Characterization and Properties of Reconstituted Mica Paper Capacitors used in High Voltage and High Temperature Power Electronics Systems

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***Abstract* – The purpose of this paper is to describe the characteristics and properties of reconstituted mica paper capacitors that are designed and manufactured for use in high voltage and high temperature power electronics systems. For the purposes of this paper, high voltage is defined as 1,000 Vdc to 50,000 Vdc and high temperature is defined as 260°C. The applications; design and construction; electrical, environmental, and physical characteristics; and reliability of this type of capacitor will be described.**

I. Introduction

High voltage - high temperature power electronics systems that are designed for commercial, aerospace, and military applications require highly reliable components. These types of power electronics circuits and systems include, or can include, the use of reconstituted mica paper capacitors. Reconstituted mica paper capacitors are particularly suited for operation where high ambient temperatures exist [1] and are an excellent choice for these types of systems.

II. Applications

Reconstituted mica paper capacitors are typically used for energy storage, filtering, coupling, etc. in high voltage - high temperature applications where radiation resistance, corona resistance, high volumetric efficiency, physical durability, and capacitance stability (with respect to temperature, voltage, frequency, or mechanical stresses) are required. These types of applications include, but are not limited to the following:

- airborne or surface radar systems,
- high voltage transmitters for missile applications,
- high voltage ECM and TWT power supplies,
- ignition systems,
- power transmission systems,
- laser devices, and
- gas and oil exploration equipment.

Small, high voltage electronic modules can be designed and manufactured to include these types of capacitors in conjunction with other high voltage components (i.e., resistors, diodes, spark gaps, strip lines, inductors, etc.).

III. Design and Construction

The dielectric material used in the design and construction of these types of capacitors is reconstituted mica paper, which is impregnated with a liquid polymer resin (i.e., polyester, epoxy, or silicone). The National Electrical Manufacturers Association defines mica paper as flexible, continuous, and uniform layers of mica reconstituted into a paper-like, electrical insulating material composed entirely of small, thin, overlapping flakes or platelets, and which has sufficient strength to be self-supporting and to be capable of being wound into roll form for commercial use [2]. Capacitor grade mica paper does not contain binders, adhesives, foreign matter, or coloring agents, and is substantially free of any substance, which will adversely affect its performance.

Capacitor grade, reconstituted mica paper is manufactured from natural muscovite mica ($K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$). An Energy Dispersive X-Ray Spectrum (EDX) for muscovite mica is shown in Fig. 1 [3].

The high quality grade muscovite mica is subjected to a process in which it is heated to approximately 840°C. This heat causes the mica crystal to partially dehydrate and release a portion of the water, which is bonded naturally in the crystal. When this occurs, the mica partially exfoliates allowing the caustic solution to saturate the expanded mica. The heated mica is then quenched in a mild alkaline solution. The mica is cooled, drained, and then subjected to a weak sulfuric acid solution.

The chemical reaction between the caustic and the acid generates a gas between the laminae, which causes the mica to expand greatly. The particle size is further reduced by mechanical methods. The mica is screened in the presence of large amounts of water on separating screens to select the

