SAFETY AND PERFORMANCE

RELIABILITY OF ELECTRICAL INSULATION SYSTEMS

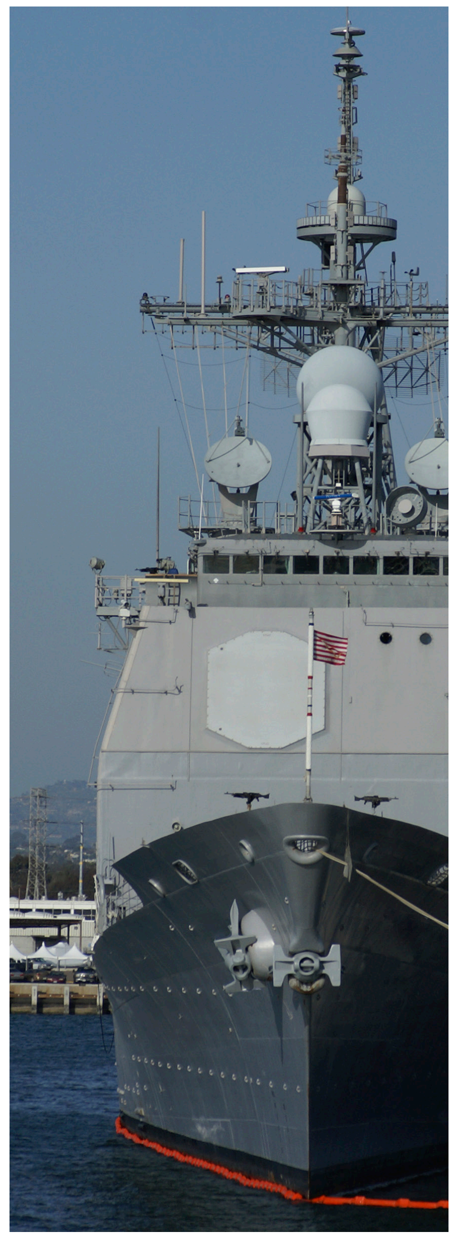
Safety and Performance

Reliability of Electrical Insulation Systems

Safety and performance reliability are essential attributes for an electro-magnetic device, such as motor, transformer, generator, solenoid, etc., and the electrical insulation system (EIS) used in the device is a critical link. An EIS is a unique combination of electrical insulating materials (EIMs) used in electrical equipment, closely packed together, operating at or below the maximum operating temperature of the device. An example is the combination of magnet wire, ground and interwinding insulation and impregnating resin in a transformer.

As these devices operate at elevated temperatures, thermal degradation of the EIMs is likely to occur, and performance reliability depends in large part on the compatibility of these materials and how they will react together as a system. While this may seem self-evident and simple to execute, the reality is that polymeric materials may not thermally perform as anticipated based solely upon the individual material thermal ratings. This is why conducting a thermal performance evaluation on the combination of materials used in the device as a system is so important.

This UL white paper will introduce the history of EIS testing, why it was developed, outline the testing options, and explore technical considerations applicable to EIS. It will include the key elements of UL 1446, the Standard for Safety for Systems of Insulating Materials, the requirements for a full thermal aging test, a discussion of the pathway for modifying existing thermally-aged EIS, and some considerations for OEM manufacturers incorporating an EIS established by an EIM supplier into their finished products.



A Brief History

After World War II, the U.S. Navy was interested in updating the motors used on their warships. With the advent of new insulating materials made of various polymeric materials that claimed higher thermal properties, the Navy needed to substantiate these claims when compared with the tried and true motor insulating materials that had been in service for years. To do this, a team was assembled to find a way to evaluate these insulation systems for thermal characteristics.

As a result, a method was developed to evaluate the combination of insulating materials by the use of representative modelling[1]. This model was initially termed a motorette, but today the design is referred to as general purpose model (GPM). This method was able to determine a thermal rating for the insulation system in a time frame much shorter than that required to test actual motors to service life failure.

