Measuring Process Temperature
In
Small Diameter Lines

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Preface

In today's high-performance process systems, measuring the process temperature in small diameter lines down to .25 inch diameter must be understood. The most common applications have processes running in the temperature range of –50°C to +200°C. Measurement uncertainties can easily reach several degrees Celsius over this temperature range due to thermodynamics that can induce conduction effects of the sensor. Other real-world factors, such as the required time response of the temperature measurement, the ability to replace sensors during process operation and the ability to clean-in-place all contribute to the difficulty of this measurement. This paper looks at several methods that can be used for making these measurements including direct immersion (without a thermowell), indirect immersion (with a thermowell), and non-intrusive methods. The temperature sensor assemblies range from a simple clamp-on surface sensor to sensors with elaborately designed thermowells. This paper will focus on measuring the process using a platinum resistance thermometer (PRT), due to the performance required for most applications. It will also discuss the advantages and disadvantages of each temperature measurement method along with uncertainty estimates based on some common conditions.

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1. INTRODUCTION

Accurate temperature measurement of a fluid flowing in .25 to 4.0 inch diameter lines can be difficult to achieve. While thermocouples, bi-metallic sensors, thermistors, or other devices may be used, they have limitations on performance that prevent them from meeting the long term accuracy, stability and repeatability performance available in platinum resistance thermometers (PRT's). Pipes larger than 4 inches in diameter provide sufficient space for mounting standard PRT assembly configurations. Lines from .25 inch to 4 inch diameter however, require special consideration. Many of the performance advantages of a PRT can be lost through improper use, or selection of a PRT that is not designed for the application.

Industry standards for industrial PRTs, such as ASTM E1137 and IEC 60751, are concentrated on cylindrically sheathed, direct immersion style sensors. These documents provide no guidance on adapting these thermometer styles for use in applications such as the ones described above. Additionally, the performance demonstrated by the sensor in a test laboratory may be completely different than the results obtained when used in a production installation.

Measuring temperature in small diameter lines presents some unique challenges. This paper examines several different methods for measuring temperature in lines down to .25 inch diameter, and provides test result for the various methods under some typical conditions.

2. DISCUSSION

A. Expectations for PRT sensors.

PRT sensors are chosen when process temperature is critical because PRTs offer superior accuracy, stability and repeatability compared to other temperature measuring devices. Many users of PRT sensors have expectations of accuracy based on the Resistance vs. Temperature tolerances in ASTM E1137 or IEC 60751, which at 100°C are ±0.3°C for the Grade A or Class A sensors, and ±0.67°C for the Grade B or Class B sensors. These tolerances apply only to the resistance of the PRT sensor when measured under ideal laboratory conditions. In addition, many users request individual PRT calibration and transmitter matching which can provide accuracy to better than ±0.05°C. While these accuracies are achievable in a vast number of process installations, they are not always achievable in unique installations like small diameter lines. In these applications errors at 100°C could easily reach 3°C or larger and can fluctuate greatly depending on ambient conditions.

B. Temperature measurement methods for small diameter lines.

Four typical methods for measuring the temperature of a fluid inside of a line will be discussed in this paper, they are:

1) using a surface sensor on the outside of the line,
2) installing a non-intrusive sensor in the process line,
3) directly immersing a sensor into the fluid flow, and
4) installing a thermowell and sensor into the line (referred to as "indirect immersion").

1. Surface Sensor.

One approach to measuring the temperature of the fluid inside the line is to clamp or glue a surface sensor on to the outside of the pipe. Figure 1 shows a sectional drawing of a surface sensor that is attached to a line with an adhesive. This method is one of the simplest to use since the process line does not need to be changed by removing a section or adding a port. While adequate performance may be obtained by simply attaching the sensor to the line, in general it is recommended that a thermally conductive adhesive or a thermal paste be used between the sensor and line to improve the heat transfer. By improving the heat transfer a more accurate and faster responding measurement can be made. To further improve the sensor accuracy and minimize the effects of ambient airflow over the sensor, insulation may be added over the top of the sensor after installation. This decreases the effects of ambient temperature on the sensor.

