# Dielectric Properties of Natural Esters and their Influence on Transformer Insulation System Design and Performance

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*Abstract*—**There is considerable knowledge of Transformer Insulation System design based on the use of cellulose insulation used in conjunction with mineral oil. This knowledge is based on over 100 years of transformer design and manufacture. Insulation design is based on the stress distribution between the solid insulation, in this case Kraft, and the fluid. In power and distribution transformers the stress is distributed in accordance with the permittivity of the various insulation components. The insulation designer must determine the stress in the fluid, in the solid insulation and along the interface. Design curves have been established for mineral oil, which give limits to the allowable stress at each of these critical areas. Considerable work has been done and is in progress to establish these criteria for Kraft insulation in Natural Ester fluids. The permittivity of Natural Ester fluid and various Kraft insulation materials including Diamond Pattern Paper (DPP), Low Density Pressboard and High Density Pressboard impregnated with Natural Ester is presented. A test program to determine the design criteria for interfacial stress (creep stress) is presented.**

*Index Terms*—**Natural Ester fluids, Mineral Oil, Creep, Kraft, Pressboard, Dielectric, Permittivity, Partial Discharge, DPP**

## I. INTRODUCTION

The insulation system of Kraft insulation surrounded with an insulating fluid has been used for power and distribution transformer for over a hundred years. The traditional fluid has been mineral oil. There have been extensive tests done on Kraft insulation in mineral oil. These tests as well as industry experience have led to insulation system design practices that satisfy the dielectric performance criteria defined in transformer standards. The use of Natural Ester as the insulating fluid is relatively new. This paper will describe the critical parameters regarding insulating materials in transformers and present data that have been measured that describe how the use of Natural Ester can influence these parameters.

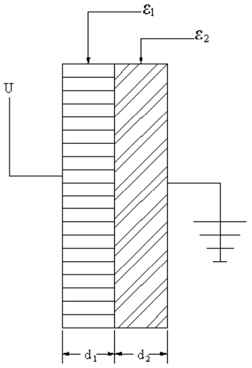
## II. INSULATION SYSTEM DESIGN

In fluid filled transformers the insulation system designer must take the entire system into consideration when he is establishing the insulation structure for a given design. The insulation must provide adequate dielectric strength for the operating and test voltage stresses that particular design will see. The insulation structure must provide adequate cooling channels to allow the fluid to dissipate the heat generated in the windings. The insulation system also must provide sufficient mechanical strength for the windings to withstand normal and abnormal service conditions such as the forces generated during through-faults.

It is beyond the scope of this paper to go into specific rationale of insulation system design. However for any specific insulation design there exists in the transformer the following critical areas:

1) Solid Insulation
2) Fluid
3) Interface between solid and fluid

In a transformer the electrical stress will distribute capacitively. A simple model showing the stress distribution between two materials in a parallel plate capacitor is given in figure 1. The voltage drop in each material is a function of the width (d) and the permittivity ( ) of the insulating material. The stress distributes inversely proportional to the permittivity of the material.



$_1$=permittivity mat. 1
$_2$=permittivity mat. 2

$Z=(d_1/\ _1) + (d_2/\ _2)$

$E_1 = U/(\ _1 * Z)$

$E_2 = U/(\ _2 * Z)$

U= Applied Voltage
$E_1$= Stress in material 1
$E_2$= Stress in material 2

**Figure 1**
**Dielectric Stress Distributes Inversely Proportional to the Material Permittivity**

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This work was supported by Cooper Power Systems, a manufacturer of natural ester fluids and transformers and EHV Weidmann Industries Inc., a manufacturer of Insulation Materials.

The dielectric strength of the solid insulation (in this case Kraft insulation impregnated with a dielectric fluid) is close to an order of magnitude higher than the fluid itself. Thus the weak material in the insulation structure is the fluid. By bringing the permittivities of the liquid and solid insulation closer together more of the dielectric stress will be distributed in the solid material. This will reduce the stress in the fluid, which typically sets the design clearance.

The dielectric strength of a given oil gap is a function of the width of that gap as shown in figure 2. [1] The insulation designer utilizes solid insulation barriers to divide an oil gap into smaller gaps in order to allow a higher average stress while preventing partial discharges. At the ends of windings, where the stress transitions from axial to radial orientation, contoured insulation is utilized.

