW/M^2 the panel dissipates incident heat almost entirely by re-radiation and micro-spallation, or the ceramic substrate's evaporation. Tran (2001) indicates that one possible use might be using these panels to protect workers in steel mills or other high-heat plants.

History of Thermal Shielding Development

NASA describes the design of the space shuttle orbiter which includes a thermal protection system that shields it from extreme temperatures encountered when the crafter re-enters the atmosphere. These temperatures can reach as high as 3,000 degrees Fahrenheit, exceeding the melting point of steel, and the 350° F threshold for the shuttle's airframe materials.

The white tiles (similar to the material used in this thesis) were designed for use in temperatures below 1200° F. In 1996 a new tile material was introduced, AETB-8 (alumina-enhanced thermal barrier) which took the existing technology further by the inclusion of alumina (Al2O3) fiber. The addition of the fiber increased thermal stability, yet added little to the weight (NASA, 2008a).

The original design for the thermal protection system of the space shuttle program consisted of four materials: reinforced carbon-carbon (RCC), low- and high-temperature reusable surface insulation tiles (LRSI and HRSI), and felt reusable surface insulation (FRSI) blankets. Later in the program NASA developed other tile materials to minimize thermal conductivity and weight, while providing maximum thermal shock resistance. The AETB-8 tile, introduced in 1996, was one of those materials. These tiles exhibit higher strength without significant weight increase (NASA, 2008a).

Commercial Application of the Thermal Protection System

NASA acknowledges that there are numerous possibilities for commercial application of the thermal protection system materials. But they also acknowledge that high costs are a distinct deterrent to further commercial development, noting “a single coated tile can cost as much as $1,000” (NASA, 2008a).

Technology from NASA however is finding its way into commercial applications. One of those technologies comes from the thermal protection system of the shuttle. Cockpit temperatures can reach 140 – 160° F, with floorboard temperature near the exhaust reaching up to 330° F. NASA notes in one of their Tech Briefs: “NASA and Penske personnel worked together to fit the (Penske) car with TPS insulation. The material added less than four pounds to the car and lowered the cockpit temperature by 50°” (NASA, 2008b).

Another thermal insulation product coming from the space program that has a proven commercial application is a highly flexible version of Aerogel. Aerogel is composed of silicone dioxide and 99.8 percent air and is used by NASA in several application related to the space shuttle, including cryogenic insulation for space shuttle launch applications. Aerogel was invented nearly 80 years prior, but had found little commercial use due in part to the manufacturing costs involved. The flexible version of the material was developed in a partnership between NASA and a small business, Aspen Aerogels Inc., of Northborough, Massachusetts. Aspen Aerogels was able to develop a manufacturing method for the material that cut both production time and costs, making it commercially viable. One current commercial use for the material is insulation for extreme weather gear (NASA, 2009).

CHAPTER 3

METHODOLOGY

As stated in the hypotheses section, the purpose of this study is two-fold: first to verify that the ceramic tile panel will indeed provide the thermal protection required, and secondly to verify that the ceramic shielding does not significantly attenuate the magnetic field generated by the sensor. To that end there will be two separate methods for gathering the data necessary. The shielding assembly will be tested in a laboratory-type setting due to the impracticality of testing at the Lone Star Steel facility. Utilizing a laboratory-type facility will provide a stable controlled environment that will allow unrestricted setup and will not be affected by outside influences that may have played a factor in a manufacturing setting. One concern however, is that the kiln used to simulate the hot piping may not be robust enough to allow continual repeated testing, and it will require a longer time period to conduct the testing.

Shielding Assembly Components

During the preliminary research little commercial information was uncovered as to potential sources for the actual ceramic tile material used by the shuttle program. The actual tiles used on the various space shuttles are closely controlled by the government, making acquisition of actual shuttle tile not possible. However, a similar tile material manufactured by Orbital Ceramics was located, and a sample of their product AETB-8 was furnished by that manufacturer. In discussions with the sales engineer from Orbital Ceramics, the ability of the ceramic material to block radiant energy at the level developed in a steel mill environment could be accomplished by a material thickness of 1/2 inch. I requested a tile sample of approximately 1-inch thickness with the intent of determining if a more substantial barrier would still allow the sensor to function properly. The actual tile supplied by the manufacturer has dimensions of 13.5” x 13.5” x 1.125”. Table 2 contains the ceramic tile material data furnished by the manufacturer.