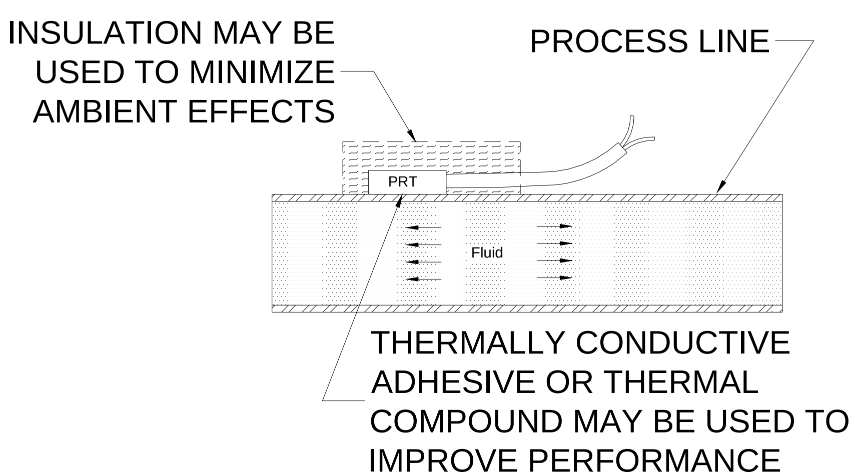

FIGURE 1 – TYPICAL SURFACE SENSOR INSTALLATION

Many users find that even with adequate installation precautions, the surface sensor method is adequate for process monitoring, but inadequate for control applications due to measurement errors and slow response times. This determination however, is highly dependent on the particular application requirements. Advantages and disadvantages of the surface sensor method are listed in Table 1.

Table 1 – Surface Sensor Advantages and Disadvantages	
Advantages	**Disadvantages**
Simple to use	Slow response time
No line modifications required	Highly influenced by ambient environment
Installation and replacement are easy	Performance variability due to mounting
No need to drain the system to replace	Exposed insulation can be undesirable
Flexibility in location possibilities	
No possibility for leaks	
No foreign material in process	
Low cost	

2. Non-Intrusive sensor

A non-intrusive sensor is typically constructed using a surface sensor where the sensing element has been attached to a short section of pipe or tubing that is designed to replace a section of the process line. The sensing element is insulated and protected by a tube over the section of line. This style of sensor offers improvements over a standard surface sensor because the element mounting and insulation is less variable than when applied in the field. In addition, the outer sheath protects the element and insulation from damage and provides for a cleaner installation. Figure 2 shows a sectional view of a non-intrusive style sensor.

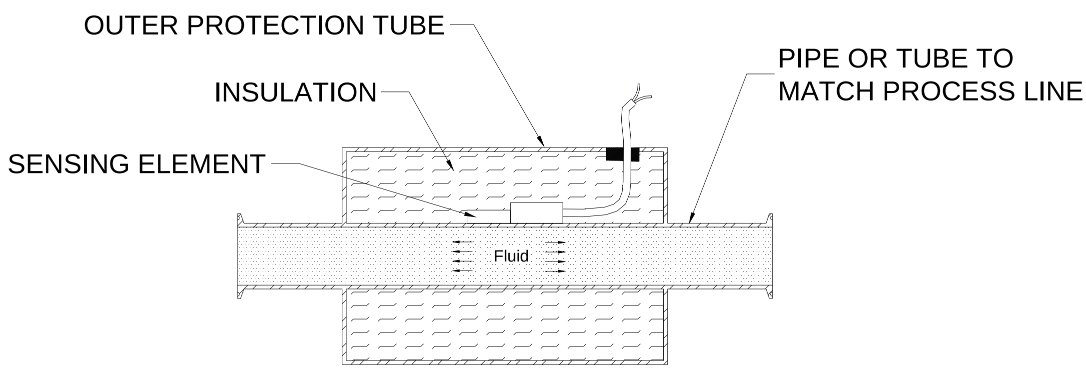

FIGURE 2 – NON-INTRUSIVE SENSOR

The non-intrusive style sensor solves several of the shortcomings of a simple surface sensor and offers improved accuracy and response time in a clean package. Advantages and disadvantages are given in Table 2.