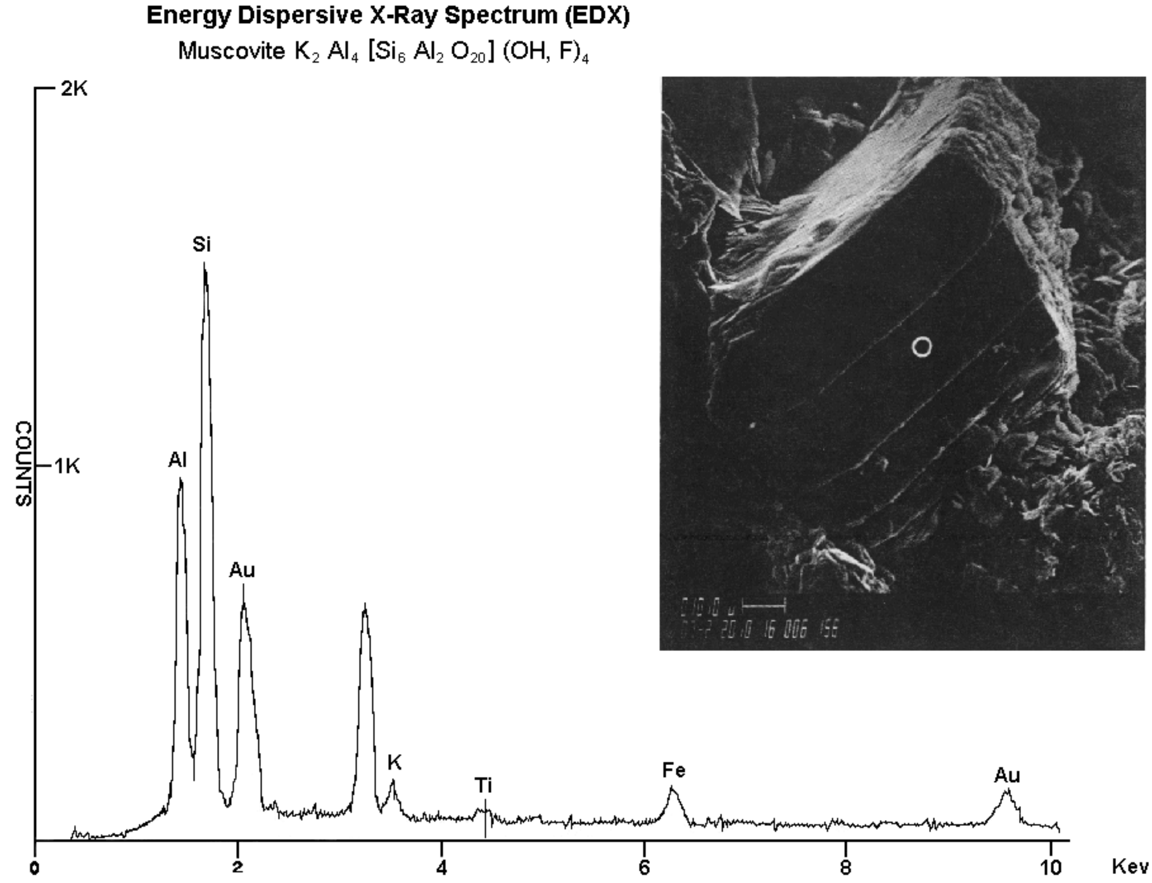

Fig. 1. EDX for Muscovite Mica

desired particle size distribution to produce the paper desired. This "pulp" is then transferred to a specially modified Fourdrinier paper machine for sheet forming and drying. The particular design of the head box and drying belts and/or drums are generally proprietary to the individual mica paper manufacturers.

The van der Waals' forces between the crystal surfaces of the mica platelets in close proximity hold the layer together. Capacitor grade reconstituted mica paper thicknesses typically range from 12.7 µm (0.0005") to 50.8 µm (0.002").

The mica paper is wound with capacitor grade aluminum foil electrodes. Nickel leads are used in "buried foil" construction to make a connection with the anode and the cathode foils. With "extended foil" construction, nickel leads are not required. Usually, two or more layers of mica paper are used in the mica paper capacitor winding. The windings are then lightly pressed into a flat configuration. The windings are then subjected to a vacuum drying cycle and a Vacuum Pressure Impregnation (VPI) process with a liquid resin material (i.e., epoxy, polyester, or silicone) of low viscosity. After the VPI process, the windings are removed from the liquid resin and are then polymerized with a heat curing process. The "cured" windings are now referred to as sections and are cleaned and tested for basic electrical properties (i.e., Capacitance, Dissipation Factor, Dielectric Withstanding Voltage, etc.). The sections are then soldered and assembled into the required configuration and packaged in one of several methods which include tape wrap and end fill, potting in a metal or fiberglass tube, or encapsulated with any one of several types of epoxy. The capacitors are then electrically tested and inspected.

Depending on the type of packaging, capacitance, voltage rating, terminations, etc., various dimensions can be achieved.

IV. Electrical, Environmental, and Physical, Characteristics

Reconstituted mica paper capacitors are well known for their outstanding electrical, environmental, and physical characteristics. Most notably, these parts exhibit long life, a very low capacitance drift over the entire temperature range, they can withstand high voltages, they are naturally resistant to the effects of partial discharges, and they exhibit low radiation-induced conductivity caused by the absorption of ionizing radiation such as X-rays, gamma rays, and neutrons. In addition, they exhibit a fractional voltage or charge loss as a function of the absorbed dose.

V. Electrical Characteristics

A. Capacitance Range: Generally, the capacitors can be designed in the 100 pF to several μF range (depending on the voltage rating). Capacitance tests are generally conducted in accordance with MIL-STD-202, Method 305 [6].