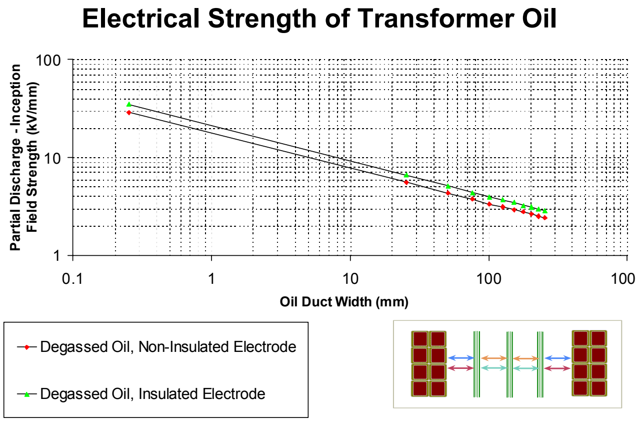


**Figure 2**
**Weidmann Oil Curve**

Despite the application of contoured insulation components, there will exist in any transformer insulation system interfacial or creep stresses along the surface of the insulation components. This is shown graphically by a plot of the equipotential lines in a typical medium power transformer as shown in figure 3.

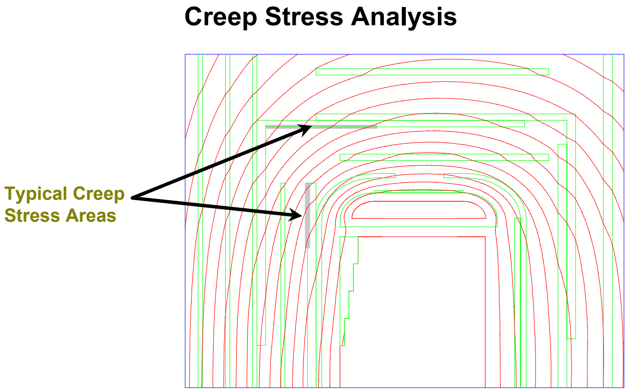


**Figure 3**
**Field Plot of End Insulation Creep Stress**

Where the equipotential lines cross the surface of a given solid insulation component there will be a voltage differential which creates a dielectric stress tangential to the surface of the solid insulation. The insulation system designer must be able to calculate this creep stress and assure that it is below design limits. EHV Weidmann maintains a creep curve, which gives the design limit for creep stress in mineral oil based on 1% probability of partial discharge inception. (See Figure 4). [2]

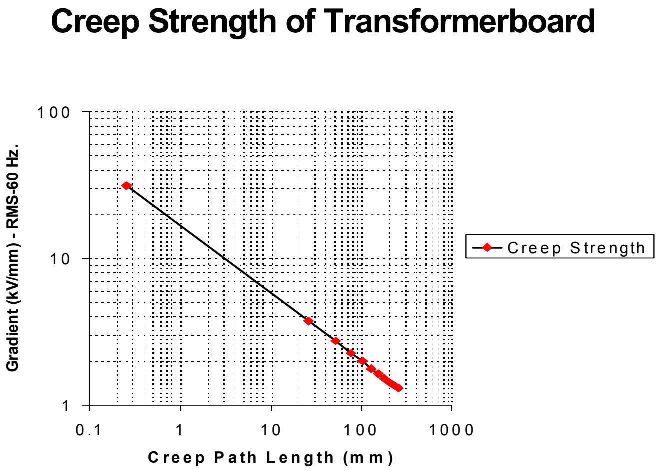


**Figure 4**
**EHV Weidmann Creep Curve**

## III. PERMITTIVITY

A test program was run to determine the permittivity of Mineral Oil and Natural Ester as well as various Kraft insulation materials impregnated with these fluids. All tests were done in accordance with the following standards:

ASTM D-2413 "Standard Practice for Preparation of Insulating Paper and Board Impregnated with a Liquid Dielectric"

ASTM D-150 "Standard Test Method for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation"

ASTM D-924 "Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids"

### Kraft Insulation Material Preparation

The following Kraft Insulation was tested:

Diamond Pattern Paper (DPP), .25mm (.010") thick
Low Density Pressboard, 3mm (.118") thick
High Density Pressboard, 3mm (.118") thick

The DPP samples were made up from "sandwiches" of ten layers of DPP with the outer layers uncoated Kraft paper. These "sandwiches" were baked under pressure to create a 3mm (.118") samples, which were then tested for dielectric properties.