Table 2 – Non-Intrusive Sensor Advantages and Disadvantages	
Advantages	**Disadvantages**
No immersion into process	Response time slower than immersion styles
No obstruction of process flow	Installations require planning
Element mounting and insulating are factory controlled for consistency	Must replace entire pipe section to replace sensor
Clean external envelope	Must drain system to replace sensor
Installation and replacement are easy	Calibration can require special baths
Faster response time than simple surface sensor	More expensive than most other PRT sensor options

3. Direct immersion sensor

A sensor that is immersed directly into the flow is the typical solution that is used on many process lines, large or small, because it provides for accurate measurement and quick response time. However, for small diameter lines the sensor immersion depth may not be adequate to obtain an accurate temperature measurement if the sensor is installed perpendicular to the flow. A general rule that is used for immersion PRT sensors is that the minimum immersion length (MIL) into the flow should be at least 10 times the sheath diameter plus the length of the sensing element. This immersion length is required to minimize the stem conduction error, the error caused by heat transfer between the sensing element and the ambient conditions at the back of the sensor. For a typical .25 inch diameter sensor with a 1 inch long element, this guideline would require a 3.5 inch immersion into the fluid. This may be achievable on lines with a 4 inch or larger inside diameter (ID), but is not achievable for lines smaller than this. For lines with an ID smaller than 4 inches, a smaller diameter sensor with a short element length may work however practical limitations on sensor construction and strength considerations make it difficult to reduce diameters to much less than .125 inches. With reduced diameters the minimum immersion will still need to be approximately 1.5 inches.

As an alternate to immersing a sensor perpendicular to the flow, the sensor may be mounted in the end of a “tee” to allow a longer immersion depth. Figure 3 shows a direct immersion installation in a perpendicular orientation and in a tee with flow parallel to the sensor sheath. While it is conceivable to achieve a proper immersion depth when mounting the sensor in a parallel manner, consideration must be given to other factors such as flow blockage, pressure drop, and drainability. Advantages and disadvantages of direct immersion sensors are shown in Table 3.

Table 3 – Direct Immersion Sensor Advantages and Disadvantages	
Advantages	**Disadvantages**
Fast response time	Installation requires planning
Unaffected by ambient conditions when proper immersion is used	Flow blockage and pressure drop must be considered
Simple installation	Installation could leak
Low cost	Stem conduction effects can be large if proper immersion is not used
	Must drain system to replace sensor