Table 2 AETB-8 Material Data.

Mechanical Data	**Test Value**
Tensile strength, psi	63.0 average
Thermal Conductivity	
Temperature ºF	1000
Absolute Pressure, atm.	1.0
Specific Heat BTU/lb. ºF	0.275
Thermal Conductivity BTU ft/h ft^2 Δ ºF	0.770
Thermal Coefficient of Expansion (77 ºF – 1000 ºF)	in/in ---1.77×10^{-6}
Average Density	8.4 lb/ft^3

The Piping Handbook gives us this concise definition of thermal conductivity: “The characteristic ability of a material to transmit energy in the form of heat from a high-temperature source to a point of lower temperature is thermal conductivity. This ability is expressed as the coefficient of thermal conductivity (*k*) whose units are a quantity of heat transmitted through a unit thickness per unit time per unit area per unit difference in temperature. For example: *k* = BTU ft/h ft^2 Δ ºF. The lower the value of *k*, the more resistant the material is to the flow of thermal energy" (Nayyar, 1992)

To place the thermal conductivity of the tile material into perspective:

- AETB-8 at 1000 ºF has a thermal conductivity of 0.770
- Pure copper at 1112 ºF has a thermal conductivity of 204
- Carbon steel at 752 ºF has a thermal conductivity of 19.

The IP sensor that will be utilized in the investigation (Turck Ni75U-CP80) has a stated range of the sensor is 75 mm (approximately 3 inches.) The sensor data sheet indicates a repeatability factor of ≤ 2% of the rated operating distance. This would mean that the sensor should function correctly consistently at a distance of approximately 73.5 mm. Turck also provides sensing distance information for the proximity sensor:

- Standard target size to be 230 mm for an axial approach (straight towards the sensor face.)
- For a lateral approach the sensor will best perform when the target has fully entered the sensor face plane to a distance 60 mm beyond the face.

The lateral approach data isn't of importance for this investigation due to the nature of the operation of the steel mill. The piping does have a lateral approach to the sensor, however, the piping being detected is over 20' in length, and the sensor can be located far enough from the end of the pipe that more than 60 mm will be covered when the pipe moves into position (refer to Figure 1). The pipe movement terminates when it strikes a pipe-stop at the end of the conveyor run. The pipe will be at rest when it is over the sensor location. The stated purpose of the sensor is to initiate mechanical lifting arms to move the pipe from the conveyor, up onto a cooling table.

The axial approach data is important; it indicates the sensor limitations on detection of mass and gives us an idea as to the shape of the magnetic field being generated by the sensor. The sensor body is rectangular, with a face that measures 80 mm X 80 mm. The recommended standard target is 230 mm wide at 75 mm from the sensor face, which indicates that the magnetic field would extend a minimum of 75 mm on either side of the sensor. This is also validated by manufacturer graphs indicating that the lateral approach is best detected when the target has fully engaged the sensor face and extends 60 mm past the edge of the sensor. In an article on IP sensor use and application Guerrino Suffi cautions that detectable object distances stated in vendor literature are usually square in shape, made of an iron (ferrous) material, with a 1-millimeter thickness, and a side equal to the diameter of the rated proximity sensor's face. Detection distances for irregular objects may not be estimable from the manufacturer's data (Suffi, 2001). Preliminary testing of the sensor utilizing a small sledge-hammer measuring approximately 120 mm X 50 mm mimicked the manufacturer's sensing range diagram, yielding sensing distances of approximately 37 – 40 mm.

Testing Method – Thermal Shielding

The surface dimension of the sensors being protected is 80 mm X 80 mm (approximately 3.15" X 3.15".) To provide an adequate radiant energy shield effect, the ceramic material measures approximately 13.5" X 13.5" X 1.18".

