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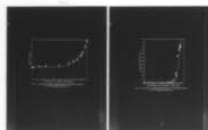
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Measurement of the Changes in Dissipation Factor and Dielectric Constant as a Method of Evaluating Degradation in Capacitor Oils.

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p> <input checked="" type="checkbox"/> The dissipation factor and dielectric constant were investigated as a method of detecting degradation of capacitor oils used in VLF transmitter capacitors. Except for water in concentrations above saturation, small amounts of polar impurities had no measurable effect on the dissipation factor of the capacitor oil now in use (an acid refined, naphthene base, hydrocarbon oil containing some aromatics). The dissipation factor of dibutyl sebacate, a possible candidate oil for use in these capacitors, however, was sensitive to polar contaminants. </p> | | |

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MEASUREMENT OF THE CHANGES IN DISSIPATION FACTOR AND DIELECTRIC CONSTANT AS A METHOD OF EVALUATING DEGRADATION IN CAPACITOR OILS

INTRODUCTION

As part of a dielectric oil study for VLF transmitter capacitors, the Naval Research Laboratory investigated the use of dissipation factor and dielectric constant measurements as a method of detecting degradation in the capacitor oils during use. A substantial increase in the dissipation factor during use of a dielectric oil was considered as a possible indication of electrical deterioration. Thus, if the failure of a capacitor in the VLF transmitter system were preceded by a deterioration of the capacitor oil over an appreciable amount of time, proper monitoring of the system by means of dissipation factor measurements might be used as an indication of incipient failure. Since the measurement of the dielectric constant is included in the measurement of the dissipation factor, it was also investigated as an indicator of the contamination of the oil. This report is therefore concerned with the following subjects:

- (a) determination of the dissipation factor and dielectric constant of dielectric oils from capacitors in use at the Annapolis VLF transmitting facility,
- (b) the relationship of the dissipation factor and dielectric constant to the amount of contaminants in the capacitor oils, and
- (c) the dielectric properties of dibutyl sebacate, a possible replacement oil.

MEASUREMENT OF DIELECTRIC CONSTANT AND DISSIPATION FACTOR

The dielectric constant ϵ may be defined from the equation for expressing the force F between two point charges, e and e' , separated by a distance r in a homogeneous dielectric:

$$F = ee' / \epsilon r^2.$$

Note: Manuscript submitted December 14, 1977.

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The dielectric constant of a material is also equal to the ratio of the capacitance, C , of a condenser with the material as the dielectric, to the capacitance of the same condenser with a vacuum dielectric, C_0 :

$$\epsilon = C/C_0.$$

Since the dielectric constant for air is essentially unity, the dielectric constant for any material may be determined by measuring the capacity of a condenser with an air dielectric and the capacity of the same condenser filled with the substance being studied.

In an ideal condenser, the charging or capacitive current is 90° out of phase with the alternating potential. In all condensers the current has a component in phase with the potential. This ohmic or loss current is due to the dissipation of part of the energy of the field as heat. The total current is the vector sum of the charging current and the loss current. If the angle between the vectors of the total current and the charging current is δ , then the dissipation factor is equal to the tangent δ or to the ratio of the loss current to the charging current.

The dielectric constants and dissipation factors were determined at frequencies of 60, 1 k, 10 k, and 100 kHz. The measurements were made with a General Radio 716 Schering Bridge system using the substitution method in which the standard air capacitor is always kept in the circuit and the unknown capacitor is substituted for a part of it. The liquids were placed in an Elliot Capacitance Cell which was designed at the Naval Research Laboratory.

MONITORING OF VLF TRANSMITTER CAPACITOR OILS FROM THE ANNAPOLIS FACILITY

It was planned that once a week samples of oil from twelve on-line capacitors would be brought to NRL for dissipation factor measurements. For comparison, a storage sample of the oil would also be evaluated. Listed in Table 1 are the dissipation factors and dielectric constant values for the first set of samples, taken May 10, 1977. Dissipation factors are very low; the negative values, caused by small errors, indicate that the measurements were taken extremely close to the zero point of the apparatus. The dielectric constants vary from 2.23 to 2.28. These differences are not considered significant, since, for example, repeated measurements on sample PA2C1 at 100 kHz gave values of 2.24 and 2.28.