Subsequent research[2] determined that materials thermally aged in combination responded differently from similar individual materials aged in isolation. These findings were further qualified in Military Specification MIL-E-917D (Navy), covering the basic requirements of electrical power equipment for naval shipboard use:

> ***"A material that is classified as suitable for a given temperature may be found suitable for a different temperature, either higher or lower, by an insulation system test procedure."***
> **(para. 3.5.2.1.10)**[3]

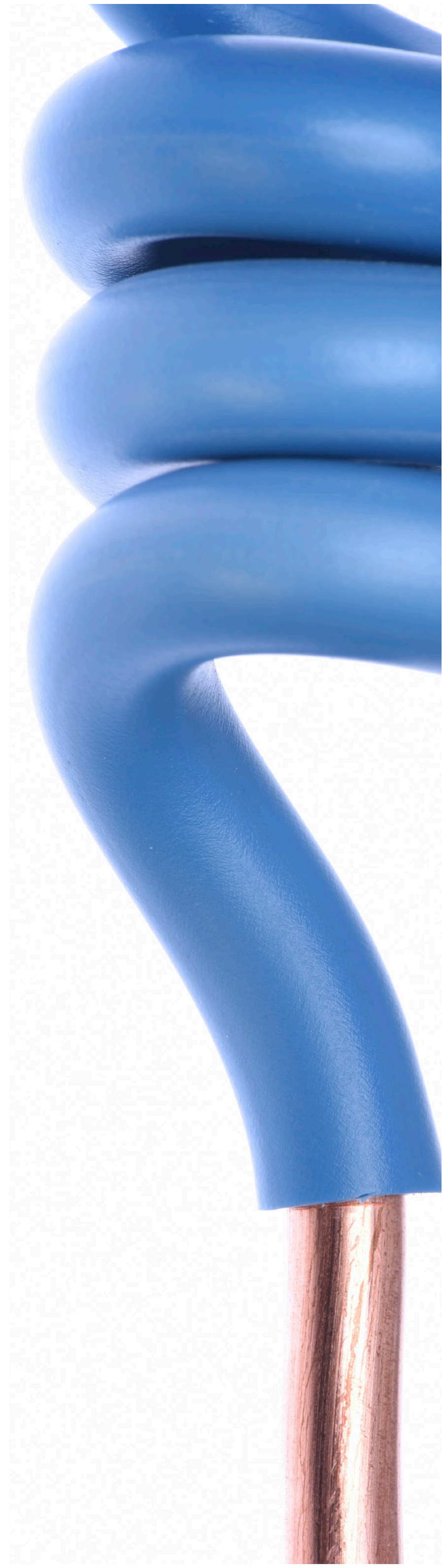
This requirement regarding material performance led to the need to conduct an EIS full thermal aging test in order to verify the temperatures under which a combination of EIMs would operate reliably.

From this work, IEEE Standard 117-1974, Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electrical Machinery, was published, which outlines the use of motorettes and the thermal aging method. In June 1978, UL 1446, the Standard for Safety for Systems of Insulating Materials – General, was issued. As result, EIS were certified to these requirements under the UL category code number OBJY2.

The importance of evaluating the combination of EIMs is supported by a recent study conducted by ELTEK International Laboratories[4], in which the thermal ratings calculated from the testing a combination of materials in a complete EIS were compared with the ratings that would have been assigned using the common (i.e., lowest) EIM rating assigned to individual EIMs. Of the 30 EIS evaluated in the study, half (50 percent) achieved a higher thermal rating based on testing of a complete EIS, while 14 (47 percent) achieved a lower thermal rating. These and similar findings support the importance of testing the combination of materials to be used in an electrical device with a full thermal aging test program.

Insulation and Electrical Insulation Systems

EIMs are used in all types of electrically-charged equipment. These materials isolate or separate sources of electrical energy and support the required flow of electrical current through the properly designed current pathways. This is absolutely critical for the safe operation of the device and reduces the potential for unexpected property damage and operator injuries. If insulation fails and allows the current flow to move to another voltage potential or grounded or dead metal, the risk of personal injury and property loss is greatly increased due to fire and electrical shock created by the material failure.



Even when subjected to normal electric loads under anticipated use conditions, EIMs can lose their effectiveness over time as a result of degradation. Although insulation degradation may be attributable to a number of different causes, thermal aging is the most common form of degradation that results from internal heating due to electrical circuits or high ambient temperatures. Thermal aging can also reduce the expected design performance of the electrical equipment, in addition to compromising safety by potential exposure to electric shock, fire or explosion.