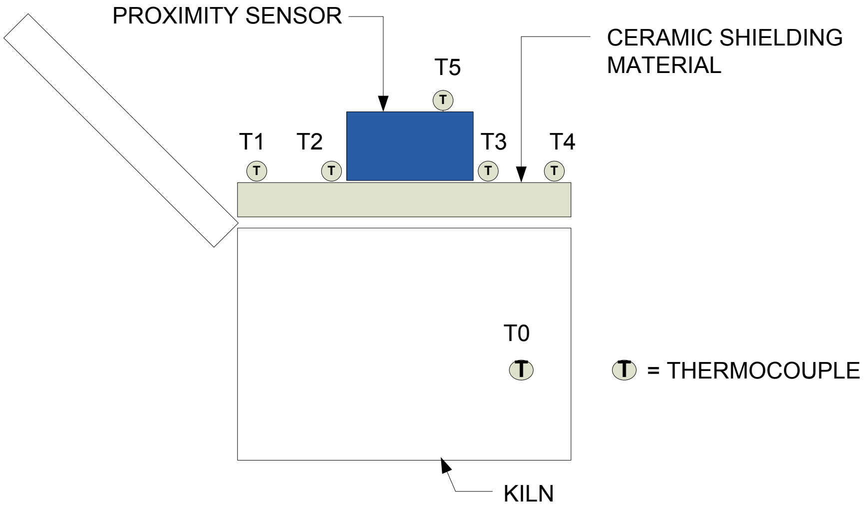

Figure 2. Shielding Assembly Arrangement and Thermocouple Orientation.

To verify the effectiveness of the ceramic material to provide the radiant energy shielding needed, a series of thermocouples will be utilized. Thermocouples will be placed on the surface of the IP sensor (opposite the shielding) to record ambient temperatures as the assembly is exposed to the heat of the kiln. Thermocouples will be placed on the cool side surface of the ceramic tile near the IP sensor to record ambient temperatures as the assembly is exposed to the heat of the kiln. An Additional thermocouple will be placed on the cool side of the ceramic panel assembly to record temperature variations around the sensor (See Figure 3). The thermal exposure will be provided by a compact ceramic kiln, capable of reaching 2350° F. The kiln has a temperature controller that will allow the setting of desired temperatures. This will allow the experiment to closely mimic actual steel mill conditions. The assembly will be tested at approximately 1100° F to match the highest entry temperatures noted in Table 1. A thermocouple provided with the kiln will monitor the kiln temperature.

The assembly will be exposed to the kiln for a period of approximately 45 to 60 seconds, which is intended to replicate the amount of time it takes for the lifting arms to move the pipe from the conveyor to the cooling table. The shielding assembly will be set directly on the kiln, in the place of the kiln cover. This will allow the kiln to maintain the temperature at the noted values for the duration of the exposure period.

Due to the high temperatures that could be recorded, a Type K thermocouple will be used that will provide a temperature range up to 2300° F. The Type K thermocouple is also the most linear of the thermocouple varieties, and has an error range of ± 4º F or 0.75% (Claggett, 1999). The thermocouples will be sampled in 15-second intervals. The thermocouple sensors being used in the test will be monitored to verify that the thermal boundary of the IP sensor has not been compromised. The thermocouples will be monitored by an Omega Engineering 8-Channel Thermocouple Input USB Data Acquisition Module. A log generated by the data acquisition module will be kept to track the cold side temperatures of the various thermocouples at 15 second intervals during the exposure period. A series of 30 exposure periods will be conducted to replicate the production cycle of the steel mill. This will accomplish two things, first it will provide an adequate population from which to draw a conclusion, and secondly it will identify thermal buildup is associated with repeated exposure is problematic.

Testing Method – Magnetic Field Attenuation

To test the effects of the shielding in terms of signal attenuation on the sensor, the shielding test assembly will be removed from the kiln and a representative sample of 4” schedule 40 carbon steel piping will be moved into a position underneath the shielding assembly, see Figure 3 below. The ability of the IP sensor to recognize the pipe will be noted, and the distance (*d*) from the face of the sensor to the leading edge of the pipe will be recorded.

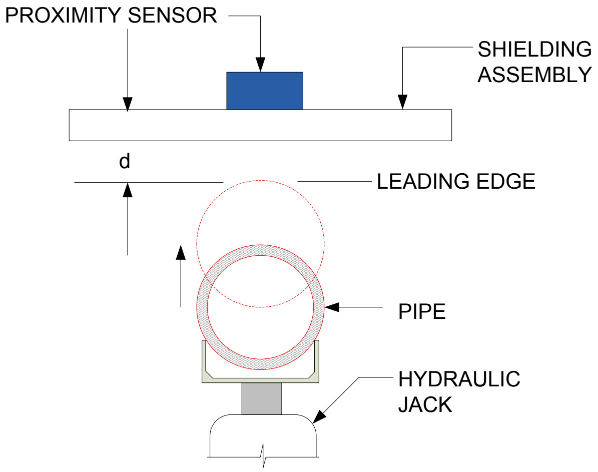

Figure 3. Shielding Assembly Attenuation Discovery Arrangement.