Summarized in Table 2 are the dielectric properties of a set of samples taken three weeks later, on May 31. Although the dissipation factors generally appear to be higher than those of the first set,

these values are comparable to those of the storage sample and all are less than 2×10^{-3} . Thus this increase can be considered to have its origin in the measuring apparatus rather than in the samples themselves. Oil from a capacitor which had failed in service, November 1976, was also examined, Table 2. This oil was blackened by particles which could be removed by filtration. The unfiltered oil, as well as the filtered sample, had low dissipation factor values, comparable to those of the storage sample. When a storage sample of the oil was subjected to electric stress, arcing for several hours in a test cell, no effect on the dissipation factor or dielectric constant was observed, as seen in Table 2.

These results indicate that the monitoring of dissipation factor changes in the capacitor oils is not an appropriate method for failure prevention. Whether or not chemical deterioration of the oil is responsible for the failures is not likely to be determined by this method. From the samples studied here there is no indication that capacitor failure is preceded by a significant increase of the dissipation factor.

THE EFFECT OF CONTAMINANTS ON THE DIELECTRIC PROPERTIES OF THE CAPACITOR OIL

It would be of value to determine just what sort of contaminants significantly raise the dissipation factor of the capacitor oil. The first contaminant investigated was water. Increments of water were added with sonic agitation which formed fine droplets of water in the oil after saturation had been reached, at about 100 ppm. Table 3 shows that no significant change in the dissipation factor was observed through 200 ppm of water even though the mixture was distinctly cloudy. At 250 ppm there is a dramatic rise in the dissipation factor measured at 60 Hz. Thus it is seen that undissolved water causes a large increase in the dissipation factor.

Since the oil is an acid refined, naphthene base, hydrocarbon oil containing some aromatics, a soluble contaminant must be considerably polar to significantly raise the dissipation factor. The results from adding several polar components are seen in Table 3. Methanol, butanol, and dimethyl succinate have huge dissipation factors, greater than 6 (this would appear as 6000 in the table since table values have been increased by a factor of 10^3). Yet when these polar contaminants are present in the amount of 200-500 ppm, the effect on the dissipation factor is negligible.

To investigate further how the dissipation factor and dielectric constant change with the concentration of a polar component, various mixtures of the capacitor oil and 2-ethylhexanol were prepared. 2-Ethylhexanol was chosen as the polar component since it has a high but measurable dissipation factor and is soluble in the oil in all proportions. Dielectric constants and dissipation factors were measured at 60 Hz over a wide range of concentrations.

Mole fractions of 2-ethylhexanol are calculated with a molecular weight value of 130 for the alcohol and 390 for the capacitor oil. The values are seen in Table 4. In Figure 1 the dielectric constant is plotted as a function of the mole fraction of 2-ethylhexanol in the dielectric liquid. There is little rise of the dielectric constant until the mole fraction of 2-ethylhexanol reaches the vicinity of 0.5. Then the dielectric constant rises rapidly. The curve drawn in Figure 1 is the equation

$$\text{dielectric constant} = 2.2 + 4.5 (\text{mole fraction of 2-ethylhexanol})^6.$$

This curve is seen to pass quite close to the data points.

In Figure 2, where the dissipation factor is plotted as a function of the mole fraction of the 2-ethylhexanol, the data points are seen to fall close to the curve represented by the equation

$$\text{dissipation factor} = 0.002 + 1.2 (\text{mole fraction of 2-ethylhexanol})^{15}.$$

Since the dissipation factor varies as the 15th power of the mole fraction of 2-ethylhexanol, the increase becomes substantial only with high concentrations. It is seen therefore, that dissipation factor measurements would be better at detecting the contamination of 2-ethylhexanol with dielectric fluid than the other way around! It is evident that the capacitor oil could be grossly contaminated with a soluble polar contaminant without significantly raising the dissipation factor. As stated before, an increase in the dissipation factor of a capacitor oil is interpreted as adversely affecting the function of the fluid. Unfortunately, it is not known if a contamination of the capacitor oil that does not change the dissipation factor means that the fluid will function as efficiently as before. It seems likely that a better interpretation of the effect of contaminants in the capacitor oil would have been possible if measurements of electric strength had also been made. A lowering of break-down voltage would certainly indicate a greater possibility of arcing during operating conditions. As the situation now stands, chemical changes in the capacitor oil that occur during use would not be expected to raise the dissipation factor.

EFFECT OF CONTAMINANTS ON THE DIELECTRIC PROPERTIES OF DIBUTYL SEBACATE

The ester dibutyl sebacate has been suggested as a possible replacement for the present capacitor oil. This liquid has been used in power capacitors. The effect of polar contaminants in this fluid was also investigated. Table 5 shows that this ester has a relatively high dissipation factor that seems quite sensitive to the presence of various polar contaminants. Percolation of the original sample through alumina and molecular sieves greatly lowers the dissipation factor. Addition of various polar materials to the treated fluid substantially increases the dissipation factor. When a sample of the treated liquid was subjected to electrical stress, arcing for several hours in a test cell, the dissipation factor was increased considerably.

