The thermal properties that influence the performance of insulation coatings used for personnel protection – redefining "Safe Touch"

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ABSTRACT

The majority of insulation coatings used today are used to provide personnel protection to workers in the oil and gas or chemicals industry. These coatings provide a reduction in surface temperature to help prevent burn injuries from accidental contact with a hot surface. Human burn hazard is defined in ASTM C1055-03 and this standard is used in conjunction with ASTM C1057-17 as a method of determining skin contact temperature from a heated surface.
In many cases, operators measure surface temperature to determine if the surface is safe to touch. In this paper, we will examine the historical evaluation of "safe touch" and define what "safe touch" really means as it is a time-dependent function.
We will describe the theory behind "safe touch" and explain the properties that are important in achieving the desired result. We will show a simulation model and how the various thermal properties are important to the overall "safe touch" properties of the coating. We will also look at how the actual measurement compares to the theoretical model and explain the key thermal properties that make a good coating for personnel protection.

Keywords: Personnel Protection, Safe Touch, Insulation Coating

Introduction

The majority of insulation coatings used today are used to provide personnel protection to workers in the oil and gas or chemicals industry. These coatings provide a reduction in surface temperature to help prevent burn injuries from accidental contact with a hot surface. Human burn hazard is defined in ASTM C1055-03[1] and this standard is used in conjunction with ASTM C1057-17[2] as a method of determining skin contact temperature from a heated surface.

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We will describe the theory behind “safe touch” and explain the properties that are important in achieving the desired result. We will show a simulation model and how the various thermal properties are important to the overall “safe touch” properties of the coating. We will also look at how the actual measurement compares to the theoretical model and explain the key thermal properties that make a good coating for personnel protection.

Human burn hazard

The chemicals and Oil industry operates many processes at high temperatures when refining and manufacturing the products that we use daily in our normal lives. The health and safety of employees when at work is the highest priority for companies operating in this area. A common problem identified is the potential for burn injuries on hot surfaces. ASTM C1055-03 is the standard used to determine acceptable surface operating conditions to prevent human burn injuries on heated systems. The acceptable temperature for any surface is determined from an estimation of the possible contact time, the system geometry, and the severity of the injury that is considered acceptable. In industrial situations, the probable contact time has been established as 5 seconds. The maximum acceptable injury is normally that causing a first-degree burn – an injury that is reversible and causes no permanent tissue damage. ASTM C 1055-03 contains a chart that shows the relation of skin contact temperature to the time needed to cause a burn and is shown in Figure 1.

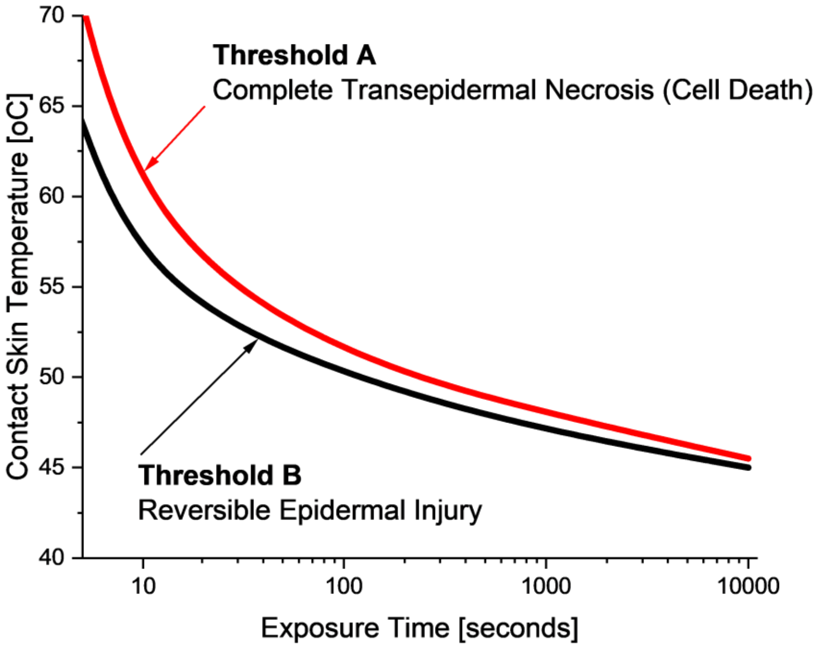


Figure 1: Temperature - Time relationship of burns

This graph shows that a contact skin temperature of 58.3ºC is the maximum skin temperature, after touch for 5 seconds, to prevent burn injuries on a metal surface.

