Abstract - Methods to measure and predict maximum sheath temperatures of mineral insulated (MI) heating cable vary by testing agency, standards writing body and manufacturer. This has resulted in confusion in the industry about the best approach to predict sheath temperatures of MI heat tracing cables. This paper presents an analysis of two different test methods for sheath temperature prediction. The test methods studied are commonly known in the industry as the ‘pipe test’ and the ‘plate test’. The paper demonstrates that the pipe test has significant variation in the measured sheath temperatures in successive test runs while the plate test produces a much more repeatable and accurate result. The paper proposes the use of the plate test as a preferred method to measure and predict maximum sheath temperature. As a related topic, the paper also presents general considerations for optimizing designs that will reduce costs and improve constructability of electrical heat tracing designs using MI heat tracing cables. A case study is presented to demonstrate application of these design optimization techniques.

Index Terms — Mineral insulated (MI) heating cable, sheath temperature, pipe test, plate test, electric heat tracing, electric trace heating, AIT

I. INTRODUCTION

In North America, the heat tracing industry has been providing MI electric heat tracing cables to industrial customers for freeze protection and for process temperature maintenance applications for more than 50 years. It is well known that because MI cables are constant wattage cables, they produce the same amount of heat regardless of the temperature of the pipe on which they are installed. When MI heating cables are used in classified areas, the Canadian and US electrical codes require that the surface temperature of electrical equipment, including MI heat tracing cables, operate below the auto-ignition temperature of flammable fluids or dusts in the area. Therefore, it is important to be able to accurately and confidently predict the maximum temperature the heating cable sheath will reach in any particular installation. For this reason, having the capability to accurately predict sheath temperatures is also required by approval agencies, such as CSA, FM and UL. In addition, from a practical standpoint, the industry also needs MI heat tracing designs to be cost-effective and easy to install and maintain. This paper proposes an improved test method to accurately predict the maximum sheath temperature as well as strategies to optimize the designs with MI heat tracing cables.

Investigations into improved methods for predicting MI cable sheath temperatures began in 2001 when it was recognized that different manufacturers were predicting different temperatures for similar cables (Figure 1), which is contrary to what the principles of thermal heat transfer would predict. The lack of consistency suggested that there was no industry-wide consensus as to the method that should be used to reliably and consistently predict the sheath temperature of MI heating cables under various conditions or that the existing methods did not produce consistent results. Some of the factors suspected of contributing to this situation were:

1. the data was based on limited measurements that were made over 30 years ago,
2. the tools and equipment used to generate the data were no longer state-of-the-art, and
3. the data existed only in the form of tables and graphs and was limited to a small subset of the conditions that were of interest.

![MI Cable Sheath Temperatures Predictions by Manufacturer](image-url)
II. TEST METHOD COMPARISON

A project was started to evaluate which of the suspected causes were contributing to the inconsistencies between manufacturers. Several MI heating cables of the same manufacturer were selected for sheath temperature testing ranging in size from approximately 3 to 11 mm in diameter. IEEE 515 “Standard for the Testing, Design, Installation, and Maintenance of Electrical Resistance Heat Tracing for Industrial Applications” [1] – contains a method known as the pipe test to evaluate sheath temperatures. This method was first selected to evaluate the sheath temperature of the MI cable. Three pipe sculptures were built that conformed with, but went beyond, the requirements of IEEE 515. Two of those sculptures are illustrated in Figure 2, and installation details showing the heating cable and some of the many thermocouple attachment points are shown in Figures 3 and 4.

