PRODUCT / APPLICATION INFORMATION

Stability Testing of Self-Regulating Heating Cables and New High Temperature Heating Cable Solutions

Abstract – This paper will discuss performance life testing and stability testing used for self-regulating heating cables. It will show how the techniques were developed and evolved from the 1970's to the present How these techniques re used to establish ratings on the latest high temperature heating cables will also be discussed.

INTRODUCTION

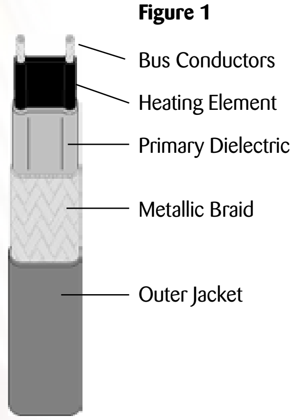
Self-regulating conductive polymer heating cables are widely used for freeze protection and process temperature maintenance in industrial applications. In these applications the cost of downtime is significant. Therefore, it is critical that heat tracing provide the required heat to maintain operating conditions over the expected life of the process unit. The question arises, "How does one establish or project long term performance and stability of a self-regulating heating cable?". The typical expectation for industrial applications is that the cable will function for 15 to 20 years.

Basic Constructions

First it is important to understand the basic constructions of self-regulating heating cables. The heating element of a self-regulating heating cable is a conductive polymer that exhibits a PTC effect. As the temperature of the heating element increases, its electrical resistivity increases. Thus, the conductive polymer has a positive temperature coefficient for resistance (PTC). The power output or thermal output decreases with increasing temperature.

A typical construction for a self-regulating heating cable is shown in Figure 1.

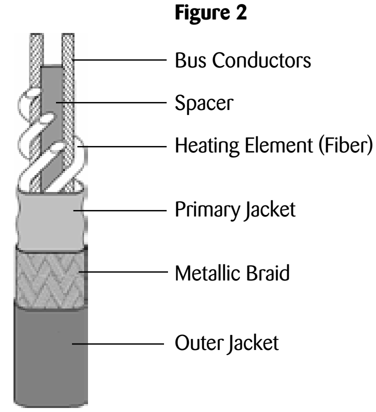
Figure 1



This shows a "monolithic" construction with the heating element or core between two conductors. This forms a parallel circuit so the heating cable can be cut to length without changing its lineal power output. The heating element consists of carbon black mixed into a semi-crystalline polymer. The melting point of the polymer dictates the self-regulating temperature or "shut-off" temperature. Polyethylene based heating cores are primarily used for low temperature, freeze protection applications, while fluoropolymer based heating cores are used for process temperature maintenance and higher temperature exposure applications. The primary jacket provides the dielectric insulation. Metallic braid, usually tinned copper surrounds the primary jacket and serves as a ground path. For additional mechanical protection and corrosion resistance there is an outer polymer jacket over the braid.

Another self-regulating cable construction is shown in Figure 2.

Figure 2



Here instead of a monolithic core or heating element, the heating element is a fiber that is spirally wrapped around two bus conductors with a non-conducting polymer spacer separating the bus conductors. This heating element fiber is a conductive polymer. Contact between the bus conductor and fiber heating element is enhanced with an electrically conductive paste. A primary dielectric jacket surrounds the fiber heating elements. Like the previous "monolithic" construction, a metal braid and outer jacket are included with the "fiber" construction self-regulating heating cable.

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Factors for Long-Term Performance and Stability

With conductive polymer heating elements, the aging mechanism is primarily oxidation with temperature and time. In most cases the resistance of the conductive polymer increases with temperature and time. Thus, the self-regulating heating cable is fail-safe from a burnout standpoint and excessive sheath temperatures in hazardous areas. However, it is important that the cable provide the rated power for maintaining the specified temperatures.

Service life of a self-regulating heating cable is not only dependent on the polymer used for the heating element using long term performance and stability but, also is dependent on the processing. There are three key factors in manufacturing a self-regulating heating cable for long-term performance and stability: heating core homogeneity, contact resistance between heating element and bus conductor, and a closely conforming primary dielectric jacket.

Heating core homogeneity - The mixing of carbon black with the polymer base is critical. Mixing is done in a compounding process. If the core does not have good homogeneity, hot spots can occur across the heating element due to localized variations in resistance. With time this results in localized thermal run away and a non-functioning heating cable.

