Chemical Interaction of Materials and Electrical Insulation Systems in End Use Products

Linking Laboratory Testing to Real World Applications

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Abstract: This paper is being presented to offer an insight as to how laboratory testing can benefit both material and end-product manufacturers. There are several areas of testing available to assist the industry in obtaining technical information on material and system performance, including compatibility. When understood the results can lead to better end products made from more durable materials with improved performance and more cost effective production techniques.

This paper will illustrate the spectrum of testing available and will cover some of the stresses test specimens can be subjected to, which simulate real-world applications. Some different exposures available for compatibility testing include transformer oil, refrigerant, cleaning solutions, thermal, and submersion in various solutions. The testing is preformed on individual materials as well as on electrical insulation systems and various set ups that represent potential end products.

Eltek International Laboratories is known worldwide as experts in Electrical Insulation Systems (EIS) and Electrical Insulation Materials (EIM) Testing. The founder and president Ed Van Vooren is involved with many IEEE and IEC technical committees and has assisted in creating many of the standards that are tested at this facility. More EIS and EIM tests are conducted via Sealed Tubes and Full Thermal Aging Programs than the rest of the world's laboratories combined.

Consumers put products through a barrage of stressors. A quality product is one that can withstand those stressors better than competitors. The better a product withstands this punishment, the more it protects the consumer from harm and the manufacturer from liability. Some important factors to be considered at the design stage of anything are physical endurance from vibration or impact, ambient conditions-will it be exposed to extreme heat, cold or high humidity; and how it responds to power surges or electromagnetic interference.

T.E.A.M. Concept

It is difficult to conduct any single test to evaluate the total multifaceted stressors of the real world, so the T.E.A.M concept is applied to all tests run. The four main areas of concern, Thermal, Electrical, Ambient, and Mechanical stressors, are evaluated one at a time.

Thermal-One of the leading causes for loss of a property is the decomposition of the molecular structure within the EIM and/or EIS. Decomposition is a chemical process. Each chemistry, or molecular structure, will have a decomposition rate based on the specific chemistry. The fact that a molecular structure decomposes does not mean that the properties will be reduced. For some molecular structures, the decomposition fragments may still have the ability to provide one property-such as electrical insulation-but not another property-such as physical strength. Hence, each key property must be evaluated for the specific application. Since decomposition due to thermal stress can be studied under controlled conditions, it is easy to determine this area of properties.

The most common properties evaluated, for retention of performance properties, on an EIM, after thermal aging are, retention of electrical insulation-the breakdown voltage is determine on both aged and un-aged samples of material and the number are then compared, retention of physical properties, tensile and/or flexural strengths can be tested; and retention of impact strength, tensile impact and direct impact strengths can be determined.

Electrical-Refers to the stressors which may cause failure of the electrical insulation due to the electrical/magnetic forces applied as a result of the energy flow through the conductor, or from the environment around the device. These electrical stressors are not the same as the electrical stress applied during a thermal aging project to determine if the insulation property has decreased due to decomposition. These stressors can be the result of electrical frequency or range frequencies encountered during operation, voltage range, voltage surges or spikes, and electromagnetic interference.

Properties of EIMs that can be tested include dissipation factor over a range of frequencies at various temperatures; dielectric constant over a range of frequencies at various temperatures; voltage withstand at various temperatures; voltage surges and impulse surges.

Ambient-The term ambient refers to the environment of the device both while being used and when it is not in use. For example, items that are to be used outdoors are much more likely to be exposed to a wide range of temperatures and humidity levels, and contact with corrosive chemicals. Much of the testing done in the Components Compatibility Lab deals with ambient stresses and includes exposure to refrigerants, oils, cleaning solutions, heat, and solutions of varying PH.

The compatibility tests are designed to determine how well an EIM retains is properties during and after exposure to the various stressors. Those properties include tensile strength, flexural strength, impact strength, shear strength, dielectric strength, and dielectric endurance.

Mechanical- usually relates to the condition of the device when it is in use. This relates to physical vibration while operating, movement of coolant, and inclusion of dust or moisture. The concern: will there be loss of properties due to exposure of the device to a specific environment?

Testing for environmental factors must be conducted in the appropriate environment in order to relate the information to the application. This means that a wide range of tests may need to be conducted on a single EIM and/or EIS. For this area of concern, it is usually assumed that the device is energized when exposed to the specific environment.