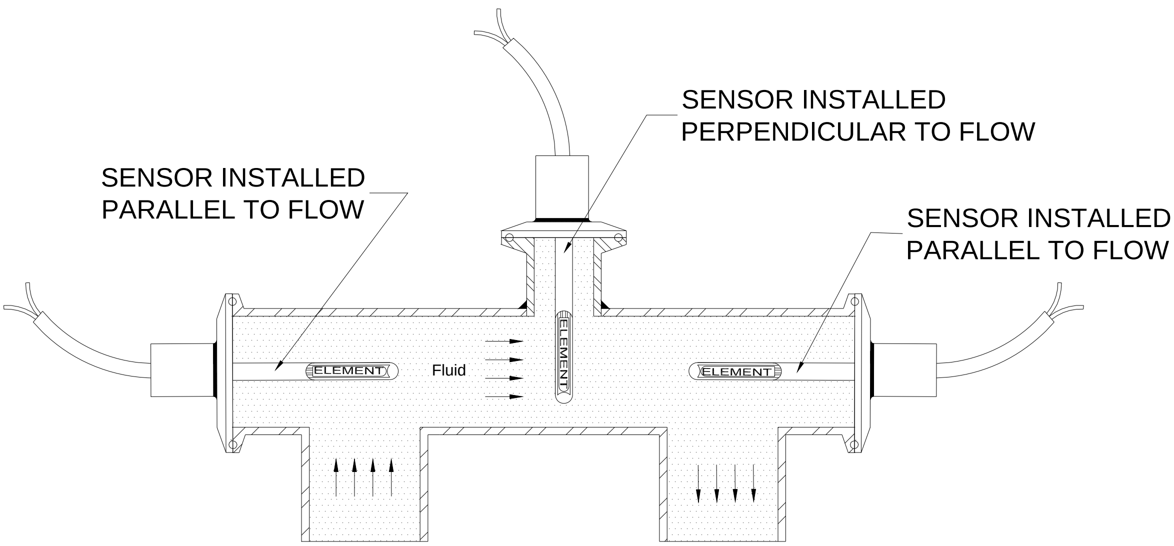

FIGURE 3 – DIRECT IMMERSION SENSOR INSTALLATIONS

4. Indirect immersion sensor

One of the most significant disadvantages of the direct immersion sensor is that the system must be shut down and drained every time a sensor is removed for routine calibration or replacement. This disadvantage can be eliminated by using a thermowell, which creates an indirect immersion of the sensor. While the addition of the thermowell makes removal and replacement of the sensor easier, it complicates the thermodynamics of the measurement and can increase the measurement error and slow down the response of the sensor. A sectional view of an elbow with an integral thermowell is shown in Figure 4.

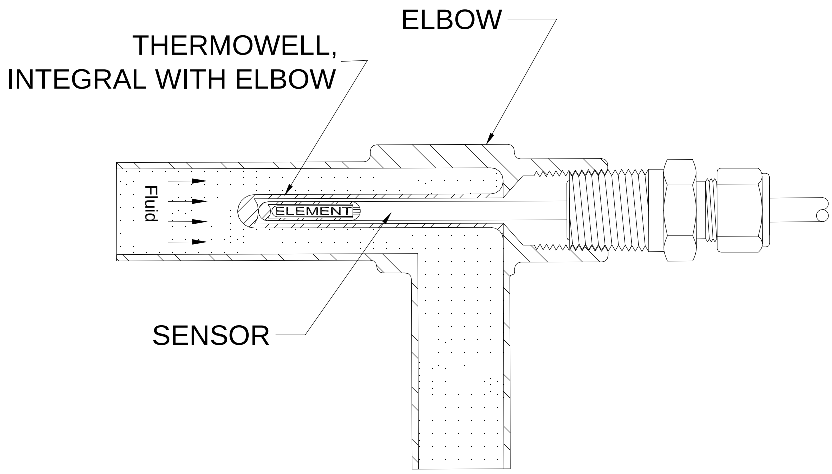

FIGURE 4 – INDIRECT IMMERSION SENSOR INSTALLATION

A significant error can occur if the sensor and thermowell are not designed as a system. It is not uncommon for the piping designer to specify the installation of an elbow with integral well where the well is made from standard .375 inch diameter tubing with a .035 inch wall thickness. While this standard size tubing is convenient to use, the resulting well has a nominal ID of .305 inch. Typical thermowells specified by instrumentation engineers for use with .25 inch diameter PRTs have a nominal ID of .26 inch. A .26 inch ID well, while less convenient to manufacture, will perform much better than a .305 ID well when used with a standard .25 diameter PRT. Further performance improvements can be made by using a PRT that has been custom designed for use in short thermowells, or thermowells with an oversized ID. A tip sensitive PRT, one that has a short element length and has the element in good thermal contact with the tip of the sensor while minimizing the thermal path to the back of the sensor, can improve accuracy and response time of the measurement. Smaller diameter thermowells with correspondingly smaller PRTs are available as well, when the application demands it.

The advantages and disadvantages of the indirect immersion method are listed in Table 4.