Contact between the bus conductor and the heating element - Reliable self-regulating heating cables have low contact resistance between the bus conductor and the heating element. Poor contact is somewhat like a "cold joint" where there is excessive heat build up. In time the localized resistance increases to the point where the heating cable is not producing its rated power.

Loose primary jacket - If there are air gaps between the heating element and the primary jacket, heat transfer from the heating cable will be impeded. This results in potentially higher than normal heating core temperatures. In turn this results in faster oxidation and reduction in heating cable output.

While there are other factors affecting life and stability, these three are the major factors.

TEMPERATURE RATINGS

Due to the temperature dependence of polymers on retained properties, the temperature rating of a self-regulating heating cable is the key factor affecting performance life and stability. However, one will find not a single temperature rating, but a number of temperature rating terms for self-regulating heating cables. These terms are described as follows:

Maximum maintain temperature – The highest temperature of the pipe or vessel that the heating cable is capable of maintaining continuously in an energized condition. The service life expectation is 15 to 20 years.

Maximum intermittent temperature - The highest temperature that the heat tracing cable may be exposed for a period of time as declared by the manufacturer.

This last definition may need more explanation. Since polymer properties are time/temperature dependent, higher ratings to accommodate exposures such as steam clean or purge could be established which are higher than the continuous temperature exposure ratings. The intermittent rating is typically 1000 hours of cumulative exposure. This addresses steam clean exposure over the expected system life (15-20 years) in industrial applications. Another factor in intermittent exposure is whether or not the heating cable is energized during the exposure. The power condition (energized or de-energized) is declared by the manufacturer.

PERFORMANCE LIFE AND STABILITY TESTING

Since the introduction of self-regulating heating cables in the early 1970's, numerous methods have been used to establish performance life and stability. This section will describe test methods used as they evolved from the 1970's to the present.

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Accelerated Aging Testing

One of the first approaches used to project life of a conductive polymer heating cable was based on the Arrhenius equation. The test technique is described in UL 746B. In the 1970's many temperature ratings for polymer dielectric insulations on wire were based on UL 746B accelerated aging techniques. The material properties such as tensile and elongation of the polymer insulation changed with time and temperature according to the Arrhenius reaction rate equation:

$$K = A \exp(-E/RT)$$

Where:

- K = specific reaction rate
- A = constant
- E = activation energy of the reaction
- R = gas constant
- T = temperature

By taking the natural log (Loge) of both sides, the equation becomes,

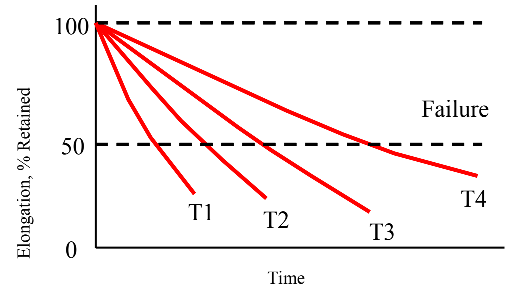
$$\mathrm{Log_e}(\text{time}) = \text{constant} + [(1/2.303)(E/RT)]$$

Or

$$\mathrm{Log_e}(\text{time}) = a + b/T$$

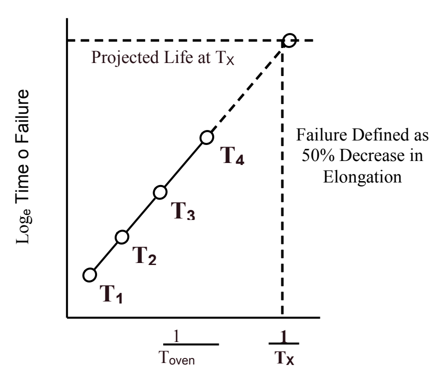
Loge(time) becomes a linear relationship with temperature. This lends itself to obtaining experimental results over short periods and being able to a project temperature at a longer time. For wire insulation an end point was typically defined such as 50% retained elongation or tensile strength. Then specimens of the polymer material were exposed to a range of elevated temperatures.Tensile and elongation measurements are made on a schedule. When the end point is attained for a given specimen, the exposure time and temperature were recorded. Figure 3 shows typical data for 50% retained elongation.