Spectrum of Testing

The flow of testing starts with the end-product. All safety and performance requirements are based on the safety and performance of the end-product. No EIS or EIM testing can totally replace evaluation of the end-product. However, evaluations on end-products can be reduced by using information about the EIS or EIM used. These end-product tests for long-term performance could last years. The affordability of such time and resources are rare in today's business world. To be competitive, it is essential to use-where appropriate-any options which can provide information about performance and safe operations.

Technical information about individual EIMs or insulation systems can, in some cases, reduce or even eliminate evaluation of the end-product. However, since safe operation and long-term performance are related to the total application environment (TEAM), a review of end-product certification programs will always be expected to start with the end-product. That is just the beginning of the spectrum of testing available though.

Prototypes can be evaluated for actual safe performance. It is intended to be a pre-production unit used for evaluation of production procedures and process. They are usually evaluated without long-term aging.

The design stage of any end-product requires knowledge of the application, performance requirements, safety requirements, operating temperature limits, material capabilities and other aspects of mechanical stressors during operation and ambient conditions (operating environment conditions). The design and redesign phase can be streamlined by researching information on the specific EIMs in the current design and the performance specifications of new EIMs that are being considered. For the design level of activity, most manufacturers require significant information from vendors. Testing conducted by vendors can be provided to any number of manufacturers which can add to cost effectiveness.

A good way to streamline the design process is to choose an already established Electrical Insulation System whose thermal rating meets or exceeds the anticipated requirements of the design, and then run compatibility tests on it to ensure that the materials used can withstand the environment of the end-product. When an EIS is evaluated for compatibility in the application environment, the information can greatly reduce the testing and evaluation needed on the end-product. Compatibility testing of an EIS can be conducted in environments related to oils, refrigerants, soaps / detergents / bleaches, or almost any potential environment. The combination of Compatibility and EIS testing provides the evaluation of the electrical insulation portion of the end-product. This may be sufficient for many end-products.

If no existing EIS can be found, then EIS testing is the next step. The entire EIS concept was developed and implemented as the result of a major research and development program initiated by the United States military and a small group of commercial manufacturing companies[1]. The program began around 1950 and continued throughout that decade.

EIS testing can be viewed as a long-term compatibility program. The rating of the EIS is based on the performance of the combined group (system) of materials composing the EIS. EIS testing is a Relative Thermal Index (RTI) level of test. EIS testing can provide the thermal rating of the end-product because of the level of conditioning and electrical stressors involved.

If a new EIS is required, compatibility testing of the material to be used may be beneficial. Compatibility of materials can reduce, or in some cases, eliminate the need for compatibility testing of end-products. Compatibility testing at the material level is of the same nature as the

EIS level; to evaluate ambient conditions and performance of the individual material/s. Manufacturers often need or require material compatibility test results before considering the material for use. The more common applications are oil-filled transformers, refrigerant units, clothes or dish-washing machines, home appliances and similar applications.

Aside from compatibility tests on materials, long-term performance evaluations provide useful information on the durability and thermal rating of a given material. This information can aid in the material selection process. Most of the long-term evaluations are limited to thermal stress because heat is more controllable, thus making the ratings more reliable. For thermal ratings, the values are called Relative Thermal Index ratings (RTI) when compared to another material's performance or Thermal Index (TI) when the rating is established by projecting life to a pre-selected time, but not by comparison to another material.

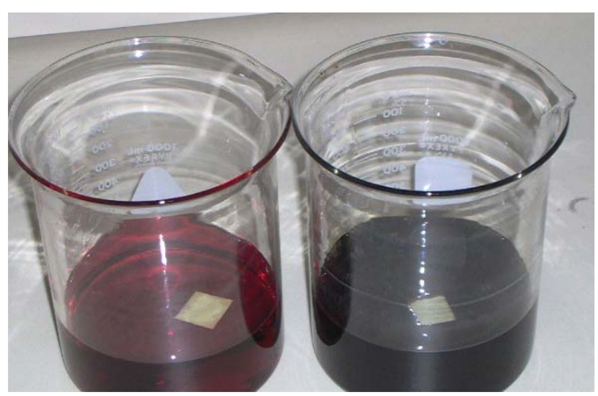
The last step in the spectrum of testing is to evaluate the performance of new materials. This information is what is typically on Material Data Sheets. It gives insight into the specific performance characteristics of a new, un-stressed material. This information benefits the material manufacturer in that it allows them to highlight the strongest properties of their product, but it is also very useful to end-product manufacturers. It provides a way for them to compare strengths and weaknesses of materials for use in their manufacturing; ensuring the material chosen will be able to withstand the production process and will be able to hold up to the stressors involved with its use.