This results in the industry-accepted practice of specifying areas safe to touch if the surface temperature is 60ºC or lower. However, ASTM C1055-03 should be used in conjunction with ASTM C1057-17 as a method of measuring or calculating the skin contact temperature from touching hot surfaces. Measurements should be done using a Thermesthesiometer[3] which is an electromechanical device that analogs the touch response of human skin to a heated surface. In practice; users measure surface temperature only as a means of preventing burn injuries.

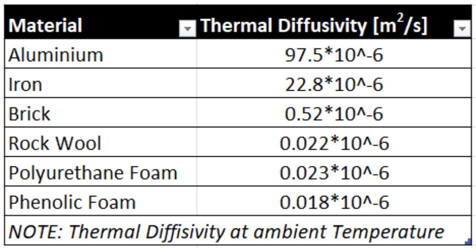
ASTM C1057 clearly shows the importance of calculation or measurement with the correct device and can really show the actual surface temperature and the potential for burn injury depending on the properties of the surface. This means that a surface can be over 80ºC and still be safe to touch.

Thermal Diffusivity (FP)

As seen above, safe touch is a time-dependent function, and therefore thermal conductivity alone is not sufficient to relate to the time of contact on a surface. Density (ρ) and specific heat (Cp) are used in the thermal equilibrium equation, especially for heat balances. The product ρ.Cp is called volumetric heat capacity and its unit is ($J/m^3.K$). This term relates to the material's ability to store heat. So, when a coating's ability to conduct heat (k) is compared with its ability to store heat (ρ.Cp), it becomes a time-related function and is called thermal diffusivity. This ratio is expressed as follows:

$$\alpha = k/\rho.Cp \qquad [m^2/s]$$

This ratio is often used in transient-related heat transfer mathematical equations.
Material with a large thermal diffusivity will respond rapidly to changes in temperature for instance (e.g. copper), whilst a low thermal diffuser will take a much longer time to reach thermal equilibrium. The thermal diffusivity of some common materials is shown in Table 1.



Material	Thermal Diffusivity [m^2/s]
Aluminium	97.5*10^-6
Iron	22.8*10^-6
Brick	0.52*10^-6
Rock Wool	0.022*10^-6
Polyurethane Foam	0.023*10^-6
Phenolic Foam	0.018*10^-6
NOTE: Thermal Diffisivity at ambient Temperature	

Table 1: Thermal Diffusivity of common materials at 20ºC.

The unit of thermal diffusivity can be represented graphically (Figure 2) and is worth remembering.

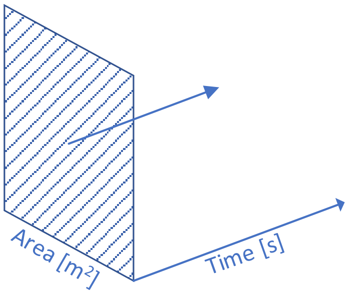


Figure 2: Units of Thermal Diffusivity.

Thermal diffusivity measures the speed at which heat travels and reaches equilibrium and is the perfect property to relate to safe touch.

However safe touch adds another dimension as it relates to the skin surface in contact with the hot surface. There will be a thermal equilibrium between the pain sensors in human skin and the hot surface. Therefore, the lower the thermal diffusivity of the surface coating, the slower heat transfer by conduction towards the pain sensors will be sensed, and the longer the surface can be touched without injury. This is illustrated in Figure 3.

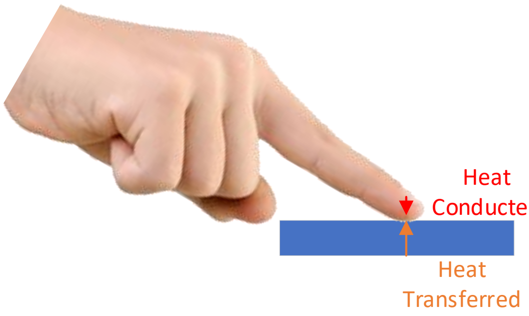


Figure 3: Thermal equilibrium between hot surface and finger

Explaining the different impacts of Cp, k, Density?