An LED indicator integral to the sensor will provide confirmation of the sensor activation during attenuation discovery. Measurements of distance will be made utilizing a 6-inch dial caliper with depth gauge. The pipe section will be raised towards the sensor assembly by use of a hydraulic jack mechanism capable of infinite positioning.

Timeframe

To prove the hypothesis a series of tests will be made over the course of several days. As mentioned previously the shielding assembly will be subjected to thermal exposures of 45 to 60 seconds in duration. This process will be repeated at intervals to replicate the production cycle at the steel mill. This will also reveal if the ceramic tile tends to ‘build-up’ heat transfer over repeated exposures.

These operations (thermal exposure and attenuation discovery) will be conducted and documented separately. The final product of this research will be a report that details the purpose of the research project, testing methods utilized, data collected, a statistical analysis of results obtained, and the conclusions drawn.

CHAPTER 4

FINDINGS

Introduction

The previous section described the methods used in the research study. This chapter will describe the techniques used to analyze the data collected. The raw data will be presented in this chapter, along with a description of the findings relevant to the research study and hypothesis.

Overview

Utilizing the methods described in chapter five, the study was developed and the appropriate data were gathered. To reiterate the two-fold statement of the problem being studied, it was as follows: (1) a ceramic tile material barrier will protect the proximity sensor at a temperature of less than or equal to 150º F, and (2) a ceramic tile material barrier will not prevent the sensor from detecting the presence of piping at a minimum distance of greater than, or equal to 30 mm. All of the data collected relate to the solution of this problem and to establishing an acceptance or rejection of the stated hypotheses. The two-fold hypotheses being that the ceramic barrier material will provide adequate thermal protection to the sensor while allowing the sensor to function normally.

Analytic Techniques

Given the type of data that was gathered, the analytic technique that is most suited to this study is the t-test. The results of these analyses are presented in two tables labeled *One-Sample*

Test. The t-distribution is recommended for small sample populations due to its shorter fatter shape increasing the need for stronger evidence to support the smaller sample population.

Description of Findings

In the thermal shielding portion of the experiment 120 thermocouple readings were used as test 'subjects.' The readings came from 4 thermocouples attached to the cool side of the ceramic tile during 30 individual thermal exposure periods of approximately 60 seconds each. The resulting temperatures recorded ranged from a low of 73.1° F to a high of 193.8 º F after correction for thermocouple error. (The K Type thermocouple has a known accuracy of ± 4 º F, using a separate digital thermometer actual thermocouple error was determined to range between -2.9 to -3.5 º F.) Interestingly, the high recorded temperature was not at the tail end of the exposure cycles.

As indicated in the method chapter, a fifth thermocouple was attached to the top of the sensor to record temperatures at that location, however the electronics are located in the portion of the sensor directly contacting the ceramic tile barrier. Temperatures recorded at that location did not reflect the thermal interface temperature and were not used as part of the sample population. The findings for the experimental thermal sequences are shown in Table 3. A't-*test'* was performed on the thermal data. Results of the analysis are presented in Table 4.

Table 3 Thermal Experimental Results (°F)