Compatibility Testing

The purpose of compatibility testing is to evaluate the effect resulting from the chemical interactions between different materials and between materials and their environments. For this concept, it helps to view each material in terms of their chemical composition. Since these chemical structures are in intimate contact with each other and their environments, there can be interactions. Incompatibility means the different chemistries interact in a manner which accelerates the breakdown of the chemical structures of the materials, resulting in reduced life.

Oil Compatibility

There are two ways to consider oil compatibility. Are the materials going to impact the insulating oil in a negative way? Is the oil going to affect the performance of the materials used? In oil filled transformers the oil is the most important insulator. For this reason it is imperative the materials used in construction of the coils don't impact the oils ability to insulate and disperse heat. For this, ASTM D3455[2] "Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin" testing can be conducted. In this test method several properties of the non-aged and non-contaminated insulating oil are tested; such as dielectric breakdown, surface tension, pH level, dissipation factor, and relative permittivity. Samples of the insulating oil are then taken and the test materials are added.



Generally, starting with one material per sample of oil will provided the most detailed information in regards to contamination; however, in order to receive certification, the full EIS must be tested with the oil. Once the materials have been added to the oil samples they are covered and thermally aged along with a sample of the oil with no materials. At the end of the 164-hour aging cycle, the test specimens are removed from the oil and the same barrage of tests are conducted. The results are not only compared to the non-aged sample of the insulating oil, but also to the non-contaminated sample that was aged. As stated in the standard (Sec. 8.2.3.1), “The magnitude of differences in properties between the reference oil and the test specimen oil that constitute a significant change should be established prior to testing, by agreement between the purchaser and seller.” In 8.2.5 of ASTM D3455, it provides “The aged properties for the reference oil specimen” in a list of typical values for most of the mineral oils presently on the market.

Tests can also be performed on the materials added to the oil both before and after aging to determine if the oil will shorten the life of the insulation materials used in manufacturing the coils. These tests include swelling or dimensional change, hardness, discoloration, tensile strength, dielectric strength or any others appropriate for the role of the material.

The ability to evaluate these potential incompatibilities on such a small scale is not only much more cost effective, but also more efficient due to manufacturer time and resources needed to construct a prototype for testing. The information also prevents any unforeseen incompatibilities which may result in catastrophic failures.

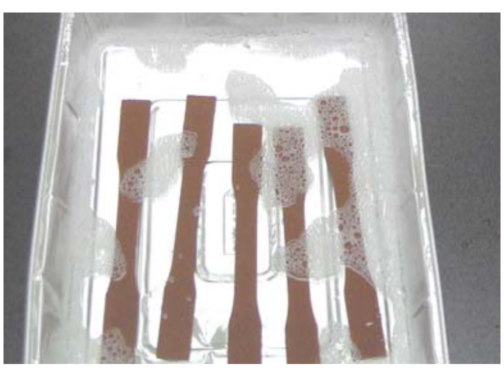
Refrigerant Compatibility

Very similar to the oil compatibility tests are those that involve refrigerants. These tests are rather valuable to those in the air conditioning markets, automotive and home, as well as large scale commercial units. Though the process is similar to that of the oil compatibility tests, these are more specifically designed to ensure the refrigerant does not accelerate the decomposition of the electrical insulation materials that come in contact with it. It is essential, though, that neither the refrigerant nor lubricating oil is contaminated by any substance being extracted from a material; this could leave residue on the mechanical parts of the compressor leading to decreased efficiency and life expectancy. This test is accomplished by placing an electrical insulation system, via a general purpose model, to be tested into a sealed vessel and introducing an appropriate amount of refrigerant (with or without lubricating oil depending on specific needs) to the environment. These general purpose models are to be constructed in a way that is representative of the system being tested, with magnet wire coils and insulating materials. The materials are to be the required minimum thickness, as well as proportionate to each other as they are in the end-product. The vessel is then aged in cycles consisting of 288 hours of exposure to heat, followed by 48 hours at room/ambient temperature. This is to be repeated until the total time exposed to heat reaches 1440 hours (UL 984[3] sec 41.13). The temperature of exposure is directly dependant on the refrigerant being used. After the final temperature cycles the general purpose models are tested. A 60 Hz ac potential of 600 V is applied

between the top and bottom winding, as well as between the windings and grounded metal; a 60 Hz ac potential is also applied between the turn-to-turn insulation. The voltage for this is dependant on the rating of the motor the model represents. The exposure is to last for 1 minute. For a successful test the current cannot exceed 0.5-0.75 A for 2-3 seconds.
This standard can also be used to test the compatibility of minor alternate insulation system parts (UL 984 Sec. 41.17-41.22). The individual materials are to be of such a size that dielectric strength testing may be conducted on them after the exposure and thermal aging is completed. For the purpose of investigating the alternate part, a reference sample set is also prepared and tested in an identical manner. This set is a combination of materials with an established history in hermetic systems. The value of the applicable property of the alternate material and its proven counterpart is to be determined by testing unexposed samples. This ratio is to be maintained when testing is completed on the exposed samples.