All samples were air dried for 24 hours at 105° C followed by vacuum drying at 105° C for 24 hours and then impregnation under vacuum with the specific fluid being tested.

### Tests

Testing for Permittivity and Dissipation Factor was done in a controlled temperature oil bath at 25, 90 and 130° C. These temperatures were chosen to simulate start-up (25° C), normal operating (90° C) and overload (130° C) conditions. The three temperatures also are sufficient to determine a curve for the property being measured versus temperature.

### Results

| | Temperature | | |
|---|---|---|---|
| Fluid | 25° C | 90° C | 130° C |
| Mineral Oil | 2.4 | 2.4 | 2.2 |
| Natural Ester | 3.3 | 3.0 | 2.9 |

**Table 1**
**Fluid Dielectric Constant**

| | Temperature | | |
|---|---|---|---|
| Material | 25° C | 90° C | 130° C |
| DPP | 3.9 | 4.3 | 4.7 |
| Low Den. Pressboard | 3.9 | 3.9 | 4.1 |
| High Den. Pressboard | 4.5 | 4.7 | 4.9 |

**Table 2**
**Dielectric Constant of Insulation in Mineral Oil**

| | Temperature | | |
|---|---|---|---|
| Material | 25° C | 90° C | 130° C |
| DPP | 4.6 | 4.8 | 5.2 |
| Low Den. Pressboard | 4.4 | 4.4 | 4.5 |
| High Den. Pressboard | 4.6 | 4.8 | 5.2 |

**Table 3**
**Dielectric Constant of Insulation in Natural Ester**

| | Temperature | | |
|---|---|---|---|
| Fluid | 25° C | 90° C | 130° C |
| Mineral Oil | 0.02% | 0.09% | 0.25% |
| Natural Ester | 0.08% | 0.64% | 3.92% |

**Table 4**
**Fluid Dissipation Factor**

| | Temperature | | |
|---|---|---|---|
| Material | 25° C | 90° C | 130° C |
| DPP | 0.5% | 0.8% | 5.0% |
| Low Den. Pressboard | 0.3% | 0.6% | 4.5% |
| High Den. Pressboard | 0.4% | 0.6% | 2.8% |

**Table 5**
**Dissipation Factor of Insulation in Mineral Oil**

| | Temperature | | |
|---|---|---|---|
| Material | 25° C | 90° C | 130° C |
| DPP | 0.6% | 1.2% | 6.2% |
| Low Den. Pressboard | 0.3% | 1.0% | 5.3% |
| High Den. Pressboard | 0.4% | 1.0% | 5.1% |

**Table 6**
**Dissipation Factor of Insulation in Natural Ester**

In graphical form the relationship between Natural Ester, Mineral Oil, and high density pressboard impregnated with these fluids is shown in Figure 5.

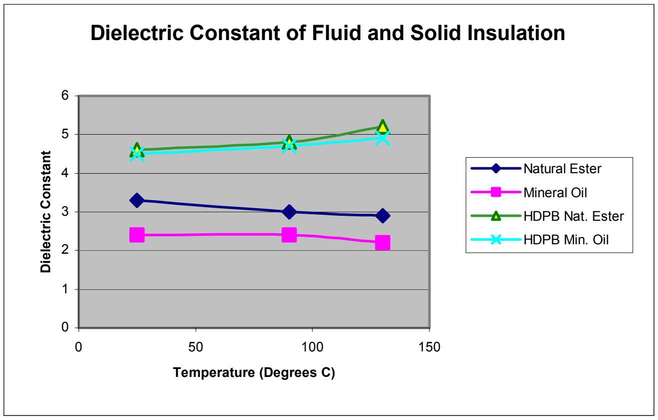


**Figure 5**
**Dielectric Constant of Natural Ester, Mineral Oil and High Density Pressboard Impregnated with each Respective Fluid**

## IV. CUMULATIVE CREEP

As has been previously presented, a critical component of insulation system design is to assure that the stresses along the solid/liquid interface are within acceptable limits.
EHV Weidmann has developed a design curve, which gives limits for the cumulative stress calculated tangentially along this interface. (See Figure 4). This curve has been developed utilizing Kraft pressboard in mineral oil. A test program is under way to verify whether this curve can be used for a Natural Ester/Kraft pressboard insulation system.