CONCLUSIONS

The main conclusion reached in this study is that monitoring of dissipation factor and dielectric constant changes in the capacitor oil now in use in VLF transmitter systems is not a satisfactory method for failure prevention. The dielectric properties of an oil from a capacitor that had experienced a catastrophic failure were unchanged. The possibility that capacitor failures are not preceded by a weakening of the electrical properties should be considered. The dissipation factor of dibutyl sebacate, however, seems quite sensitive to the presence of polar contaminants. The use of dielectric measurements to monitor deterioration of capacitor oils of this type would seem quite feasible.

Table 1

Data from Capacitor Oil Samples Taken May 10, 1977

| Oil Sample | Dissipation Factor x 10 ³ | | | | Dielectric Constant | | | |
|---------------|--------------------------------------|-------|--------|---------|---------------------|-------|--------|---------|
| | 60 Hz | 1 kHz | 10 kHz | 100 kHz | 60 Hz | 1 kHz | 10 kHz | 100 kHz |
| Storage | 0.51 | 0 | 0 | -0.43 | 2.26 | 2.26 | 2.26 | 2.23 |
| PA1C1 | 0.77 | 0 | -0.43 | 1.72 | 2.25 | 2.25 | 2.27 | 2.24 |
| PA1C2 | 0.77 | 0.43 | 0.43 | 2.1 | 2.24 | 2.24 | 2.26 | 2.24 |
| PA1C3 | 0.76 | 0.43 | -0.85 | 1.71 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA1C4 | 0.51 | 0 | 0.43 | 0.85 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA1C5 | 0.51 | 0 | 0.86 | 0.85 | 2.24 | 2.24 | 2.25 | 2.26 |
| PA1C6 | 0.51 | 0.42 | 0.42 | -0.85 | 2.27 | 2.26 | 2.28 | 2.28 |
| PA2C1 | 0.51 | 0.85 | 0.85 | -1.27 | 2.26 | 2.26 | 2.27 | 2.28 |
| PA2C2 | 0.51 | 0.43 | 0.85 | 0.85 | 2.26 | 2.26 | 2.25 | 2.26 |
| PA2C3 | 1.03 | 1.28 | 0 | 0.43 | 2.23 | 2.24 | 2.26 | 2.25 |
| PA2C4 | 1.54 | 1.28 | -0.43 | - .43 | 2.24 | 2.25 | 2.26 | 2.23 |
| PA2C5 | 0.51 | 0 | -0.85 | 1.28 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA2C6 | 0.51 | 0.43 | 0 | -0.43 | 2.28 | 2.26 | 2.27 | 2.26 |
| PA2C1 | 0.25 | 0.43 | 0.85 | -0.43 | 2.26 | 2.26 | 2.28 | 2.24 |

Table 2

Data from Capacitor Oil Samples Taken May 31, 1977

| Oil Sample | Dissipation Factor $\times 10^3$ | | | | Dielectric Constant | | | |
|---|----------------------------------|-------|--------|---------|---------------------|-------|--------|---------|
| | 60 Hz | 1 kHz | 10 kHz | 100 kHz | 60 Hz | 1 kHz | 10 kHz | 100 kHz |
| Storage | 1.27 | 1.27 | 1.27 | 0.42 | 2.26 | 2.26 | 2.26 | 2.27 |
| " | 1.27 | 1.27 | 0 | 0.42 | 2.26 | 2.26 | 2.26 | 2.26 |
| " | 1.02 | 0.42 | 0 | 0.42 | 2.26 | 2.26 | 2.26 | 2.27 |
| " | 1.02 | 0 | 0.85 | 0 | 2.26 | 2.26 | 2.25 | 2.25 |
| PA1C1 | 1.27 | 0.85 | 0.43 | 0.42 | 2.25 | 2.26 | 2.25 | 2.26 |
| PA1C2 | 1.02 | 0 | 0.42 | 0.42 | 2.26 | 2.26 | 2.25 | 2.26 |
| PA1C3 | 1.02 | 0 | 0 | 0.42 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA1C4 | 1.02 | 0 | 0.42 | 0.42 | 2.26 | 2.26 | 2.26 | 2.27 |
| PA1C5 | 1.02 | 0.42 | 0.85 | 0.42 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA1C6 | 1.02 | .85 | -0.43 | 0.42 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA2C1 | 1.02 | 0 | 0 | 0.42 | 2.26 | 2.26 | 2.25 | 2.25 |
| PA2C2 | 1.02 | 0 | -0.42 | 0 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA2C3 | 1.02 | 0.42 | 1.27 | 0.42 | 2.26 | 2.26 | 2.26 | 2.26 |
| PA2C4 | 1.78 | 0.85 | 0 | 0 | 2.26 | 2.25 | 2.25 | 2.25 |
| PA2C5 | 1.27 | 1.69 | -0.42 | 0.42 | 2.26 | 2.26 | 2.26 | 2.27 |
| PA2C6 | 1.02 | 0.42 | 1.27 | 0.85 | 2.26 | 2.26 | 2.26 | 2.26 |
| From Failed Condenser | | | | | | | | |
| Unfil- tered | 1.01 | 0.42 | 0 | 0.85 | 2.28 | 2.28 | 2.28 | 2.27 |
| Fil- tered | 0.51 | -0.43 | -0.43 | 0.43 | 2.26 | 2.26 | 2.27 | 2.24 |
| Electrically Stressed in a Test Cell | | | | | | | | |
| | 0.50 | 0 | 0 | 0.42 | 2.27 | 2.27 | 2.27 | 2.29 |