	Day 1				**Day 2**			
Exposure	TC1	TC2	TC3	TC4	TC1	TC2	TC3	TC4
1	76.5	76.2	76.2	76.4	73.2	73.1	73.2	73.8
2	114.3	114.6	120.9	115.2	133.0	132.1	146.5	146.4
3	122.7	126.1	129.4	125.5	138.9	137.7	152.5	147.7
4	166.3	166.5	174.2	156.3	145.6	148.7	163.6	159.3
5	100.1	104.5	106.6	101.1	142.1	145.9	161.5	153.8
6	128.2	130.0	132.8	122.3	136.6	150.6	163.8	150.5
7	152.7	156.2	164.5	152.2	137.7	150.5	160.9	149.4
8	152.3	156.1	165.8	151.4	149.3	160.6	175.4	163.8
9	168.0	172.7	182.5	165.9	152.8	165.0	183.0	169.5
10	177.4	182.7	192.6	171.9	160.9	173.9	192.3	180.1
11	161.1	179.8	187.8	167.3	154.7	174.7	193.8	180.4
12	111.8	123.0	124.4	112.1	146.6	166.0	180.1	166.6
13	119.1	127.6	126.9	120.9	147.6	166.0	177.1	163.3
14	147.6	157.5	160.3	148.8	150.7	169.2	181.6	168.7
15	162.9	165.9	177.9	162.9	139.0	162.2	176.0	162.0

Table 4 Thermal Experimental T-Test Results

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
TC Data	120	147.292	28.7662	2.6260

One-Sample Test

Test Value = 150						
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
TC Data	-1.031	119	0.305	-2.7080	-7.908	2.492

After standardizing the thermocouple sample statistic utilizing the t-test distribution, the resulting test statistic indicates that the average temperature that can be expected will range from a low value of approximately 142° F to a high value of approximately 152.5° F. Based on these values hypothesis H1 can be rejected, and the null hypothesis $H1_0$ accepted, a ceramic tile material barrier will not protect the proximity sensor at a temperature of less than, or equal to 150° F. As an additional measure to confirm this decision a frequency of temperatures is presented in Table 5.

Table 5 Temperature Frequency

Temperature Group	Frequency
0-80	8
81-120	10
121-140	21
141-150	13
151-160	17
161-180	40
181-190	8
191-195	3

As shown in Table 5 there were 68 instances where the temperature exceeded the 150° F threshold established in the hypothesis. Further analysis of the thermocouple data indicates that the data is skewed slightly to the lower temperatures and the curve is somewhat more pointed than a normal bell shape, descriptive statistics are provided in Table 6.

Table 6 Descriptive Statistics – Skewness and Kurtosis.

Descriptive Statistics

	N	Statistic		Mean	Skewness		Kurtosis	
	Stat.	Min.	Max	Std. Error	Statistic	Std. Error	Statistic	Std. Error
TC Data	120	73.1	193.8	2.6260	-0.978	0.221	0.581	0.438
Valid N (listwise)	120							

In the attenuation portion of the experiment 30 caliper measurements were used as test 'subjects.' The resulting measurements ranged from the shortest distance of 48.01 mm to the longest distance of 50.55 mm for pipe detection. The findings for the experimental attenuation measurements are shown in Table 6. A 't-test' was performed on the attenuation measurement data. Results of the analysis are presented in Table 7.

Table 7 Attenuation Experiment Results.

Test	Inches	mm		Test	Inches	mm		Test	Inches	mm
1	1.96	49.78		11	1.97	50.04		21	1.95	49.53
2	1.95	49.53		12	1.94	49.28		22	1.97	50.04
3	1.98	50.29		13	1.93	49.02		23	1.93	49.02
4	1.98	50.29		14	1.94	49.28		24	1.93	49.02
5	1.99	50.55		15	1.95	49.53		25	1.96	49.78
6	1.98	50.29		16	1.96	49.78		26	1.96	49.78
7	1.97	50.04		17	1.95	49.53		27	1.97	50.04
8	1.99	50.55		18	1.89	48.01		28	1.98	50.29
9	1.98	50.29		19	1.95	49.53		29	1.94	49.28
10	1.96	49.78		20	1.95	49.53		30	1.95	49.53

Table 8 Attenuation Measurement T Test Results.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Attenuation Measurement	30	49.71	0.546	.100

One-Sample Test

	Test Value = 30					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Attenuation Measurement	197.612	29	0.000	19.708	19.50	19.91

After standardizing the attenuation measurement sample statistic utilizing the t-test distribution, the resulting test statistic indicates that the average distance the sensor will detect the presence of piping ranges from a near distance of approximately 49.5 mm to a far distance of approximately 49.9 mm. Based on these values hypothesis H2 can be accepted, a ceramic tile material barrier will not prevent the sensor from detecting the presence of piping at a minimum distance of greater than, or equal to 30mm.