Figure 3
Tensile Elongation vs. Time & Temp



T1 is the highest temperature exposure and T5 is the lowest. As the Arrhenius equation would predict, as temperature decreases, it takes longer to reach the end point. By taking this data and plotting it with Loge (time) on the y-axis and the reciprocal of absolute temperature on the x-axis a straight line is formed. Time/temperature data taken for 6 months to 24 months that will provide adequate data for a straight-line correlation that can be extrapolated to longer times (years) to find the intersection of 1/T. The resulting temperature becomes the rated temperature for that time period or life definition. Refer to Figure 4.

Figure 4
Projected Life, Tensile Elongation



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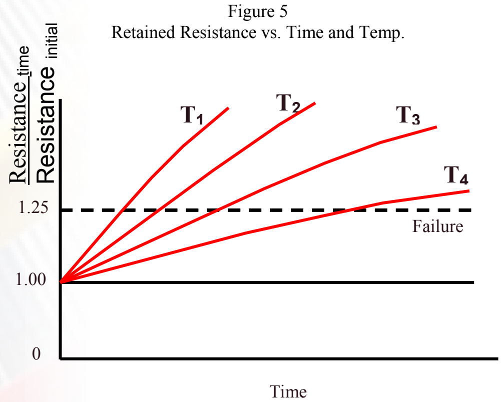
For conductive polymer heating cables the same concepts can be applied except with a different end point criterion. As stated earlier, conductive polymer heating cables increase in resistance with time and temperature. Therefore, retained power % or percentage resistance increase is the most indicative end point for long-term performance projections.

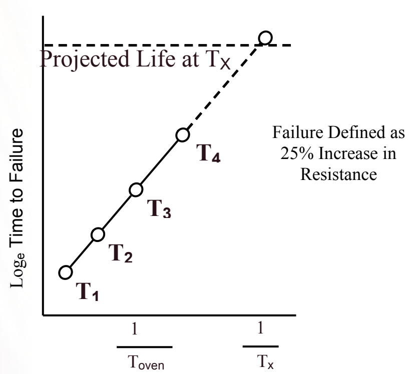
In this case the time and temperature data is recorded for the 25% resistance increase end point. Refer to Figures 5.

Figure 5
Retained Resistance vs. Time and Temp.



Similar to the wire insulation case, data can be acquired over a period of 6 months to 24 months, and then an extrapolation can be made for establishing the temperature rating for 20 years or more for the heating cable. Refer to Figure 6.

Figure 6
Projected Life S/R Heating Cable



UL 746B provides a basis for accelerated aging and life projections of materials. In the case of wire insulating material the test specimens are strips of the polymer to be evaluated. In the case of conductive polymer heating cables, sections or short lengths of heating cable are used. Strictly adhering to UL 746B, the specimens are placed in the various temperature controlled ovens in a passive or de-energized state. However, the heating cable is an active element and the test can be constructed to develop the correlation with the heating cable specimen active or in an energized condition. To do this the cable temperature in the oven must be measured and this temperature used for the time/temperature end point.

However, while accelerated aging testing provided a basis to project life of a self-regulating heating cable at a temperature, other forms of testing are necessary. A heating cable can have a 20-year life expectancy based on passive accelerated aging testing and yet degrade to an unacceptable level of performance in weeks under active conditions of voltage and temperature cycling. This can be due to the previously mentioned processing conditions that result in poor heating core homogeneity, high contact resistance between heating element and bus conductor, and a loose primary dielectric jacket. For example, a heating cable with poor contact between the bus conductor and heating core would not exhibit any abnormal degradation in performance with passive (non-energized) accelerated aging testing, but would increase rapidly in resistance with active (energized cyclic testing. As a result, various forms of short term active cyclic testing were developed to assure stability.