Several cable sizes were tested at power levels between 10 and 50 watts per foot and at pipe temperatures of 50, 150 and 300°C with 2-inch calcium silicate insulation. The pipe temperature was maintained using an internal heater and a controller. The sample heating cable was powered at each wattage level and allowed to stabilize. Using thermocouples fixed at many key points on the pipe, valve, and flanges, and on the cable sheath, it was observed that it was very difficult to obtain reproducible temperatures and that the “hottest spot” varied from run to run and from pipe to pipe. This was true in spite of the fact that extra efforts were taken to attempt to control heat loss, including the use of supplemental heaters inside the pipe, plugging of all the gaps in the insulation by additional fibrous insulation and sealing the seams in the insulation with tape (see Figure 5 and 6). After these extraordinary steps were taken to try to get consistent results, it was found that the measured temperatures still varied widely. This can best be seen in Figure 7 which is a graph of temperatures at various locations as a function of time and heating cable power. It can be seen that the temperatures at the pipe, valve, and flange identified as T18, T13 and T14 respectively in Figure 6, differ by as much as 87°C at 10 W/ft, even after steps to minimize temperature variation were taken. The figure illustrates the effect on the pipe temperature of using aluminum tape to plug the gaps in the insulation. The figure also illustrates that the value and flange temperatures are much lower than the set-point of 300°C at 10 and 20 W/ft while they are close to or higher than 300°C at 30 and 40 W/ft. The amount of heating cable installed on these pipe features is not adequate at lower wattages. This demonstrates the difficulty of obtaining uniform pipe temperatures along the length of the pipe especially with a constant wattage product. This variation in the pipe temperature at different locations is one of the key reasons for variability in the measured sheath temperature in the pipe test. Figure 6 also demonstrates the effect of plugging the gaps in the insulation using an aluminum tape on the corresponding pipe temperature and sheath temperature. Using aluminum tape resulted in increasing the corresponding pipe temperature T15 from 268°C to 293°C with a similar increase in local sheath temperature T1 from 478°C to 503°C. The key point is that the insulation installation affects the local pipe and sheath temperature and if the local pipe temperature is not measured, the sheath temperature measurements could be misleading.
Similar results were obtained when the pipe temperature was not controlled using the internal heater and controller. The sample heating cable was powered at various wattages and the entire system was allowed to stabilize. For example, figure 8 shows that the pipe temperature at six different locations varies by 80°C at 30 W/ft.

To further illustrate the lack of consistency in the pipe test methodology, data was plotted in an “Isoplot” format. In this plot, data is measured twice, by taking data from the same point on a cable installed on two pipes. In an ideal, repeatable test, these duplicate temperature measurements would be the same, and the plot would give a straight diagonal line. It can be seen in Figure 8 that the data points do not fall on the line, but rather indicate an unacceptably large measurement error of over 100°C. Figure 9 also shows that the variation in the sheath temperature measurement in the pipe test increases at higher sheath temperatures i.e. at higher wattages and higher pipe temperatures. Under these conditions, it is believed that the variation in the insulation installation and cable installation plays a larger role in affecting the sheath temperatures.

Recognizing that it was going to be difficult to generate reproducible sheath temperatures using the pipe test, a second sheath temperature test method was evaluated. This test, which is a modified version of the test described in BS 6351 “Electric Surface Heating. Code of Practice for the Installation, Testing and Maintenance of Electrical Surface Heating Systems” [2], is commonly referred to as the “plate test”. This test uses a 600 mm x 600 mm x 50 mm metal plate which is air cooled, electrically heated and well insulated. In the procedure, the cable is laid on the plate over a trough to simulate the field condition where the heating cable is not in direct contact with the pipe. Figure 10 illustrates a typical plate test set up, with the heating cable in place, and the plate surrounded by thermal insulation, but left uncovered to illustrate the location of the cable and thermocouples. After many trials, it was determined that deeper troughs produce higher sheath temperatures up to a 5-mm trough depth with no additional effect beyond a 5-mm depth.

Fig 7 – Pipe Sculpture Sheath Temperature Measurements

Fig 8 - Pipe Sculpture Sheath Temp Measurements without the controller

Fig 9 – Pipe Sculpture Repeatability
Two plate test set-ups were used with different plates and calcium silicate insulation. To fit the cable, a \( \frac{3}{4} \)" wide groove was machined in the insulation with ends plugged to prevent air flow. 2-inch calcium silicate insulation was used in both plate test set-ups. The sheath temperatures under the same operating conditions in the two plate set-ups are plotted in the isoplot in Figure 11. It can be seen that with two different set-ups, the plate test gave much more reproducible results than the pipe test.