Table 3

Data from Samples of Capacitor Oil with Various
Added Components

| Storage Sample plus Contaminant | Dissipation Factor $\times 10^3$ | | | | Dielectric Constant | | | |
|---------------------------------------|----------------------------------|-------|--------|---------|---------------------|-------|--------|---------|
| | 60 Hz | 1 kHz | 10 kHz | 100 kHz | 60 Hz | 1 kHz | 10 kHz | 100 kHz |
| Water | | | | | | | | |
| none | 0.51 | 0 | 0 | -0.43 | 2.26 | 2.26 | 2.26 | 2.23 |
| 100 ppm | 0 | -1.27 | -0.43 | 0.43 | 2.27 | 2.27 | 2.27 | 2.26 |
| 200 ppm | -0.76 | 0.43 | -0.85 | 0.85 | 2.27 | 2.26 | 2.27 | 2.26 |
| 250 ppm | 20.2 | 0 | -1.28 | 2.98 | 2.28 | 2.26 | 2.26 | 2.27 |
| 300 ppm | 836 | 65.3 | 4.26 | 2.98 | 2.55 | 2.18 | 2.27 | 2.26 |
| 500 ppm | 2140 | 194 | 28.4 | 3.06 | 2.91 | 2.27 | 2.21 | 2.19 |
| Methanol | | | | | | | | |
| 500 ppm | 2.26 | | | | 2.26 | | | |
| Butanol | | | | | | | | |
| 500 ppm | 1.97 | | | | 2.27 | | | |
| Dimethyl Succinate | | | | | | | | |
| 200 ppm | 1.73 | | | | 2.26 | | | |
| 2-ethyl- hexanoic acid | | | | | | | | |
| 500 ppm | 1.52 | 0.42 | 1.69 | 0 | 2.25 | | | |
| 1% | 1.53 | 1.27 | 0.42 | 0 | 2.23 | | | |
| 2-ethyl- hexanol | | | | | | | | |
| 500 ppm | 1.52 | | | | 2.25 | | | |

Table 4

Dielectric Properties of Mixtures of Capacitor
Oil and 2-Ethylhexanol

| <u>Mole Fraction</u> <u>2-Ethylhexanol</u> | <u>Dielectric</u> <u>Constant</u> <u>at 60 Hz</u> | <u>Dissipation</u> ₃ <u>Factor x 10</u> <u>at 60 Hz</u> |
|---|---|--|
| 0 | 2.22 | 2.51 |
| 0.029 | 2.10 | 4.2 |
| 0.136 | 2.30 | 2.68 |
| 0.250 | 2.36 | 3.8 |
| 0.500 | 2.42 | 3.96 |
| 0.667 | 2.85 | 10.9 |
| 0.750 | 3.21 | 17.1 |
| 0.818 | 3.55 | 68.5 |
| 0.875 | 4.07 | 265 |
| 0.900 | 4.37 | 194 |
| 0.923 | 4.80 | 732 |
| 0.964 | 5.81 | 904 |
| 0.983 | 6.16 | 986 |
| 0.997 | 6.70 | 1032 |
| 1.000 | 6.95 | 971 |

Table 5
Dissipation Factors for Various Samples of
Dibutyl Sebacate

| <u>Sample Treatment</u> | <u>Dissipation Factor x 10³ at 60 Hz</u> |
|---|---|
| Original Sample | 96 |
| With Alumina and Molecular Sieves | 10 |
| after electrical stressing in a test cell | 49 |
| with 500 ppm 2-ethylhexanoic acid | 37 |
| with 500 ppm 2-ethylhexanol | 50 |
| with 500 ppm butanol | 20 |