Table 4 – Indirect Immersion Sensor Advantages and Disadvantages

Advantages	Disadvantages
Sensor is replaceable without draining the system	Installation requires planning
Less effected by ambient conditions than surface methods	Flow blockage and pressure drop must be considered
No possibility for leaks	Stem conduction effects can be large
Sensor removal will not introduce contaminants into the process	More expensive than direct immersion methods

C. Analysis of Measurement Errors

It is beyond the scope of this paper to discuss the mathematical models that describe the heat transfer relationships for all the different styles of sensors. Suffice it to say that when a high quality PRT is used to measure temperature, in most installations and under steady state conditions, thermal conduction effects are the dominant source of error. This error is directly related to the magnitude of the difference in temperature between the fluid being measured and the ambient surroundings, this difference is referred to as "Delta T" (ΔT).

It can be shown that under steady state conditions the conduction error may be represented as a percent of ΔT. A very simplistic interpretation is to view every installation of a PRT as having a thermal profile that goes from “near fluid” temperature to ambient environment temperature. The goal for an accurate temperature measurement is to have the PRT sensing element located in the “near fluid” portion of this profile. The best way to accomplish this is to thermally couple the PRT element to the process fluid, and thermally isolate the PRT element from the ambient environment.

3. EXPERIMENTATION

A. Accuracy Testing.

Accuracy testing was performed in a laboratory controlled “sample process” on several of the different types of sensors described in section 1 of this paper. The “sample process” that was used to test these sensors was hot water flowing at approximately three feet per second through a .5 inch outside diameter stainless steel tube with an 0.065 wall. A brief description of the sensors that were tested are as follows:

Surface sensor – a typical clamp-on style surface sensor was tested as installed with and without thermal compound at the sensor to line interface, and with and without insulation over the sensor.

Non-intrusive sensor – a sensor of construction similar to that shown in Figure 2 with a .5 inch diameter process line with a 0.050 wall.

Direct immersion sensor – a .125 inch diameter by 1.0 inch long sensor with a sanitary cap process connection installed perpendicular to the flow.

Indirect immersion sensor – a process line elbow with an integral thermowell similar to that shown in Figure 4. The well was approximately 2 inches long by .375 inch OD with either a .305 or .260 ID and was tested with both a standard .25 inch diameter PRT and a tip sensitive .25 inch diameter PRT.

All of the PRTs used for this testing were calibrated at multiple temperature points using a method typical for industrial PRT calibration, the uncertainty of the calibration was estimated not to exceed 0.025°C. This calibration was performed so that the individual resistance vs. temperature characteristics for each sensor could be used to accurately calculate the temperature and determine the measurement error. The sensors used for monitoring the water supply and ambient air temperatures were a secondary standard grade PRT that was matched to a precision digital thermometer, the overall accuracy of these monitoring systems is estimated to be less than 0.035°C.

Two variations of the test were performed. The first variation was at a fluid temperature of approximately 50°C with no ambient airflow over the portion of the sensor outside the process. The second condition was similar to the first except a 4 inch diameter fan was placed 12 inches from the sensors to circulate ambient air over the portion of the sensor outside the process. This was done to determine the sensitivity of the measurement method to ambient conditions. The results of the test are given in Table 5 and shown graphically in Figure 5. To account for variation in fluid temperatures, the errors are presented as a percent of ΔT. Presenting the results as a percent of ΔT not only normalizes the data, but also allows the data to be used to estimate expected errors under different temperatures. For example, a sensor that exhibited an error of 0.7% of ΔT, if used in a 121°C sterilization process (with similar heat transfer characteristics) would have an estimated error of 0.7°C (0.7% of the 100°C ΔT between the process temperature and ambient surrounding temperature). Therefore, the accuracy recorded can be used to approximate the actual uncertainty in a 121°C sterilization process.