Further, when the plate test results are compared with the pipe test results, it can be seen in Figure 12 that the plate test data approximates the highest found temperature in the pipe test. This was verified for various MI cables under wide range of operating conditions. This means, if the sheath temperature was measured at many locations along the length of the MI cable, the maximum sheath temperature measured in the pipe test would be in agreement with the maximum sheath temperature measured in the plate test.

The variables that impact the sheath temperature of MI cable include system variables such as cable diameter, cable material, substrate (pipe or plate) material, insulation type and thickness. The variables also include operating conditions such as substrate temperature and cable wattage. The installation variables that affect the length and depth of the air-gap between the MI cable and the substrate also impact the measured sheath temperature. In the case of the pipe test, due to the inherent variability in cable installation, it is difficult to maintain a well-defined depth and length of air-gap between the cable and the pipe. It is believed that due to variability in the insulation installation and heat loss characteristics of pipe features, it is difficult to maintain a uniformed pipe temperature. These installation variables are the main cause of variability in the measured sheath temperature in the pipe test. Hence, it is difficult to develop a sheath temperature algorithm based on the pipe test that will provide accurate and consistent results. Moreover, the maximum sheath temperature was obtained at different spots in different pipe sculptures which means that to capture the highest sheath temperature, multiple thermocouples are needed making the test cumbersome for sheath temperature verification purposes. The plate test is more reproducible because the air-gap is well defined, the insulation installation is better controlled, the plate can be uniformly heated using internal heaters or cooled using air channels and the maximum sheath temperature location is easy to capture on the cable at the center of the air-gap. The maximum sheath temperature obtained using the plate test is in-line with the maximum sheath temperature obtained on the pipe test provided the sheath and pipe temperatures are measured at many locations along the length of the pipe. While we understand that the pipe test intends to resemble real life installation of heating cable on a pipe, the difficulty in controlling the variables mentioned above makes the test cumbersome and difficult to reproduce. The plate test provides an easy, reliable and cost-effective way for manufacturers to develop and verify their sheath temperature predictions.

A plate test apparatus was modeled using finite element analysis (FEA) software. It was thought that developing a predictive model of the test would verify that the experimental predictions are consistent with basic principles of heat transfer science, and would create a method to perform sensitivity analyses and to model various installation scenarios that might be difficult to test experimentally. Although the model was quite complex and required the effects of radiation, convection, and conduction to be included, the output of the FEA confirmed the...
experimental results since the agreement between the two data sets was excellent. The graphical output for one experimental condition is illustrated in Figure 13, confirming the temperature range over the length of the modeled heating cable. Figure 14 shows good agreement between the data predicted by the FEA for cables at 50°C and 300°C and the data obtained experimentally on the plate test.

The experimental results show that the plate test is a more repeatable and accurate method of predicting maximum sheath temperatures for MI heat tracing cables.

III. DESIGN OPTIMIZATION TECHNIQUES

After addressing the industry need to reliably and accurately predict the MI sheath temperatures, it was decided to develop design optimization techniques to further improve and optimize the electrical heat tracing designs using MI heating cables. The driver behind this initiative was the industry need for simple, cost effective, constructible, and easy to install and maintain electrical heat tracing designs using MI cables. There are many opportunities to optimize designs and reduce costs especially in the applications where the desired temperature to be maintained is relatively high and the area temperature rating is relatively low. In these cases, the standard heat tracing designs would require multiple passes of MI cables with lower wattage in order to keep the maximum sheath temperatures below the area temperature rating. The design techniques listed below are used to improve constructability by reducing the number of passes while still ensuring reliable performance of the heat tracing systems. These methods have been proven effective for various real life applications and are continuing to be employed in improving electrical heat tracing system designs:

a) Investigate use of polymeric heating cables – Use of a self-regulating, power-limiting or other heating cable technology may be a suitable alternative since polymeric heating cables do not have similar sheath temperature considerations as MI cables. However, the user must ensure that the alternate technology is applicable for the given maintain and exposure temperatures as well as ensure that the alternate technology provides a benefit in reducing the number of heating cable passes as compared to the MI cable design.