B. Capacitance Tolerance: The general capacitance tolerance is ±10%. Other tolerances are available.

C. Dielectric Constant (K): The dielectric constant of reconstituted mica paper is approximately 6.5 to 8.5 [1,4,5]. As a result of the impregnants used with the reconstituted mica paper, the "effective" K of the reconstituted mica paper capacitors is approximately 5 to 6. It is interesting to note that the K value for most polymer films that are used as the dielectric material for high voltage capacitors is in the range from 2 to 3.5 [4].

D. Voltage Range: Voltage ratings are from 1 kVdc to 50 kVdc. Typically, each capacitor is designed and manufactured for a specific application.

E. Dielectric Withstanding Voltage (DWV): This test (also referred to as a high potential, high pot, over potential, or dielectric strength test) is conducted at a voltage higher than the rated voltage for a specific amount of time and is used to prove that the capacitor can operate safely at its rated voltage and that it can withstand a momentary overvoltage condition due to switching, surges, and other similar phenomena. DWV tests for reconstituted capacitors are typically conducted for 15 seconds at 110% to 200% of rated voltage (depending on the design stress of the capacitor) in accordance with MIL-STD-202, Method 301 [6].

F. Dissipation Factor (df): The df is defined as the ratio of the effective series resistance to the capacitive reactance at a frequency [4]. It is also the inverse of the Quality Factor (Q). The df of reconstituted mica paper capacitors increases with temperature and frequency. Typical df values range from 0.5% maximum at 25°C to 1% maximum at 125°C. The df measurements are typically conducted in accordance with MIL-STD-202, Method 306 [6].

G. Insulation Resistance (IR): The insulation resistance of reconstituted mica paper capacitors is 5000 megohms (MΩ) x microfarads (μF) minimum or 100,000 MΩ minimum (whichever is less) at 25°C and 25 MΩ x μF minimum or 1,000 MΩ minimum (whichever is less) at 125°C. Insulation resistance is typically measured at 500 Vdc after two minutes of electrification in accordance with MIL-STD-202, Method 302, Test Condition B [6].

H. Thermal Coefficient of Capacitance: The thermal coefficient of capacitance of reconstituted mica paper capacitors is approximately + 5% maximum from 25°C to 125°C and - 3% maximum from 25°C to -65°C.

I. Inductance: The inductance of reconstituted mica paper capacitors can range from approximately 5 nH for "extended foil" designs to approximately 100 nH for "buried foil" designs.

J. Energy Density: Typical energy densities range from 0.0061 J/cc (0.1 J/in^3) for a low capacitance, low voltage capacitor to 0.061 J/cc (1.0 J/in^3) for a capacitor designed for short life applications. The individual design will determine the energy density value.

Per cent capacitance change, dissipation factor (in %), and insulation resistance (in MΩ x μF) from -55°C to 125°C for typical reconstituted mica paper capacitors are shown in Fig. 2. The values from -55°C to 200°C are shown in Fig. 3.

VI. Environmental Characteristics

A. Operating Temperature: Depending on the impregnant, reconstituted mica paper capacitors can withstand the following temperature ranges:

- Epoxy: -65°C to 125°C
- Polyester: -55°C to 200°C
- Silicone: Up to 260°C

B. Thermal Shock: With the exception of unencapsulated reconstituted mica paper capacitors, reconstituted mica paper capacitors are designed and manufactured to pass the thermal sock tests defined in MIL-STD-202, Method 107, Test Condition B [6].