## Conceptual Development of Test Arrangement

In developing an electrode and sample arrangement to verify and develop a creep design curve there are several critical parameters, which must be controlled. The test arrangement must be designed such that the breakdown or even more importantly the initiation of the breakdown is related to tangential interfacial stress and not other rogue contributors.

In order to accomplish this the test arrangement should avoid the presence of any oil wedges where partial discharges could originate. There also should not be any sharp points on the electrodes where the local stress concentration can initiate breakdowns independent of any materials present.

In order to verify the creep curve a test program with the following parameters has been developed:

Creep Distance to be evaluated:
- 25mm
- 40mm
- 50mm

Insulating Fluid to be evaluated:
- Mineral Oil
- Natural Ester

Test Conditions
- AC breakdown & pd inception
- Full wave positive impulse 1.2x50
- Full wave negative impulse 1.2x50

Number of specimens per condition
- 25

Based on three dimensional finite element analyses an electrode configuration has been developed which will achieve the objective of developing a test arrangement in which the interfacial tangential stress (creep stress) is the critical breakdown location in the test arrangement. By optimizing the electrode system for this configuration the partial discharge inception and breakdown data will be a direct result of the creep stress applied and the materials tested.

## Verification of Electrode Configuration

The electrode configuration was developed through the use of three dimensional finite element analysis. The stress levels were measured and compared to the EHV Weidmann design curves so that the creep stress would be above the design curve (greater than the deign limit) and the stress in the oil would be below the design curve (less than the design limit).

The electrode configuration is shown in figure 6. The high voltage electrode will consist of a copper or brass tube shaped into a "U" form. For each test sample a Kraft crepe insulation tube will be placed over the high voltage electrode. A block of laminated pressboard will be the insulation component, which exhibits creep stress. The ground electrode will be a metallic disc with a machined radius edge. For each test a disc of pressboard will be placed on the top of the ground electrode.

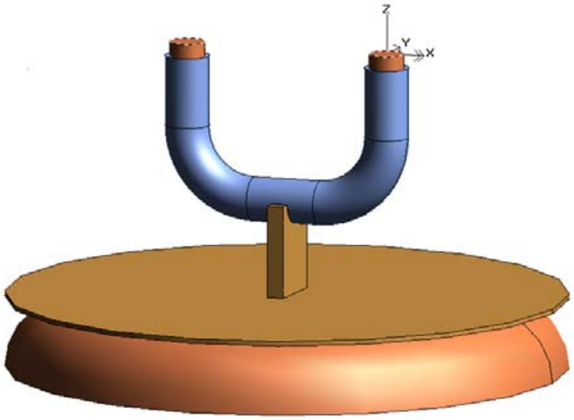
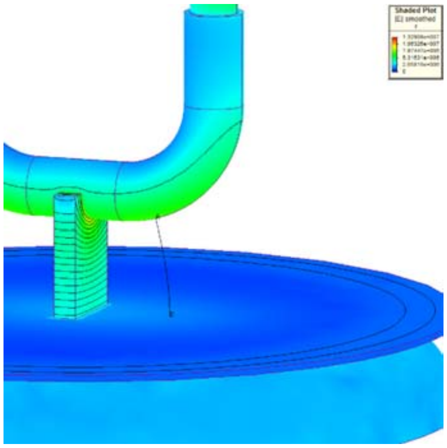