Thermal diffusivity is not a constant because thermal properties vary as the temperature changes. Both Specific Heat and Thermal Conductivity change whilst density are constant through the temperature range. The following graph (Figure 4) highlights the change in thermal conductivity of a thermal insulating coating material within the range of 0-60°C. The density of the material has the largest influence on thermal diffusivity. This may come as a surprise but mathematically, as density is on the denominator of the thermal diffusivity equation, thermal diffusivity decreases with higher-density thermal insulation coating.

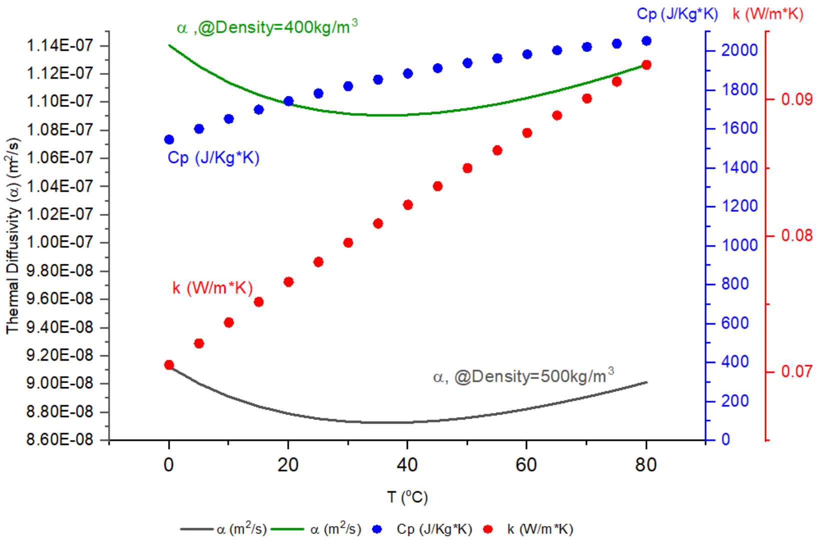


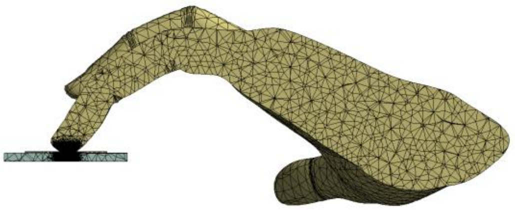
Figure 4: Variability of Thermal Diffusivity v Thermal Property change.

Interestingly, in the range of temperatures studied, thermal diffusivity is at its lowest at 40°C. Again, mathematically it can be explained as the rate of change of thermal conductivity is greater than specific heat. For this particular material, the lowest thermal conductivity almost corresponds to the safe touch pain threshold of 60°C.

Modelling Safe Touch

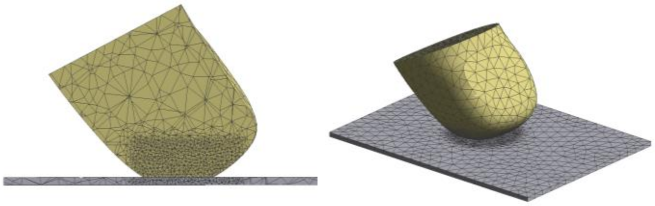
A finite element model was built of the hand and the middle finger touching the thermal coating on a hot steel substrate as shown in Figure 5. The 3D mesh represents the calculations point that is used to evaluate the temperature gradient across the various materials.