b) Review the area T-rating – Engineering assumptions for establishing T-Ratings are often generalized for entire facilities instead of considering the actual materials in a specific section of the facility. Considering the AIT of the specific hazards in the area may allow raising the acceptable equipment temperature, thus allowing higher outputs for a given cable and reducing the number of cable runs required.

c) Review the minimum ambient temperature assumption – Heat loss calculations are based on a certain minimum ambient temperature assumption. This minimum ambient temperature may be increased based on the actual history at the location which will potentially reduce the calculated heat loss and number of passes of heating cable.

d) Review the required maintain temperature assumption – The heat input to maintain a pipe at a certain temperature can be reduced if the required temperature at which the pipe is to be maintained can be lowered based on the actual fluid characteristics.

e) Rationalize the safety factor – As in any engineering design, safety factors are used in EHT system design to ensure that design assumptions made can withstand a certain level of variation from assumed values as actual operating conditions change. Often the safety factors used can be rationalized for practical considerations. In particular, as the Nominal Pipe Size (NPS) increases, the safety factor (SF) for the EHT design can be reduced without adversely affecting system performance given that larger thermal mass will exist in a pipe as the diameter increases. As the safety factor is reduced, the calculated heat loss is reduced which may reduce the number of passes of MI heating cables. The decision to reduce the safety factor will also depend on the durability of the insulation and cladding material as well as the quality of the insulation installation. These factors must carefully be considered before proceeding with a safety factor reduction.

f) Use insulation with improved K-Factor – Improving the thermal resistance of the insulation has the same effect as increasing the insulation thickness, thereby reducing the heat loss to ambient. There are several alternative
insulations available beyond the standard mineral wool and calcium silicate insulation that are available for use, with a potential to reduce the number of passes of MI heating cables.

g) Use a larger diameter MI heating cable – Under identical conditions, the sheath temperature for a larger diameter MI cable will be lower than that of a smaller diameter cable. Thus use of a larger diameter MI cable may enable higher wattage cables thereby reducing the number of passes.

h) Limit design to a single flow path where ‘control limited’ methods can be used – The sheath temperature of the MI cable can be limited using controllers if a single flow path design is used rather than multiple flow paths under a single heat tracing circuit.

i) Increase insulation thickness – Increasing the insulation thickness will reduce the heat loss thereby reducing the number of passes of heating cables. However this could be a potentially expensive option and should be used if and only if the standard design is not acceptable.

j) Consider the use of small, step-down low voltage transformers – Using a step-down transformer will reduce the voltage supplied to an MI heating cable and consequently reduce the sheath temperature and number of cable passes. Typically a 10 kVA transformer will have 120 V primary supply with tap-selectable secondary supplies of 10, 20, 30, 40, 50 and 60 V. This can often be a cost effective method to reduce the number of passes of heating cable.

IV. CASE STUDY

In order to demonstrate these design optimization techniques, an actual installation was chosen and selected techniques were applied from the base design to show how the techniques can assist in developing EHT designs that are constructible and maintainable while using the higher sheath temperatures as measured on the plate test.

The case study is illustrated in Appendix A, showing four variations of an EHT design of a particular pipe segment. Figure 1 is the base design where the designer has chosen to use multiple passes of a lower wattage cable, thereby lowering the sheath temperature to meet the area temperature rating of 260°C. This design results in 7 passes of cable along the main section of the pipe segment. Although this technique of using more passes of a lower wattage cable achieves a design that meets the area temperature rating, it has the significant drawback of having too much cable to actually physically assemble on the pipe, along with the associated problems with maintenance of valves or pumps and having to disassemble and re-assemble the multiple passes. Further steps are needed here in order to optimize the design and reduce the number of passes of cable.