**Figure 6**
**Test Arrangement**



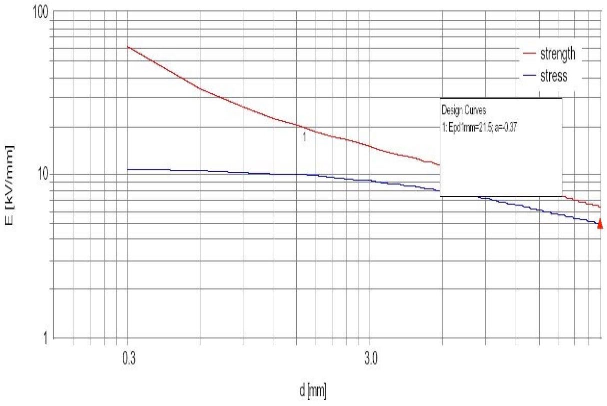
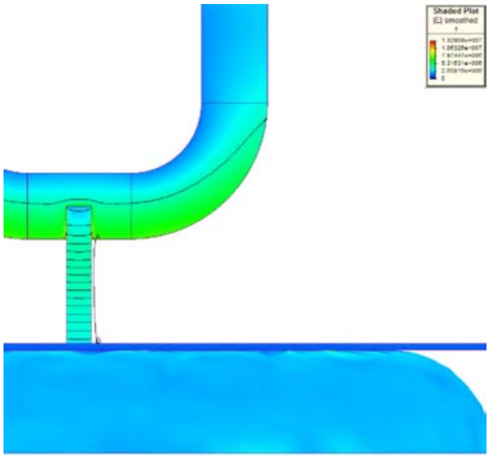


**Figure 7**
**Measurement of Stress in Fluid.**
**Stress is less than Strength.**
**Oil breakdown should not occur.**



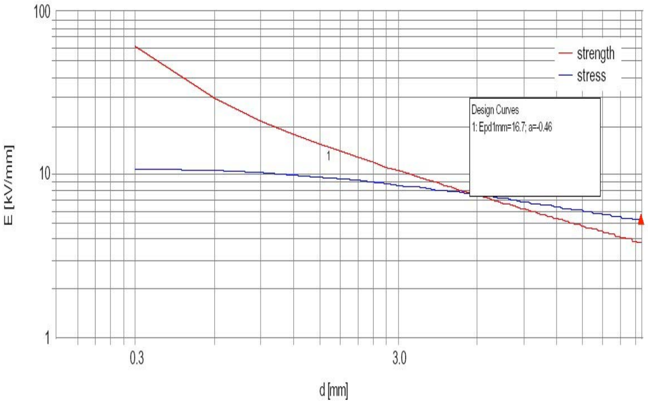


**Figure 8**

**Measurement of Creep Stress.**
**Stress is greater than Strength.**
**Creep breakdown should occur.**

## V. CONCLUSION

The use of Mineral Oil in conjunction with Kraft solid insulation has been well understood for many years. The use of Natural Esters in place of Mineral Oil has many advantages. The insulation system needs to be designed with the dielectric properties of the materials in mind. The permittivity of Natural Ester Fluid is higher than the permittivity of Mineral Oil. This will affect the permittivity of the Kraft insulation, which is impregnated with the respective fluid. The electrical stress in a solid/liquid insulation system will distribute inversely proportional to the permittivities. Because the permitivitty of Natural Ester Fluid is closer to that of impregnated Kraft than Mineral Oil there will be more stress in the solid insulation in the case of Natural Ester Fluid. This needs to be analyzed by the insulation system designer with the use of Finite Element Modeling. However it should be an advantage where the stress in the fluid limits the average stress.

Another important criteria in Insulation System design is the interfacial stress between the liquid and solid. A test program has been presented which will verify whether the Creep Curve developed by EHV Weidmann for Kraft insulation in Mineral Oil is applicable to Natural Ester.

## VI. REFERENCES

[1] Moser H.P., “Transformerboard”, Scientia Electrica, 1979

[2] Nelson J.K., “An assessment of the physical basis for the application of design criteria to dielectric structures”, Trans. IEEE, Vol. EI-24, 1989, pp 835-47

## VII. BIOGRAPHY

**Thomas A. Prevost** is an active member of IEEE. He is currently the secretary of the IEEE PES Transfromers Committee. He is a past-chair of the IEEE PES Standards Coordinating Committee and served on the IEEE-SA Board of Governors from 2002 – 2004. Thomas is the Vice President of Technical Service at EHV Weidmann Industries in St. Johnsbury, Vermont where he has been employed since 1985. Prior to that he worked at Tampa Electric Company as an engineer in distribution and production. Thomas received his BSEE from Virginia Polytechnic Institute.

Thomas is also active in ASTM D-9 Committee on Solid Insulating Materials. He has written several technical papers on the subject of Electrical Insulation Materials.