Stability Testing of Self-Regulating Heating Cables and New High Temperature Heating Cable Solutions

IEEE 515 Benchmark Test - 1997

In the early 1990s self-regulating heating cables were the most common approach to electrical heat tracing. Users relied on manufacturer's ratings for long-term performance. IEEE Standard 515 had been in use since 1983 yet did not have any testing requirements addressing longer-term performance and stability. The IEEE 515 Working Group established for the second 5-year review cycle decided to address this issue. The matter was compounded in complexity because no longer was maximum maintain temperature the only temperature rating; maximum intermittent temperature was frequently used. Key elements for test conditions were identified:

- High temperature exposure
- Power/voltage cycling (active testing)
- Heating cable specimens based on the entire resistance range

The resulting test conditions incorporating these elements in the IEEE 515 Std – 1997 are:

- Test specimens are selected to represent the maximum and minimum resistance
- Exposure at the maximum declared maintain temperature
- Heating cable is continuously cycled - 12 minutes energized at rated voltage and 3 minutes de-energized
- Duration of the test is 32 weeks (5376 hours)
- If intermittent temperature rating is used
  - Heating cable is exposed to declared maximum intermittent temperature for a time period of 8 hours per week
  - Power ON or OFF condition during this exposure is based on the manufacturer's rating

At the completion of the test after 32 weeks the acceptance criterion is based on power output change. The window is,

$$0.75 < P_{final} / P_{initial} < 1.20$$

This requires the heating cable to retain 75% of its initial power output and to not increase in power by more than 20%.

The IEEE 515 – 1997 Service Life Performance Benchmark test provided a means of establishing long term performance and stability based on the stated temperature ratings of the cable. Since the heating cable is energized for the maximum maintain temperature exposure, and if specified for maximum intermittent exposure, actual worst-case conditions are tested. In North America approval agencies have adopted this test as a requirement.

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IEEE 515 Benchmark Test – 2004

In the 1990s higher temperature cable options were being developed. Polymers such as perfluoroalkoxy fluorocarbon resin (PFA) were being used for the heating element. At the time PFA was introduced, accelerated aging testing per IEEE-1 and UL 746B found no correlation to enable projection of a temperature rating for 10 or 20 years. For wire and cable applications long-term performance was established by measuring retained properties over 20,000 hours at 285 C which is just below the melt temperature of PFA. Therefore, use of UL 746 B for projecting life and establishing temperature ratings was not possible with these higher temperature conductive polymer self-regulating heating cables.

The IEEE 515 - 1997 Service Life Performance Benchmark test required 32 weeks. Since this test had become part of the approval process, the time required for the test became a factor in product development time and market introduction. The CSA 130.3 Working Group in Canada as well as the IEEE 515 Working Group in the USA (established for the third 5-year review cycle) decided to address this issue. The goal was to develop an equally stringent test which would provide an indication of long-term performance but which could be accomplished in a shorter period of time. The key factor is doing this was introducing thermal stress.

The new shorter duration test incorporated the following:

- Test specimens are selected to represent the maximum and minimum resistance
- The heating cable is thermally cycled
  - Between the manufacturer's declared maximum maintain temperature and 23 C
  - Minimum time dwell at each extreme temperature is 15 minutes.
  - Total duration is 1500 cycles
- Following the 1500 cycles is the test for maximum intermittent temperature rating
  - The cable is exposed at the maximum rated temperature for 250 hours.
  - Power ON of OFF condition during this exposure is based on the manufacturer's rating

After these exposures the same acceptance criterion as used in the IEEE 515 1997 Benchmark test which is based on power output is applied.

$$0.75 < P_{final} / P_{initial} < 1.20$$

To further validate this test, self-regulating cables with a known long-term stable performance were tested along with cables that had shown deterioration in performance with time. The results confirmed the 515-2004 Benchmark test is a reliable screen or indicator of long-term life and stability of self-regulating heating cables.

NEW HIGH TEMPERATURE HEATING SOLUTONS

In the past twenty years compounding equipment and extrusion techniques have advanced. This has provided the capability to manufacture self-regulating heating cables with high performance high temperature polymers such as PFA.

A recently introduced self-regulating cable based on a PFA polymer heating element was developed with goal of (1) high heating core homogeneity, (2) no contact resistance between bus conductors, and (3) tight primary jacket over heating core.

For this new heating cable a high degree of homogeneity is achieved through use of state-of –the-art compounding equipment and techniques. The contact between the bus conductors and polymer is optimized with a monolithic type heating element construction. The primary dielectric jacket is integral to the core, which maximizes heat transfer from the heating element. The combination of the monolithic construction and integral jacket results in uniform power flux and the lowest core temperature for the lineal heating provided.