Table 5 – Accuracy Test Results for 4 different sensors on ½ inch diameter line
Water at 50°C (ΔT = 28°C), 3 feet per second

PRT sensor type	Error (% of ΔT) No ambient airflow	Error (% of ΔT) With ambient airflow
Surface Sensor – clamped on with:		
No thermal compound, no insulation	9.7%	26.6%
No thermal compound, insulated	7.0%	8.0%
With thermal compound, no insulation	4.7%	11.1%
With thermal compound, insulated	1.8%	2.0%
Non-Intrusive	0.7%	2.4%
Direct immersion (.125 diameter x 1.0 long)	0.2%	0.2%
Indirect immersion (.25 dia PRT):		
.305 ID well – standard PRT	3.7%	6.3%
.305 ID well – Tip sensitive PRT	0.4%	0.8%
.260 ID well – standard PRT	0.3%	0.6%
.260 ID well – Tip sensitive PRT	0.3%	0.0%

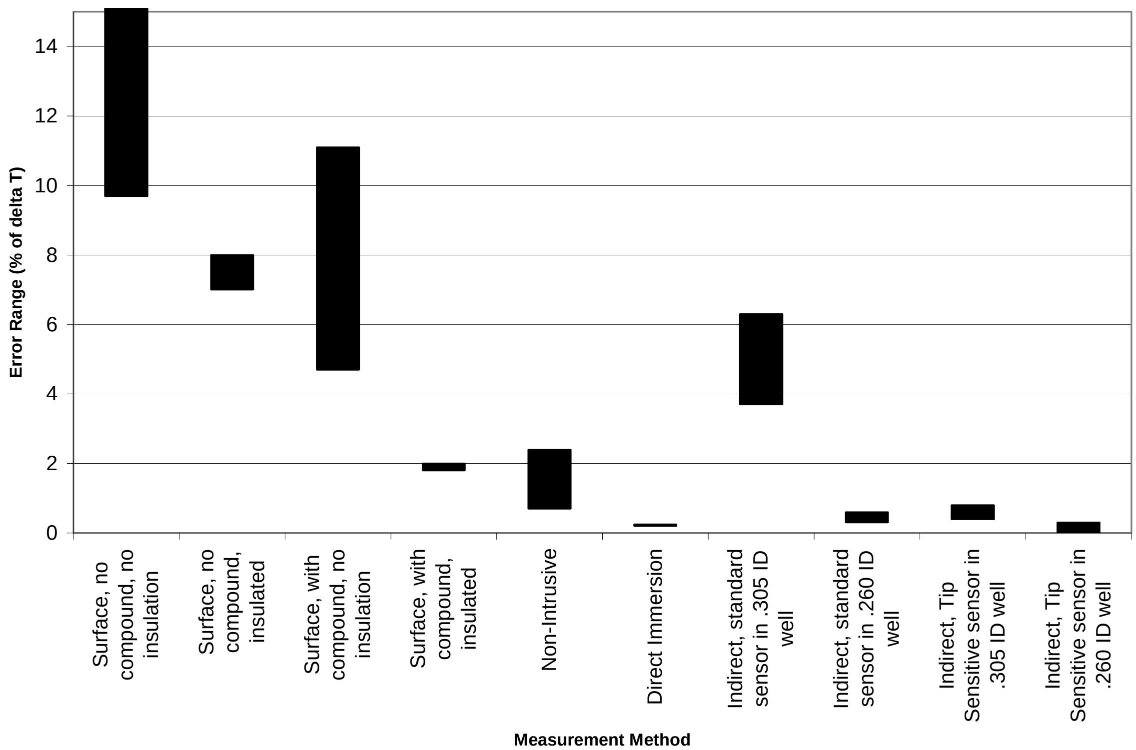

FIGURE 5- ACCURACY COMPARISON GRAPH

B. Response Time Testing.

A test was conducted to determine the relative response time of the various PRT measurement methods. The test was conducted by pumping hot water through the lines, which were initially at room temperature, and determining how long each measurement method took to reach 63.2 percent of the step change in temperature. Since all methods were tested using identical flow conditions a direct comparisons can be made between methods. It is important to note that actual installation conditions will significantly effect this result, so this test was meant to give relative information only. The results are given in Table 6 below and shown graphically in Figure 6.