3D cad model of hand, thermal coating and substrate



3D mesh representation

3D mesh of the steel and coating



Emphasis on increased density mesh

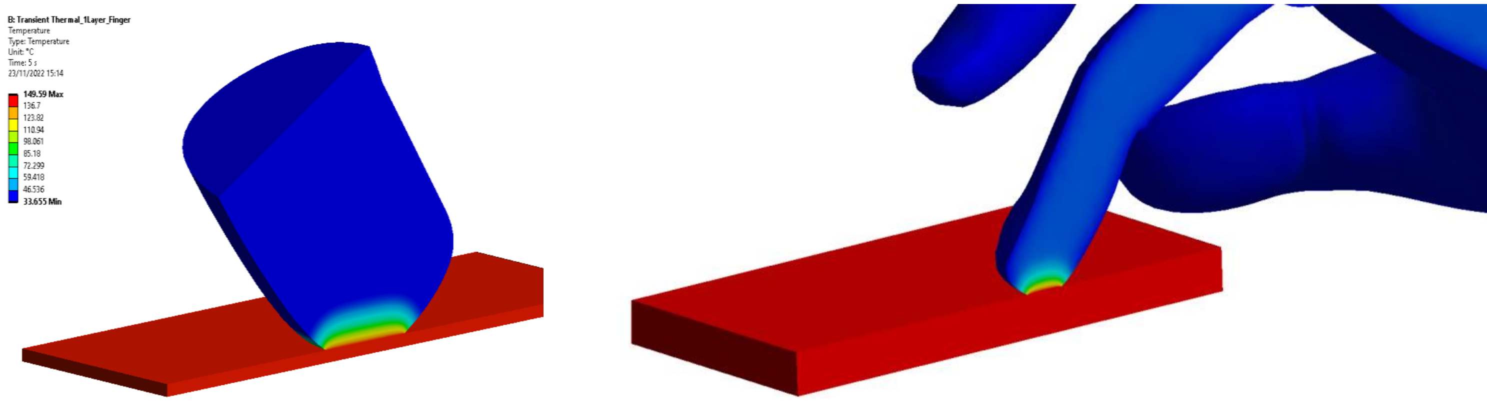


Figure 5: Finite element model of finger touching a hot surface.

Experimental data versus model data

We have developed a new, acrylic-based, coating for use in personnel protection when operating temperatures are as high as 177ºC / 350ºF. We have measured the applied density (when spray applied), thermal conductivity according to ASTM C518[4,] and specific heat capacity in accordance with ASTM E 1269[5]. This data has been fed into the model described earlier of a finger touching a hot surface.

Actual measurements have been then done in the laboratory using the test methodology described in NACE TM21423 (Determination of substrate and surface temperature limits for insulative coatings used for personnel protection)[6]. For this study, we are going to look at the results for a single coat application of 2mm / 80 mils of insulative coating on epoxy-primed steel of 5mm / 0.188". The panel was dried at ambient temperature for 7 days and then conditioned to remove all volatiles by heating at 0.6ºC/1ºF, to avoid any blistering, to 177ºC/350ºF and then held at this temperature for 24 hours. This is the methodology described in NACE TM21431[7]. Safe touch testing is then done after the panel has cooled to ambient temperature. The results are shown in Table 2 as the substrate temperature is increased the surface temperature of the insulation coating is measured with a digital thermometer that has a partially enclosed wire probe from Kimo Instruments. The thermocouple is placed directly on the insulation coating surface until a steady reading is achieved. An IR meter is not used to measure the surface temperature of coatings in this work and the authors acknowledge that more work is needed to investigate accurate methods or determining the actual surface temperature. These results are indicative only and are likely to be much lower that the actual surface temperature but show the type of data obtained in real life against using a thermethesiometer reading taken after 5 seconds of contact time on the insulation coating.

Temperature / ºC	40	50	60	100	125	150	175
Thermocouple	29	35	44	47	55	66	76
Thermethesiometer	32	31	37	44	47	52	55

Table 2: Surface temperature of 2mm insulation coating v substrate temperature.

This data is also shown graphically in Figure 6:

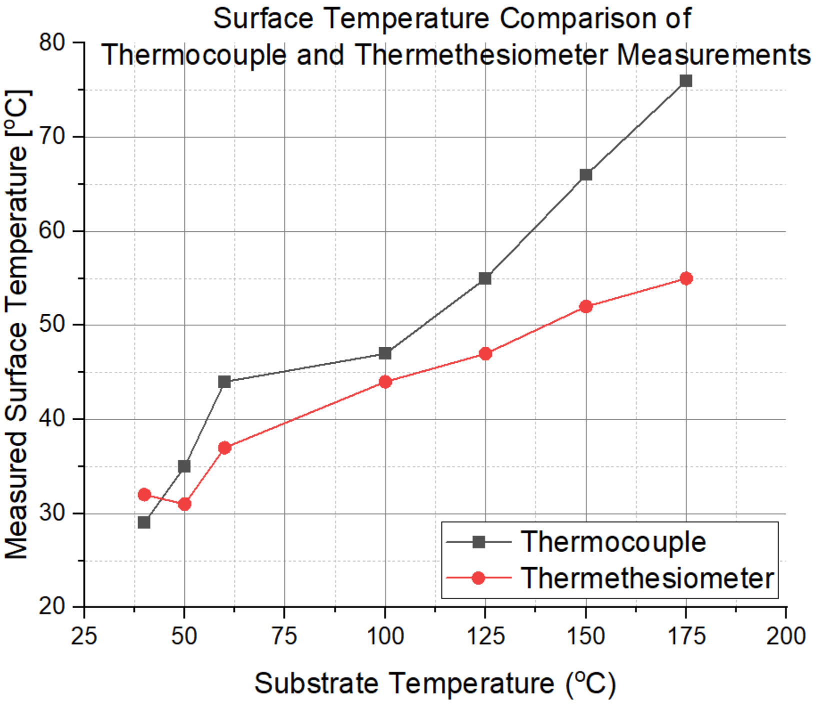


Figure 6: Surface temperature comparison from Thermocouple v Thermesthesiometer

This comparison study shows that for a coating of 2mm / 80 mils the thermocouple reading is above 60°C while the Thermesthesiometer reads below 60°C for all temperatures. Most Oil and Gas companies would subsequently fail this coating system for service above 150°C even though it clearly meets the requirements of ASTM C1057.

What does the model tell us?

The model as, described earlier, can be used to predict the coating thickness needed to prevent burns according to ASTM C1057. The key data that is imputed into the model is:

- Coating thickness (mm) and in this case we use the 2mm from the laboratory testing
- Substrate temperature of 150°C
- Convection – in W/m^2
- Emissivity of the coating
- Ambient air temperature of 15°C

The model data is shown in figure 7:

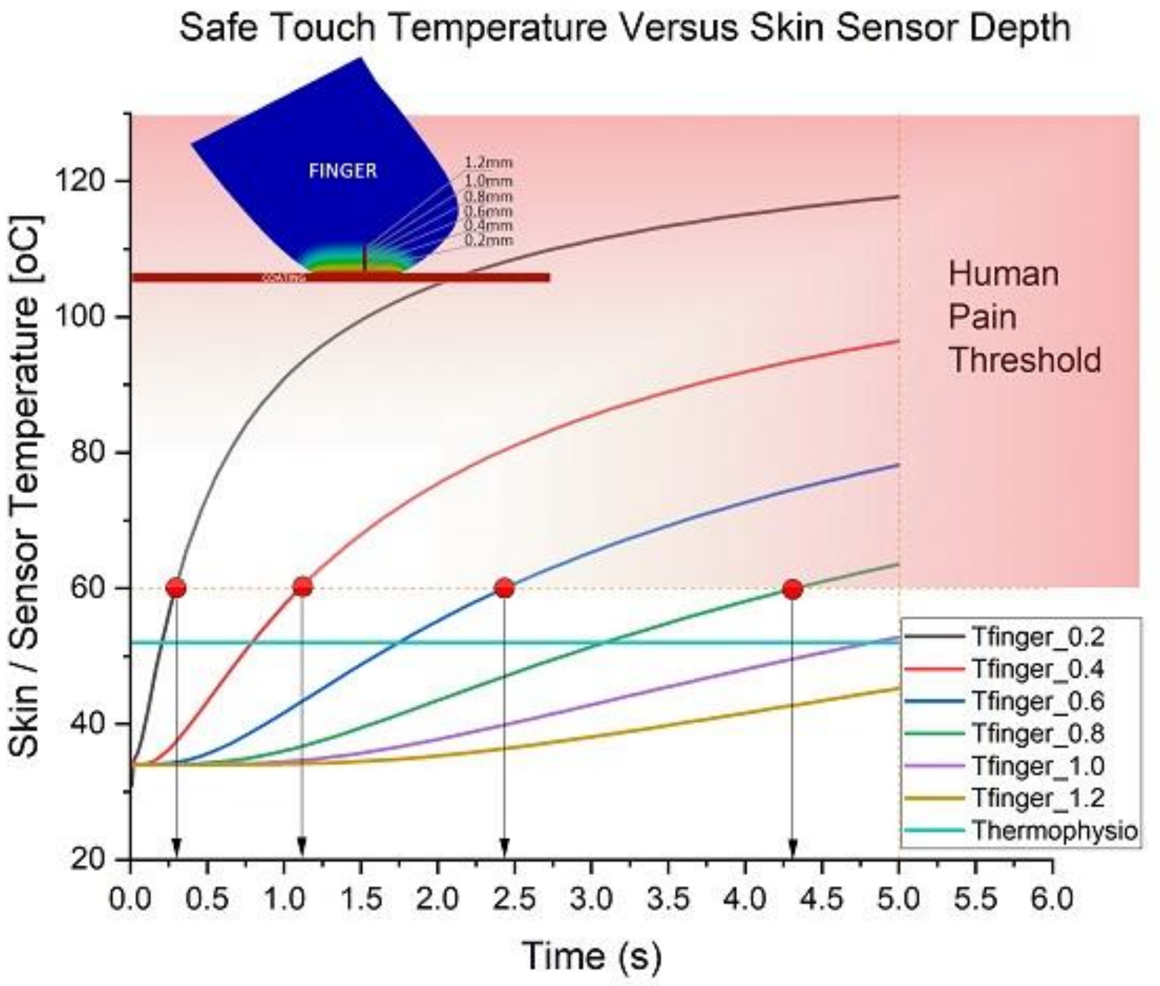


Figure 7: Model of skin temperature against time of contact on a hot surface

The graphs demonstrate the correlation between skin temperature and time for various depths of pain sensors in the finger. As the pain sensor is placed deeper within the tissue, the temperature that it detects decreases over time. The data from the thermesthesiometer was used to validate the location of the pain sensor by comparing it to the temperature predicted by the model. The results suggest that when the pain sensor is located at 1.0 mm, the temperature predicted by the model aligns with the temperature measured by the thermesthesiometer after 5 seconds of contact. This does not correlate well with the model used in ASTM C1057 which uses a depth of 0.08mm to describe skin contact temperature. However, the model shows some promise in its ability to accurately predict safe touch temperatures, but it would need to be adjusted for different materials and substrate temperatures.

CONCLUSIONS

The safe touch area is a complicated area because of the potential to harm personnel. ASTM C1057 is used to specify surfaces as “safe to touch” but most operators do know to use the standard correctly. They specify a surface temperature of 60ºC which is the temperature you will get a burn injury on bare metal. Insulation coatings have a lower thermal diffusivity than metal and that lowers the rate of heat transfer from a hot to a cold surface. The easiest analogy to consider is the use of a metal v a wooden spoon when cooking. The thermal diffusivity means that even at a high surface temperature the skin temperature (as measured by a thermesthesiometer) is still below 60ºC after 5 seconds of contact meaning that the surface can be safely touched for 5 seconds without suffering a burn injury.

We have developed a model, using measured thermal and physical data of the insulation coating, which can be used to accurately predict the safe touch temperature for the insulation coating at the desired operating temperature.

REFERENCES

Author’s initials, Author’s last name, “Title of Paper,” Name of Conference, paper number (City of publisher, State of publisher: Name of Publisher, Date of Conference/Publication), Page number(s).

1. ASTM C 1055 (latest revision), “Standard Guide for Heated System Surface Conditions that Produce Contact Burn Injuries” (West Conshohocken, PA: ASTM).

2. ASTM C 1057 (latest revision), “Standard Practice for Determination of Skin Contact Temperature from Heated Surfaces Using a Mathematical Model and Thermethesiometer” (West Conshohocken, PA: ASTM).

3. therm-x.com/standard-products/thermesthesiometer.html

4. ASTM C 518 (latest revision), “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus” (West Conshohocken, PA: ASTM).

5. ASTM E 1269 (latest revision), “Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry” (West Conshohocken, PA: ASTM).

6. NACE TM21423-2017 “Determination of Substrate and Surface Temperature Limits for Insulative Coatings used for Personnel Protection” (Houston, TX: NACE, 2017).

7. NACE TM21431-2020 “Test Methods to Evaluate Thermal Properties and Performance of Insulative Coatings” (Houston, TX: NACE, 2020).