This new high temperature heating cable is capable of lineal power output of 64 W/m @ 10 C with an operating voltage of 230 Vac. Based on the IEEE 515 - 2004 Benchmark test, the temperature ratings achieved are:

Maximum maintain temperature - 121 °C
Maximum intermittent temperature
Energized - 215 °C
De-energized - 250 °C

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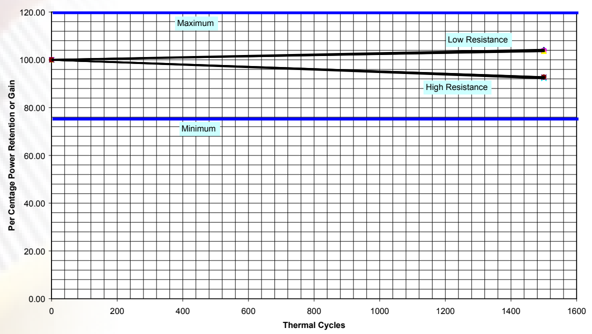
Test results for the energized exposure are shown in Figure 7. After 1500 cycles from 23 °C to 121 °C and a 250 hour exposure to 215 °C, the change in power output were an increase of 4% for the higher wattage cable and a 8% decrease for the lower wattage cable. These changes are well within the requirements of IEEE 515 and indicate stability

Figure 7
Performance After Thermal Ageing Benchmark Maintain Temp 121°C Maximum Intermittent Exposure Temp Power On 215°C.



SUMMARY

With the advent of self-regulating conductive polymer heating cables in the early 1970's, a method to establish product life and stability was needed. Accelerated aging testing based on the Arrhenius equation was used along with short term cyclic testing. Heating cable life could be projected as a function of rated operating temperature. However, manufacturing faults were not always detected with accelerated aging tests based on UL 746B and IEEE 1. Active testing (heating cable energized) was employed in the 1980's to detect improper processing faults that can lead to deterioration in power output with time. These active testing methods were refined and became part of the IEEE 515 -1997 heat tracing standard as the Benchmark Service Life Test for heating cables. This test provided basis for intermittent temperature exposure ratings of S/R heating cables. It also provides the ability to establish temperature ratings for S/R cables using high temperature polymers such as PFA which do not follow Arrhenius techniques for projecting life at a rated temperature

In the latest version of CSA 130.3 published in 2003 and IEEE 515 published in 2004 , the severity of the exposure is increased by changing from voltage cycling to thermal cycling. This allowed a reduction is in test duration from 32 weeks to 12 weeks. The major North American approval agencies, UL and FM use the IEEE 515 - 2004 Benchmark test and CSA uses the virtually identical Performance After Thermal Ageing Test in CSA 130 .3 as a requirement in approvals for self-regulating heating cables.

With advances in processing equipment and techniques that address some of the processing challenges of the past, self-regulating heating cables are available with high lineal power outputs and high temperature exposure ratings. Their temperature ratings for long -term life and stability are established with service life tests such in IEEE 515-2004 and CSA 130.3.

REFERENCES

[1] IEEE 1-2000 Recommended Practice: General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation. Reaffirmed September 22, 2005.

[2] IEEE Standard 515 - 2004 IEEE Standard for the Testing, Design, Installation, and Maintenance of Electrical Resistance Heat Tracing for Industrial Applications. Revision of IEEE Std 515-1997

[3] UL 746B Standard for Polymeric Materials; Long Term Property Evaluations. August 28, 1996.

VITAE

Richard H. Hulett received a BSME, in 1964 and an MSME in 1965 from Stanford University. He is the Senior Vice President of Electrical Products for Thermon Manufacturing Company, where he has been employed for 10 years. He was previously employed by Raychem for 20 years. He has been a member of the IEEE and the IEEE/IAS/PCIC for the past 25 years. He is currently a member of the IEEE Standards Board. As a member of PCIC, he has been on the Standards Subcommittee, where he has served as chair, from 1993-present. He has been a member of the IEEE 515 Working Group since 1979, where he has served as Chair, since 1985. He is also a member of the Codes and Regulations Working Group and the Chemical Subcommittee. Mr. Hulett is a member of the American Society of Mechanical Engineers, since 1964. He has received the David C. Azbill Award and the IEEE Standards Medallion.