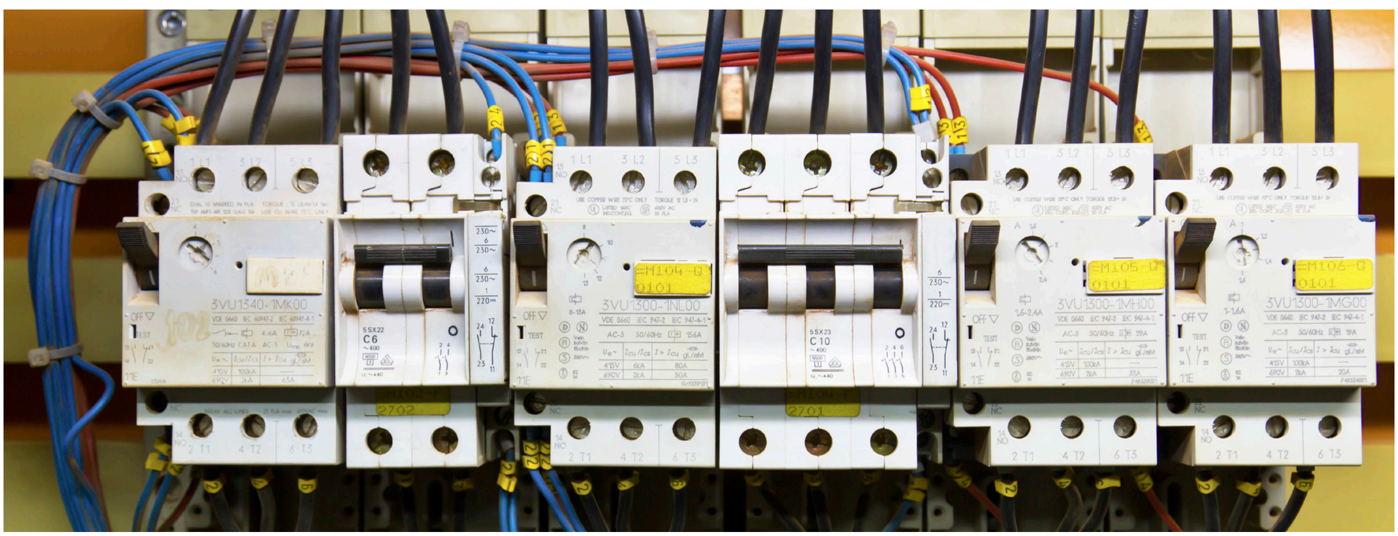
To mitigate these effects and to reduce overall safety risks, electrical equipment developers and designers should rely on the use of a thermally-aged EIS in the construction of their motors, coils or transformers. A thermally-aged EIS is evaluated for thermal degradation to which the electrical equipment is likely to be subjected. Because the known thermal rating of an EIS is determined by testing the combination of EIMs as a whole system, a thermally-aged EIS can extend the useful life of electrical equipment while reducing potential safety risks.

About UL 1446

UL 1446 sets out the requirements for the testing of EIS where thermal factors are the primary cause of material degradation. It also includes requirements for the thermal evaluation of magnet wire and varnishes used in thermally-aged EIS. Now in its sixth edition, UL 1446 has served as the model for a number of international standards applicable to insulation materials and systems, including:

- **IEC 62114,** Electrical Insulation Systems—Thermal Classification
- **IEC 60505,** Evaluation and Qualification of Electrical Insulation
- **IEC 61857,** Electrical Insulation Systems—Procedures Part 1: General Requirements-Low Voltage
- **IEC 61857-21,** Electrical Insulation Systems—Procedure Part 21: Specific Requirements for General Purpose Model-Wire Wound Applications
- **IEC 61858,** Electrical Insulation Systems—Thermal Evaluation of Modification to an Established Wire-Wound EIS

The test methodologies presented in UL 1446 make it the standard of choice for assessing the safety and performance of an EIS. Equally important, EIS that have been tested and found compliant with the requirements of UL 1446 are likely to achieve acceptance into the certification of the electro-magnetic device and thereby speed up that certification process.



Testing and Recognition to UL 1446

UL 1446 is applicable to EIS used in electrical equipment and components which are subjected to operating temperatures greater than 105o C. As a result of testing to the standard, EIS are then certified to one of the two following categories:

- **Systems, Electrical Insulation (OBJY2)**—This category applies to complete EIS built or assembled by a magnetic device manufacturer from a unique combination of components.
- **System Components, Electrical Insulation (OBJS2)**—This category applies to complete EIS that are established by an EIM manufacturer, typically, moldable resins, sheet films and impregnating varnishes manufacturers.