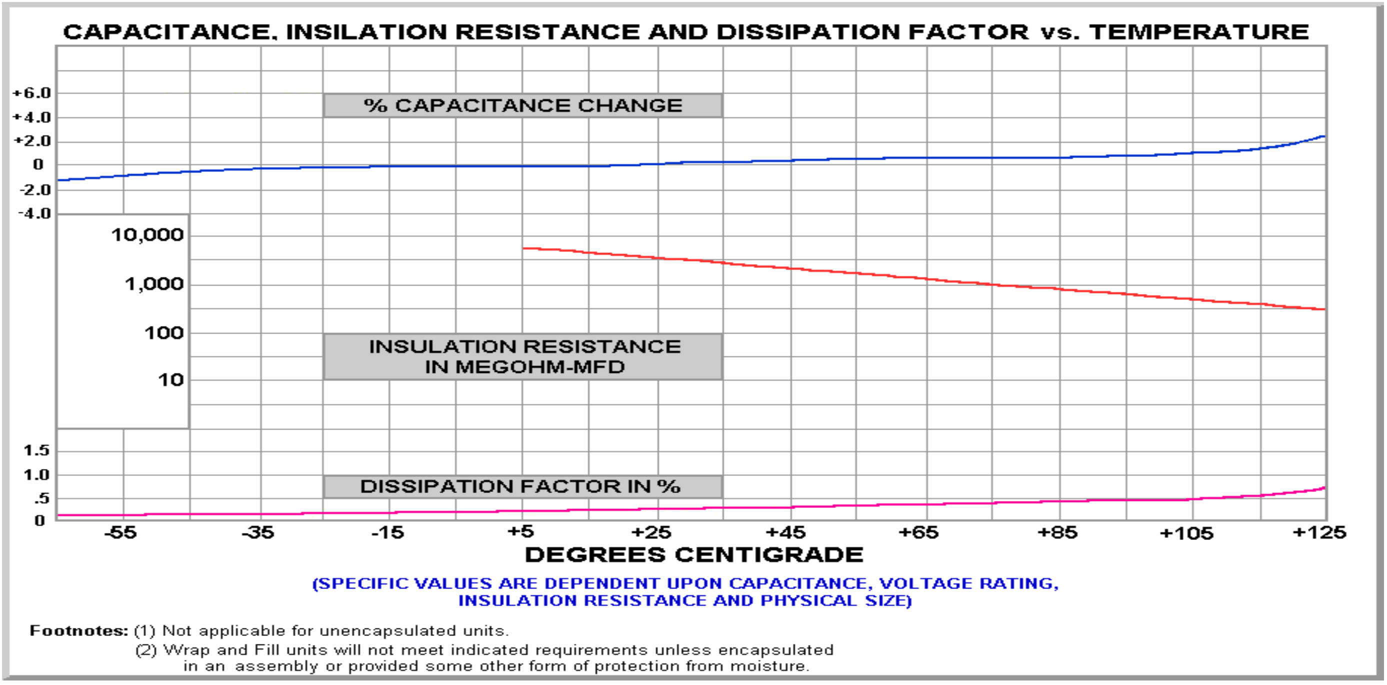

Fig. 2. Capacitance, IR, and df vs. Temperature (from -55°C to 125°C)