Table 6 –Response Time Test Results for 4 different sensors on ½ inch diameter line Step change in water from 22°C to 50°C, 3 feet per second	
PRT sensor type	**63.2% Response**
Clamp On Surface	
No thermal compound, no insulation	38 seconds
No thermal compound, insulated	55 seconds
Thermal compound, no insulation	17 seconds
Thermal compound, insulated	20 seconds
Non-Intrusive	11 seconds
Direct immersion (.125 diameter x 1.0 long)	<5 seconds
Indirect immersion (.25 dia PRT):	
.305 ID well – standard PRT	91 seconds
.305 ID well – Tip sensitive PRT	40 seconds
.260 ID well – standard PRT	30 seconds
.260 ID well – Tip sensitive PRT	22 seconds

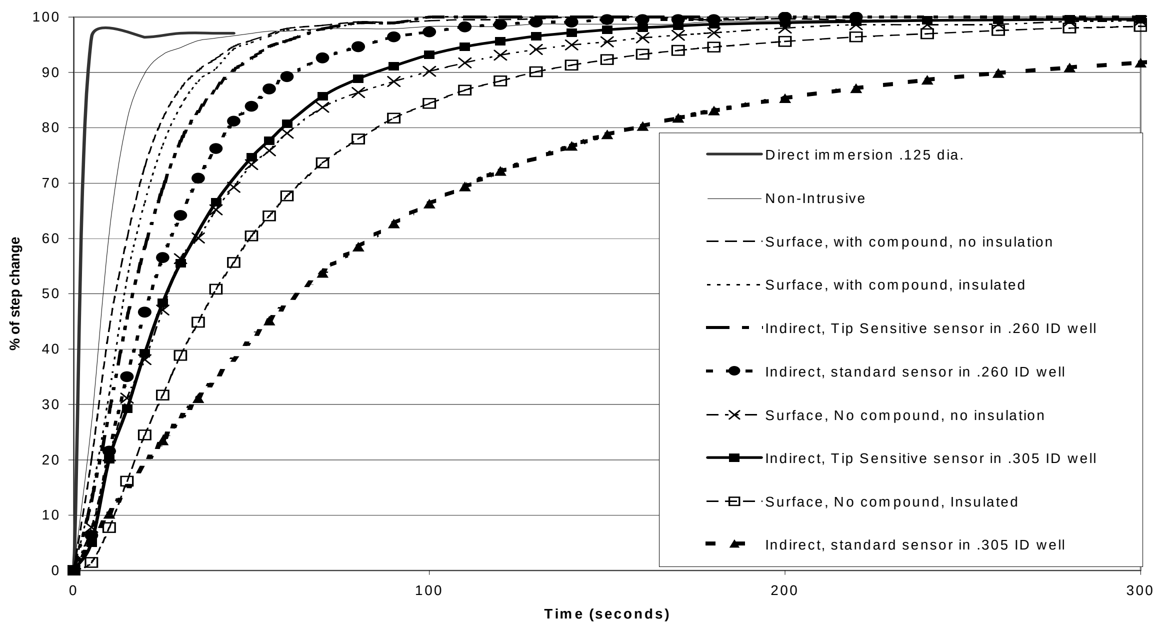

FIGURE 6 – RESPONSE TIME COMPARISON GRAPH

4. CONCLUSION

To achieve accurate temperature measurement in lines from .25 to 4 inches in diameter requires special consideration. Standard PRT sensors do not perform the same in small line installations as they do in calibration baths in laboratories primarily due to thermal conduction effects and ambient environment influences. Accuracy and response time can vary significantly based on the type of PRT used and the process conditions in which it will be used. The user needs to understand the accuracy and response time requirements in order to choose a measurement method which will meet the requirements, and avoid unexpected errors due to misapplication of an otherwise accurate PRT. Direct immersion PRT's should be considered where the highest accuracy is required for control of the process temperature. Non-intrusive or surface mount PRT's may be used where best accuracy is not required, such as process monitoring. Additional requirements such as the convenience of clamping a surface sensor on to the outside of a line, or the ability to remove a sensor without draining the system will also impact the final decision. With the proper choices, an accurate, stable, and repeatable measurement can be achieved.