The first step in creating an EIS is to determine the function of the materials used in the device. Effectively, start with the two most important parts, that is, the winding wire and the electrical insulating material (also referred to as "major components"). The winding wire may be enameled magnet wire, bare metal wrapped with electrical sheet insulation or tape, or a combination of materials that may include an impregnating resin. The EIM may be sheet film insulation, moldable resins, epoxy powder coating, impregnating resins, etc.

The main function of the EIM is to provide a dielectric barrier between a voltage potential and another voltage potential, or between ground or dead metal. All other materials used for mechanical support or construction purposes and are not relied upon to provide electrical protection are considered non-electrical insulating materials (NIMs, also referred to as "minor components").

After determining what materials are EIM and what materials are NIM, the next step is to decide in what configuration the combination of materials should be tested. This may be the actual device itself or a representative model. Frequently, representative models or GPMs are used for the opportunity to evaluate more than one EIM in a single test program.

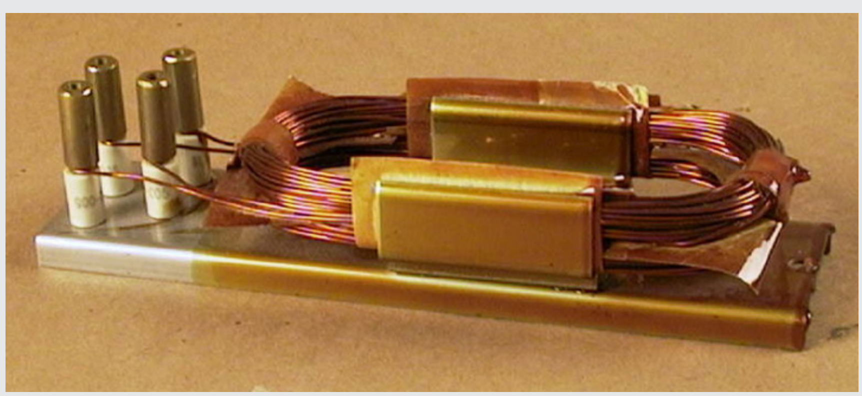


Figure 1: General purpose model

Testing and Recognition to UL 1446

The GPM allows for testing different types of magnet wire, sheet insulations and molded resins for use as EIMs. This may be advantageous when considering multi-sourcing materials for production. For example, several different grades of nylon molding resin may be tested in one GPM, providing flexibility in sourcing that material for a production run.