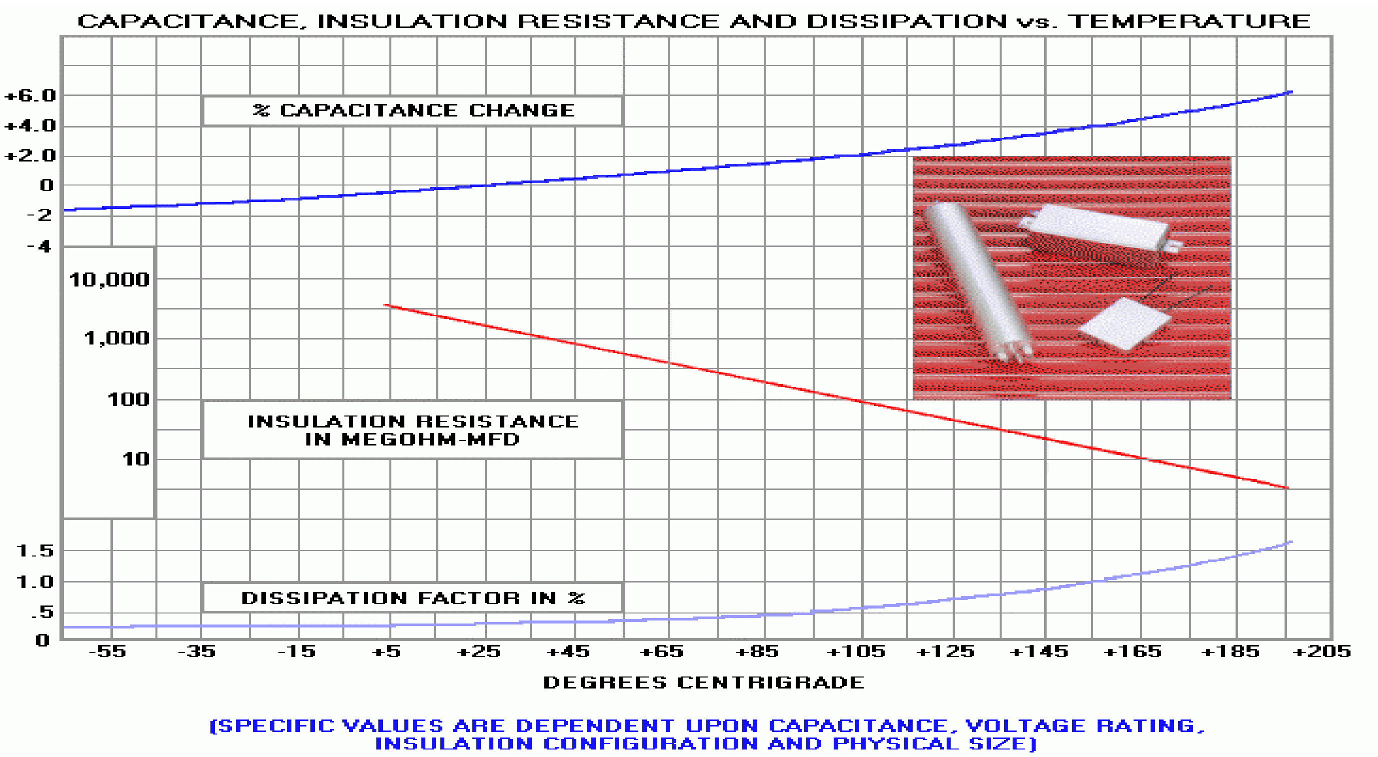

Fig. 3. Capacitance, IR, and df vs. Temperature (from -55°C to 200°C)

C. Immersion: With the exception of unencapsulated reconstituted mica paper capacitors, reconstituted mica paper capacitors are designed and manufactured to pass the immersion tests defined in MIL-STD-202, Method 104, Test Condition B [6]. "Wrap and Fill" units will not meet these requirements unless encapsulated in an assembly or provided with some other form of protection from moisture.

D. Humidity Resistance: Moisture in the capacitor dielectric can cause a large reduction in leakage resistance and increases in the df [4]. Reconstituted mica paper capacitors can be subjected to and pass humidity resistance tests that are conducted in accordance with MIL-STD-202, Method 103, Test Condition B [6]. This type of test is not applicable for unencapsulated capacitors.

VII. Physical Characteristics

A. Vibration: Reconstituted mica paper capacitors are designed to pass the vibration tests defined in MIL-STD-202, Methods 201 and 204 [6].

B. Shock: Reconstituted mica paper capacitors are designed and manufactured to pass the shock tests defined in MIL-STD-202, Method 213 [6].

C. Solderability: Reconstituted mica paper capacitors are designed and manufactured to pass the solderability requirements of MIL-STD-202, Method 208 [6] and J-STD-002, Test A [7].

D. Resistance to Soldering Heat: Reconstituted mica paper capacitors are designed and manufactured to pass the resistance to soldering heat tests defined in MIL-STD-202, Method 210, Test Condition C [6].

E. Terminal Strength: Reconstituted mica paper capacitors are designed and manufactured to pass the applicable terminal strength requirements of MIL-STD-202, Method 211 [6].

F. Resistance to Solvents: The purpose of this test is to verify that the markings will not become illegible on the capacitors when subjected to solvents and processes normally used to clean solder flux, fingerprints, and other contaminants from the surface of the capacitors. Reconstituted mica paper capacitors are designed and manufactured to pass these tests and are conducted in accordance with MIL-STD-202, Method 215 [6].

VIII. Reliability

High reliability is the number one "strength" of reconstituted mica paper capacitors. A complete understanding of the customer's requirements, a proper design, the selection of highly reliable materials, and a tight control of the manufacturing and testing processes, as described previously in this paper, all lead to the reputation that these types of capacitors have.

Studies are currently being conducted to determine the voltage and temperature acceleration factors for the dc life of reconstituted mica paper capacitors. A voltage acceleration factor of 7 to 10 is typically used for reconstituted capacitors.

Standard electrical tests (i.e. Capacitance, Dissipation Factor, and Dielectric Withstanding Voltage) are completed for every capacitor. Other electrical tests that are normally conducted on a sampling basis include Insulation Resistance, ac and dc Partial Discharge, Burn-In, Pulse Discharge, and Inductance.

Environmental tests are frequently conducted in accordance with customer and/or military specifications. For example, these tests include Temperature Shock, Barometric Pressure, Humidity Resistance, Extreme Temperature, etc.

Typical physical tests include Shock, Vibration, Solderability, Resistance to Soldering Heat, Resistance to Solvents, and Terminal Strength.

IX. Conclusion

The manufacture and the characteristics of reconstituted mica paper have been addressed. The applications; design and construction; electrical, environmental, and physical characteristics; and reliability of mica paper capacitors have been described.

High reliability reconstituted mica paper capacitors provide outstanding characteristics when properly designed, manufactured, tested, and applied to high voltage and high temperature power electronics systems.

X. References

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