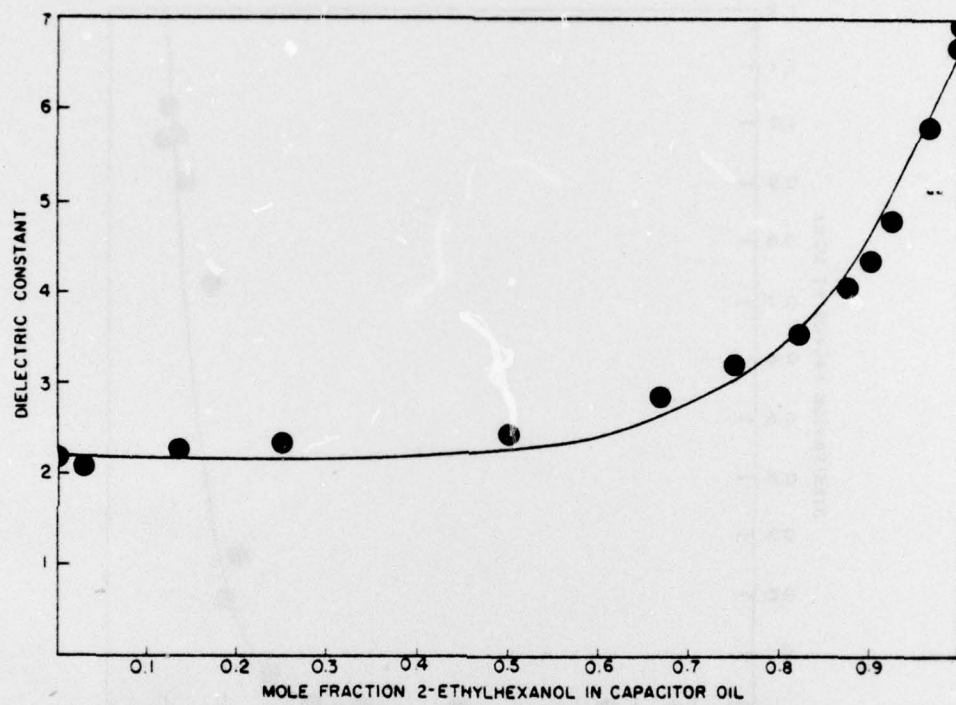


Fig. 1 — The effect of added 2-ethylhexanol on the dielectric constant of VLF transmitter capacitor oil

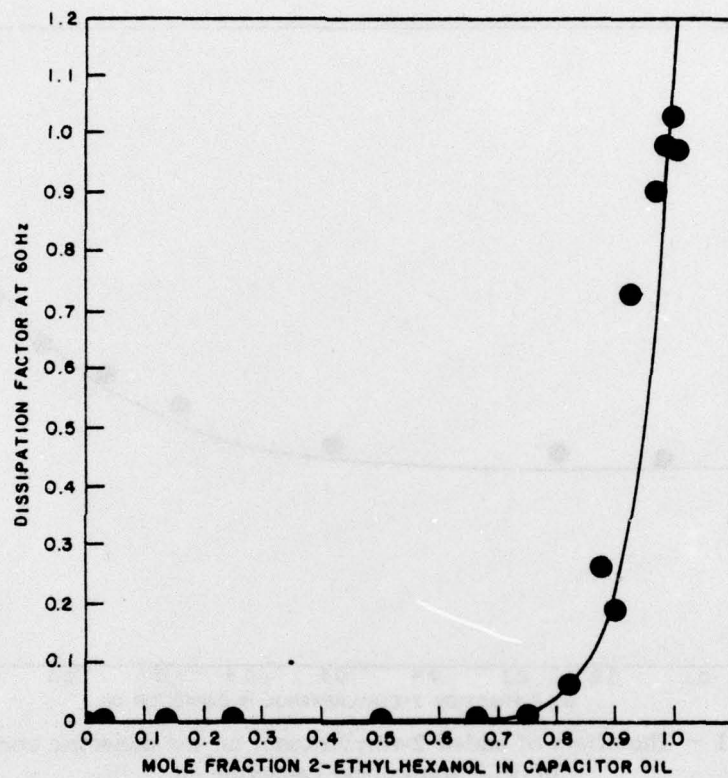


Fig. 2 — The effect of added 2-ethylhexanol on the dissipation factor of VLF transmitter capacitor oil