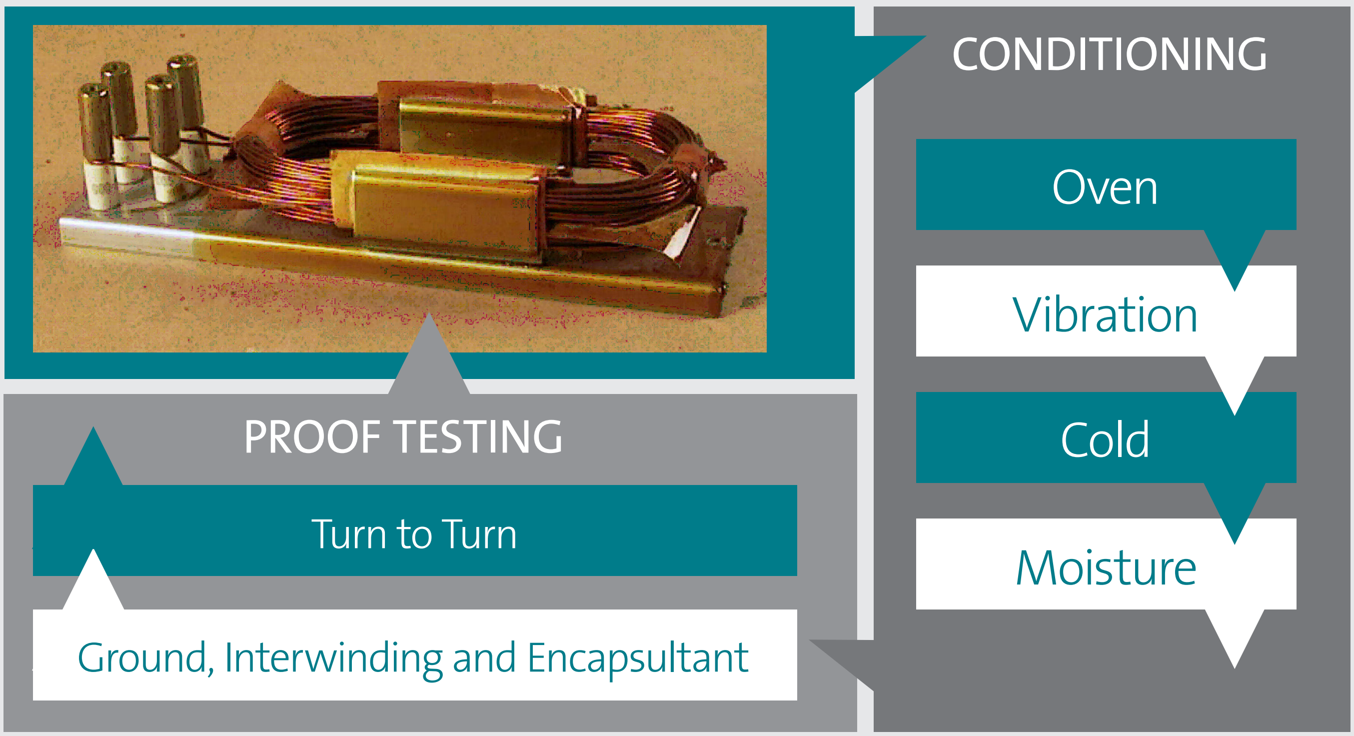


Figure 2: Full thermal aging test cycle

The next step is to determine test time and temperature. To do this, it is important to understand that a full thermal aging test involves the aging of both a "control EIS" (that is, a previously evaluated EIS with a confirmed thermal rating) and the proposed EIS at three or more elevated temperatures. After each heat cycle, test samples are subject to mechanical stress, cold shock, and moisture exposure, followed by dielectric proof voltage testing.

Testing and Recognition to UL 1446

Upon completion of testing, results for the proposed EIS are compared with the results from the control EIS. The evaluation process involves calculations of slopes and intercepting points on these slopes. The result of this calculation is an insulation system classification given as a relative thermal index (RTI) rating, as follows:

System Class	Maximum Hot Spot —Temperature Deg. C
120 (E)	120
130 (B)	130
155 (F)	155 (F)
180 (H)	180
200 (N)	200
220 (R)	220
240 (S)	240
Over 240 (C)	Over 240

Figure 3: Insulation system relative thermal index ratings

For the proposed EIS, there may be short term test data generated for the actual device using the EIS that indicates at what temperature class the device is operating and the hottest spot in the device. This class rating can then be used to determine the elevated temperatures for testing. For example, a device with a heat rise temperature of 148°C would require a Class 155 (F) EIS. For the EIS thermal aging, select a lowest temperature that is no more than 20°C above the rating (in this case, 175°C), and then select two more higher temperatures, the highest being no more than 40°C higher than the lowest temperature. Finally, choose a heat aging cycle time for each temperature. The lowest temperature would have the longest cycle time and the highest temperature would have the shortest cycle time.

Now that a test model and test program has been established, the EIS full thermal aging may begin. When a test sample fails the dielectric proof voltage test, the cycle time is recorded. When all test samples have failed dielectric proof voltage test at a given temperature, regardless of temperature level, a geometric mean time can be calculated for that temperature. The lowest aging temperature result is to have a geometric mean lifetime of at least 5000 hours and the highest temperature is to have 100 hours minimum.

Testing and Recognition to UL 1446

When all test samples have failed for control and proposed EIS, these time values can be expressed in a linear slope for both control and proposed EIS, and the temperature rating is determined by an intercepting of the control EIS correlation time with the proposed EIS. This slope is referred to as the insulation system life line.