Soap and Detergent Compatibility

This test is set up to determine if the materials to be used in the construction of dishwashing machines are capable of withstanding repeated and prolonged exposure to the most common detergents and other solutions including water softeners. Initial values for tensile and impact strength are taken for the materials under test. Then a specific solution is



prepared and several test samples are submerged and aged. At varying intervals, samples are removed and tested for tensile and impact strength. If the material is not compatible with the detergent the values tested will be noticeably lower (UL 749[4], UL 921[5]).

Sealed Tube Compatibility Testing

By far the most common compatibility test conducted at Eltek, sealed tube testing provides a way to evaluate the compatibility of non-electrical materials or components with an established EIS. While sealed tube testing does not establish new Electrical Insulation Systems, it does confirm which materials can be used with a given EIS in end-product manufacturing from a chemical compatibility standpoint.

When talking about sealed tube compatibility tests, two concepts must be understood. The first is that of Major Insulation. Major Insulation is each of the materials used in an Electrical Insulation System, established and rated by long-term thermal aging.

Next is Minor Insulation. Minor Insulation is any of the wide variety of materials or compounds used in the manufacturing of an end-product, but not specifically used as an electrical insulation barrier. Though the use of these minor components in the end-product may increase the total insulation, the actual electrical insulation is derived from the major insulation materials.

Sealed tube tests are comparative tests. The control tube is loaded with only the Major Insulation materials and conductors, in the form of twisted pairs, used in the EIS. The candidate tube/s are loaded with the Major materials as well as any additional materials to be used in the production of the end-product (minor materials).

The tubes are sealed and then aged at an elevated temperature, which is based off the rating of the EIS used in the control, for 336 hours or two weeks. After the aging process is completed, the twisted pairs of magnet wire are removed and a dielectric breakdown test is performed on them. Each tube will contain between five and ten twisted pairs of each magnet wire type being tested. The results for each tube are averaged. The results for each candidate tube are then compared to that of the control. If the results are within the tolerance established in the standards the candidates pass. Note that a successful test does not create a new Electrical Insulation System; however, it does establish a list of materials that are compatible for use with an already certified system. The sealed tube test evaluates only the interaction of volatile or out-gassed components. The end-product manufacturer is expected to conduct any other compatibility tests related to the actual application.

Commonly Asked Questions

How Does a Sealed Tube Test Work?
By conducting the material compatibility test in a sealed environment at an elevated temperature, chemical out-gassing can be investigated. Essentially, the test verifies if any breakdown of the materials used affects the insulation on the magnet wire. Through prolonged use of an electrical appliance, materials are exposed to heat which can cause chemical decomposition. That may result in a release of a volatile gas. If this gas attacks the enamel coating of the magnet wire, it can severely decrease the performance of the insulation, allowing potential shorts to occur.

After a successful test, can a Minor Component be assigned the level of a Major Insulating Material?
While no would be the easy answer this is not always the case. In certain situations a material labeled minor on the list for a sealed tube can be used as Major Insulation. However, this is true only if the minor material in question is the same chemical make up and thickness as the Major Insulation material in the original EIS. For example: An established EIS uses a 0.127mm PET film for ground insulation. The sealed tube tests results show a laminate of Polyester Mat and PET film to be compatible with the system. The manufacturer can now use the laminate as ground insulation, as long as the PET film portion of it is a minimum thickness of 0.127mm.

Laboratory testing done with the end-product and its use in mind can be conducted in such a way to give a strong representation of life expectancy and compatibility. From the material level to full system compatibility, the information available can be used to improve efficiency and reduce research and development costs.

[1] NAVAL RESEARCH LAB, “Reliability Prediction Studies on Electrical Insulation: Navy Summary Report”, 07-13-1977, 138 pages

[2] ASTM, “Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin”, Designation: D 3455 – 02

[3] UL, “Hermetic Refrigerant Motor-Compressors”, UL 984, 09-23-05

[4] UL, “UL Standard for Safety Household Dishwashers”, UL 749, 01-31-2008

[5] UL, “UL Standard for Commercial Dishwashers”, UL 921