CHAPTER 5

SUMMARY AND DISCUSSION

Introduction

In the previous chapter, the data for the study was presented and the statistical analyses of the data were described. This chapter will discuss the statistical analyses results and summaries of the study problem and methods will be presented.

Restatement of Problem

Protection of electronic sensing instrumentation in extremely high thermal environments was the subject of this research study. Inductive proximity sensors utilized to detect piping traveling between the reheat furnace and the delivery area are subjected to periods of extreme thermal exposure, resulting in constant maintenance due to thermal failure. An effective thermal barrier could extend the life cycle of the sensors and reduce operating costs.

The hypotheses for the study were two-fold. First, the barrier must permit sensing of the piping at a distance sufficient for clearance of pipe travel, and second, it must provide a level of thermal protection that maintains the sensor at a temperature within the environmental specifications of the electronics in the sensor. Two separate experiments were conducted during the research phase of the study: attenuation detection of pipe and thermal testing and measurement.

Restatement of Method

Methodology utilized during the research study was as follows: for the attenuation experiment an inductive proximity sensor (with a specified range of 3 inches) was placed on the ceramic tile sample which was secured in a fixed position. A 4-inch section of carbon steel piping was located directly below this assembly and slowly raised until the sensor detected the presence of the pipe. This operation was repeated a series of 30 times, data was collected and recorded documenting the detection distances. For the thermal shielding experiment the ceramic tile sample (with sensor in place) was placed directly on a ceramic kiln at an exposure temperature of approximately 1100° F (to replicate piping temperatures in a steel mill) for a period of approximately 60-seconds. Five thermocouples attached to the cool side of the assembly monitored temperatures. The assembly was exposed a total of 30 times, yielding 120 individual thermal samples. Data was collected and recorded documenting the thermal changes.

Summary of Findings

Results of the findings were previously presented in Table 3 and Table 7. The results indicate that the ceramic tile material was unable to provide adequate thermal shielding over a course of repeated exposures. Heat build-up in the tile was noted due to the short timeframe between exposures. Research hypothesis One predicted that, “A ceramic tile material barrier will protect the proximity sensor at a temperature of less than or equal to 150° F.” As evidenced by the temperature frequency results presented in Table 5, there were 68 instances where the temperature recorded exceeded this threshold.

The results of the attenuation study indicate that the ceramic material did not prevent the sensor from detecting the pipe at a distance sufficiently far enough away to provide a workable configuration. Research hypothesis two predicted that, “A ceramic tile material barrier will not prevent the sensor from detecting the presence of piping at a minimum distance of greater than, or equal to 30 mm." As evidenced in Table 7, there were no instances where the measured distance was less 48 mm.

Conclusions

Based on the statistical analysis of the two methods utilized in this experiment, it does not appear appropriate to consider commercial use of this type of material in a high volume steel mill application utilizing the configuration tested. While the material does significantly reduce the transmittal of thermal energy it was unable to consistently maintain a temperature within the rated operational range of the proximity sensor.

The ability of the sensor electronics to penetrate the ceramic shielding however did prove satisfactory. The distance achieved would allow the installation clearance required to safely pass the piping along the conveyor. This coupled with the availability of a sensor with a longer range would seem to indicate that signal attenuation is not a problem.

Although the temperatures recorded exceeded the levels required they were close enough to the desired temperature threshold that a revised testing configuration might be successful. As stated earlier it was not practical to conduct testing in an operation mill setting. However, the difference in orientation of the heat source from below the ceramic tile to a position above (as would be the case in a mill) might allow for some additional heat dissipation and ambient cooling effects, resulting in less thermal build-up. While every attempt was made to replicate conditions in the mill, further experiments involving collecting additional steel mill operational data, or the ability to conduct actual testing in place, may provide renewed interest in additional studies for the use of low density ceramic material as a high temperature barrier.

Implications

The results from this research may indicate that ceramic tile material used in this configuration is not suitable for application in a harsh steel mill environment. This study has served to benefit steel manufacturers in that it has revealed the limitation of the ceramic barrier material to provide adequate protection.

The implications from this research are that utilizing a low-density ceramic barrier, such as the AETB-8 material, may not provide adequate protection for sensitive electronic components. It would not be appropriate for a steel mill to use AETB-8 material as a means to extend the life of an inductive proximity sensor.

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