Insulation System Life Line

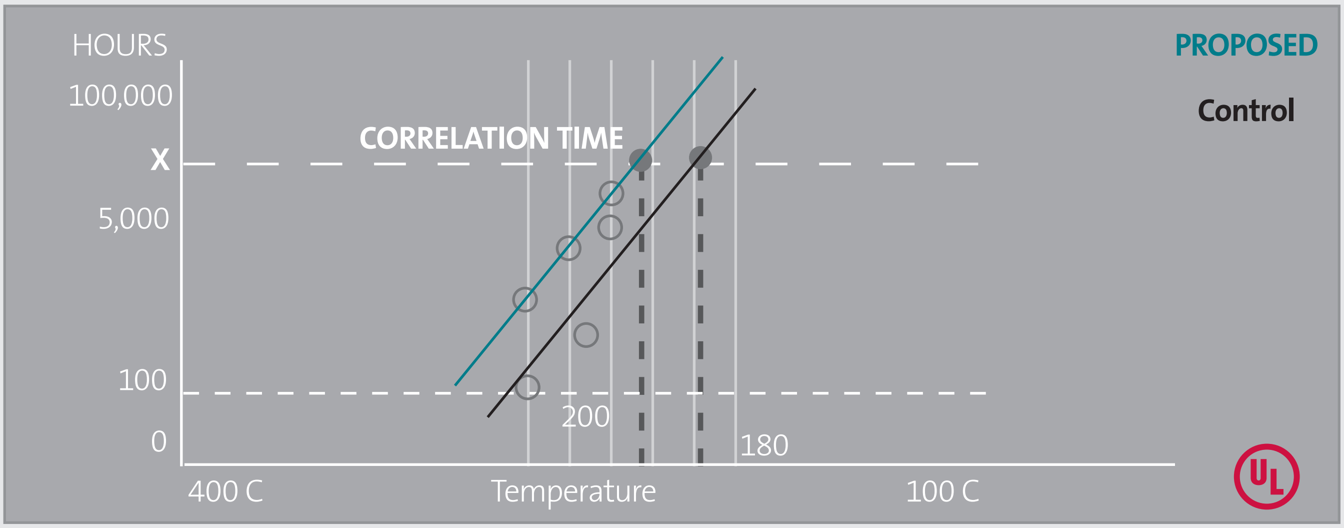


Figure 4: Insulation system life line analysis

Modifying a UL 1446-Recognized Electrical Insulation System

Because the lowest test temperature is required to age for 5000 geometric hours, the testing of a new EIS may take more than a year to complete. However, the advantage of using this method is that the thermal rating of the EIS and its unique combination of materials is now a known quantity. This helps to provide important assurances that a device will perform as anticipated at the rated temperature for the life of the device. Having the EIS UL Recognized serves as evidence that the materials are compatible for the intended temperature use application.

UL 1446 also allows for modifications to a Recognized EIS under certain conditions. This is important since manufacturers often wish to incorporate into a previously recognized EIS new or additional non-electrical insulating material components, such as tapes, tie cords, sleeving, potting compounds, balancing compounds and other materials used in typical mechanical applications. Instead of requiring a manufacturer to conduct another full thermal aging test to evaluate these additional components, a technique known as sealed tube component compatibility testing can be used to assess the chemical compatibility of these additional components with the turn insulation of the winding wire used in an existing EIS.

Sealed tube testing involves the aging of representative samples of the entire system for two weeks in a sealed environment at the system rating temperature plus 25o C. To conduct sealed tube testing, materials that were subjected to the original thermal agingtest are placed in one tube (the "reference tube"). A second tube, the "proposed tube," contains the same materials as those placed in the reference tube as well as the additional components. Both tubes also include lengths of winding wire. After the two week aging period, test samples of winding wire from both tubes are subjected to dielectric breakdown strength testing. Average dielectric breakdown data of samples taken from the proposed tube are then compared with that derived from samples in the reference tube to determine if degradation of the wire in the proposed tube has occurred that signals a reduction in the dielectric strength of the samples.

Dielectric retention results of 50 percent or greater for samples from the proposed tube allows for the use of these additional components in the existing Recognized EIS. This testing quickly determines whether the collective gaseous by-products of all of the EIS materials are detrimental to the winding wire turn insulation in the EIS.

Adopting a Recognized Insulation System

When manufacturers of electrical equipment want to use a tested EIS with a certified thermal rating for their product, there is another option that allows for quicker access to achieving compliance with applicable safety standards and regulations. A number of EIM component suppliers have established EIS ratings by conducting the thermal aging test and sealed tube component compatibility test to create an EIS under UL's OBJS2 category. These EIS may be adopted by an OEM into a UL OBJY2 certification.