The next technique applied to the base design is shown in Figure 2. In this design, the T-rating of the hazardous location was T2 (300°C) based on the auto-ignition temperatures of flammable fluids in the area. With the new T-rating, 7 passes in the base design are reduced to 5 passes in the Figure 2 design. Although 5 passes is more manageable from an installation and maintenance standpoint, some further optimization can still be performed.

The technique in Figure 3 uses the design from Figure 2 (T-rating change) and rationalizes the safety factor. Here the safety factor has been rationalized from 25% to 15%. This results in the removal of one more pass of cable from 5 passes in the Figure 2 design down to 4 passes in the Figure 3 design.

Finally in Figure 4 the designer has re-zoned the area and limited the zone to a single flow path and has calculated the sheath temperature as a control limited design instead of a stabilized design. This results in an EHT design using only 3 passes of cable, down from the original base design of 7 passes.

V. CONCLUSIONS

The current IEEE 515 contains a pipe test to predict MI heating cable sheath temperatures which can lead to inaccurate and varied sheath temperature predictions throughout the industry. The plate test method has proven to be a much more repeatable, cost-effective and accurate method of predicting and verifying sheath temperatures. Maximum sheath temperatures measured using the plate test are in agreement with the maximum sheath temperatures measured on the pipe test, with the plate test having the significant advantage of being able to easily capture the hottest temperature along the cable sheath. Due to the variability in the cable and insulation installation in the pipe test, the location where the maximum sheath temperature is measured varies from one set-up to the other and cannot be recorded reliably. The plate test should be considered as the method of choice to verify and predict the maximum sheath temperatures in future releases of the IEEE 515 standard, with the goal of entirely phasing out the pipe test method. The paper also presents optimization strategies to reduce costs and improve installation and maintenance of the electrical heat tracing designs while ensuring reliable system performance. These methods have proven effective for various real life applications and are continuing to be employed in EHT system design.

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VII. REFERENCES


VIII. VITA

Ron Jurchuk has a 1975 Electronic Technology diploma from Fanshawe College and a 1981 Bachelor of Applied Science Degree in Electrical Engineering from the University of Waterloo. Ron has 20 years’ experience with Imperial Oil and
Suncor in the petroleum refining and oil sands industries. He is currently employed by Tyco Thermal Controls in Fort McMurray, Alberta. He has been with Tyco Thermal Controls for 9 years. Ron is a Certified Engineering Technologist in Alberta as well as a registered Professional Engineer in the provinces of Ontario & Alberta. He is a 35-year member of the IEEE and has authored 2 IEEE PCIC conference papers.

Ron Derworiz received his Bachelor’s of Science degree in Electrical Engineering from the University of Alberta in Edmonton, Alberta, Canada in 1992. He is with Shell Canada Energy in Fort Saskatchewan, Alberta, Canada as the Upgrader facility Electrical Engineering Manager. He is a 19-year Member of the IEEE and author of two IEEE papers.

George Brady graduated from Northern Alberta Institute of Technology, 1988 and has spent 30 years in the petro-chemical industry in maintenance, reliability and project roles. Presently he is Senior Project Manager with Syncrude Canada and is the author of many IEEE papers and PCIC presentations.

Richard Loiselle graduated from the University of Saskatchewan with a Bachelor of Science in Electrical Engineering in 1989 and has spent 20 years in the petro-chemical industry in maintenance, reliability and project roles and is the author of many IEEE papers and presentations.

Sudhir Thorat received his Bachelors of Science in Chemical Engineering from the University of Mumbai in 1998, Masters in Materials Science and Engineering from the University of Tennessee, Knoxville in 2000 and Masters in Business Administration from California State University, East Bay in 2007. He has 9 years of experience in heat tracing systems working for Tyco Thermal Controls and has published 2 international papers in the Journal of Applied Polymer Science. He is presently Product Marketing Manager at Tyco Thermal Controls.

Blair McGrath received his Bachelor of Mechanical Engineering and Management from McMaster University in Hamilton, Ontario in 1993. He is presently Product Marketing Manager at Tyco Thermal Controls and is a registered Professional Engineer in the province of Ontario.
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