UL maintains a comprehensive database (available at http://iq.ul.com/systems) that allows interested parties to search for EIS that are UL 1446 Recognized Components under the OJBS2 category. These EIS have been evaluated for EIM component suppliers, such as manufacturers of sheet insulation, varnish or bobbin materials. These suppliers have gone through the cost, time and process of testing in order to offer "off the shelf" EIS. If any of these Recognized OBJS2 EIS are found to meet specific OEM application requirements, adopting such an EIS is a far more efficient and cost-effective approach to establishing OBJY2 certification for the OEM.

EIS that are adopted without any changes will not require further testing of the EIS. In cases involving changes or additions to non-electrical insulating material components, the sealed tube component compatibility test is likely to be sufficient to demonstrate compliance. Of course, changes or modifications to an adopted system involving EIM will require full thermal aging testing.

OEMs seeking to obtain UL Recognition under OBJY2 of an EIS certified under OBJS2 notify UL of the Recognized EIS they wish to adopted as well information regarding its intended use. In addition, an OEM may need to obtain a letter of release from the owner of the OBJS2 Recognized EIS, so that UL can legally release proprietary information related to the original Recognized EIS in cases where sealed tube component compatibility testing is needed.

Other Recognition Options for Manufacturers

In some cases, a manufacturer may want to seek Provisional Recognition of an electrical insulation system that is undergoing full thermal aging. Provisional Recognition can be granted after approximately 2000 hours of thermal aging testing if the data generated at two or more temperature points is consistent with the manufacturer's desired thermal class rating. The Provisional Recognition of an electrical insulation system is temporary and subject to modification, and the thermal rating assigned under Provisional Recognition may be raised or lowered upon the completion of full thermal aging testing.

Finally, as previously noted, the test methodologies for electrical insulation systems presented in UL 1446 have been widely adopted in international standards, and testing requirements found in current versions of IEC 61857 and IEC 61858 are nearly identical to those in UL 1446. As a result, testing to the requirements of UL 1446 can also support the generation of a test report as evidence of compliance with applicable IEC standards without the need for duplicative thermal aging testing. This provides a clear pathway for global market access for UL 1446-Recognized electrical insulation systems through the IECEE's CB Scheme.

Summary and Conclusion

It is still a common practice by some agencies to determine the thermal class rating of an EIS from only the individual EIM component ratings, by using the rating of the lowest rated material as the rating of the EIS. Unfortunately, this approach does not account for potential chemical reactions between different types of EIM that are placed in direct contact with each other. Over time, such chemical interaction induced by heat may lead to the deterioration of an EIM's insulating properties that is not consistent with the individual thermal rating. This deterioration can compromise the integrity of the EIS and lead to potential performance degradation and an increased risk of safety-related hazards in the device.

The thermal aging methods presented in UL 1446 for testing of specific combinations of materials used in EIS helps identify the potential for unique chemical interactions between individual electrical insulating materials that can accelerate material aging and compromise overall EIS performance. This systemic and holistic approach to testing helps to increase overall confidence in the long-term safety and performance of both the EIS and the electrical device.

UL is a pioneer in the development and application of standards applicable to EIS, and offers a wide range of testing and certification services for various types of insulation systems and components. For further information about UL's electrical insulation system services, contact imdquote@ul.com.

1) "Functional Evaluation of Motorette Insulation Systems," Brancato, Johnson, Campbell & Walker, Electrical Manufacturing, March 1959.

2) Declassified results of this research were ultimately presented in "Reliability Prediction Studies on Electrical Insulation: Navy Summary Report," Brancato, Johnson, Campbell & Walker, U.S. Naval Research Lab, Washington, D.C., July 1977. Web. 4 April 2016. *http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA044156.*

3) MIL-E-917D, Military Specification: Electric Power Equipment Basic Requirements, January 1965.

4) "Material Thermal Class Ratings vs EIS Thermal Class Rating," Eltek International Laboratories, May 22, 2015. Web. 4 April 2016. *http://elteklabs.com/wp-content/uploads/2016/03/EIS-Evaluation-a-comparison-of-EIS-and-EIM-thermal-rating-Reviewed-by-JC-7March2016-2.pdf.*