Tapchangers for De-energized Operation in Natural Ester Fluid, Mineral Oil and Silicone

L. Dix, Senior Member, IEEE and P. J. Hopkinson, Fellow, IEEE

***Abstract*—Natural Ester seed oil is a biodegradable fluid that is increasingly being used as a replacement for mineral oil and for high temperature flashpoint liquids, including silicone and RTEMP. Electrical contact coking in mineral oil and in silicone has been a common problem with many types of contact materials in tapchangers for de-energized operation and also the reversing switch in load tapchangers. In recent years, an accelerated aging functional life test has been developed and presented to the Transformers Committee of IEEE that has had a good correlation with field data to sort out stable versus unstable combinations. This paper presents a comparative look at Natural Ester fluid versus mineral oil and silicone for several popular contact pairs. In addition to its biodegradability, Natural Ester is shown to have considerably better thermal stability with contact pairs that are unstable in both mineral oil and silicone.**

***Index Terms*—Life estimation, Contact coking, Mineral oil, Natural Ester, Silicone, Tapchangers.**

I. NOMENCLATURE

Natural ester fluids are a class of insulating oils that are derived from vegetable seeds, such as soybeans. Retrofills are transformers that were originally manufactured and filled with mineral oil and that are subsequently drained and filled with alternative fluids such as natural esters. Less flammable high flashpoint oils refer to a class of insulating oils that have flashpoints in excess of 300ºC. Tapchangers are multi-position switches that are intended for connecting alternative winding taps in power transformers, to obtain desired voltage ratios. Tapchangers for de-energized operation are designed for switching connections only when the transformer is de-energized. Contact coking refers to electrical contacts in a switch or tapchanger that overheat in service, breaking down the insulating fluid, and forming carbon.

II. INTRODUCTION

Liquid-filled Distribution and Power transformers are robust and designed to provide long life when loaded in accordance with IEEE C57.91 Loading Guides and properly protected against over-voltage and through faults. Considerable investigation of insulation system life as well as dielectric performance over the last century have provided excellent technical basis for the proven empirical life. One limitation to the otherwise long life of transformer cores and coils is found in the electrical contacts of tapchangers for de-energized operation. Such contacts are most often set in a position when new and never moved again for the remainder of the life of the transformer. This lack of scrubbing action, which occurs when tapchangers are moved, requires that the contacts are fundamentally resistant to corrosion for survival. When the contacts are not stable, then thermal run-a-way is likely to occur. In a meeting of the Association Of Edison Illuminating Companies (AEIC), the authors learned that coked contacts are a serious and common occurrence. Responding to this concern, a Functional Life Test has been applied that is intended to simulate 30 years of thermal life in a period of 30 days on test. This test has been applied successfully by one large manufacturer for nearly 40 years as criteria for selecting contacts and compatible fluids. The authors are not aware of contacts having field problems when they are able to pass this test. This report describes the test, the basis for its life acceleration, and test results on Copper-Copper, Silver-Copper and Silver-Silver contacts in Natural Ester, Mineral Oil and Silicone.

III. TAPCHANGER FUNCTIONAL LIFE TEST TECHNICAL WORK PREPARATION

The objective of an accelerated aging functional life test is to simulate the many years (30 years for transformers) of normal service in a brief period of time. The chosen period for this test is 30-days. For this work to be accurate, each day of test must equal 1 year of service, resulting in an apparent acceleration factor of 365:1. Recognizing that normal service is characterized by uneven load cycles and suspecting that this operating condition plays a part in the problems often found in de-energized and load tapchangers, it is also desirable to test the full swings of load that transformers may see.

A. Insights from Holm

Ragnar Holm in “Electric Contacts” makes reference to measurements that defined the growth of Cu_2O and CuO as a function of temperature (through the range of 100 to 200ºC) and time. The derived formula for the growth of the oxide films has an exponential rate that closely follows the 10ºC rule across this range of temperatures.

Holm also notes that “Silver oxidizes to Ag_2O at room temperature only in the presence of ozone. Ag_2O is soft, easily removed mechanically and decomposes at 200ºC. It seldom disturbs the performance of contacts.”

B. Work By Slade

Paul G. Slade in “Electrical Contacts” described considerable studies of activation energy and variables that affect contact corrosion and concluded:

1. That electrical contact corrosion follows a classical Arrhenius relationship with time and temperature.
2. That tests can be accelerated by temperature in theory.
3. That the acceleration follows the 10ºC rule, wherein

every 10ºC hotter cuts the time by half, and every 10ºC lower doubles the time.

4. That the Arrhenius relationship is generally linear up to temperatures as high as 300ºC, although most life testing work is generally performed at lower temperatures, like 150ºC.

One of Slade's experiments examined rates of corrosion via weight gain. The authors were able to duplicate this finding and independently were able to demonstrate the validity of the 10ºC rule in earlier assignments.

C. IEEE Transformer Loading Guide

IEEE C57.91 is an IEEE loading guide for liquid-filled Distribution and Power Transformers. The maximum listed loading in this document is 2 times rated load for ½ hour each day. In line with the loading limit of IEEE C57.91, 2 times rated load was selected as the value of loading that would be placed on the tapchanger for a realistic functional life test. Studies by NEMA's transformer section in NEMA TP-1 and individual load studies by some manufacturers and users have concluded that the rms equivalent load that most accurately characterizes medium voltage transformers is 50% load. While this is the case it is important to mention that real transformer loading tends to follow a daily and seasonal cyclical pattern. This pattern consists of a few periods of significant load followed by periods of low quiescent load. Residential transformers, along with specialty type transformers such as motor starting transformers, rectifier transformers, induction furnace transformers and arc furnace transformers are particularly susceptible to highly variable load cycles. Larger commercial, industrial and utility transformers have considerable load diversity and thus see smaller load swings.

D. Daily load cycle

Cyclical loading is a desirable part of a realistic load cycle for accelerated aging. The goal was to determine temperatures that would be required to have one day relate to one year in service, and to have a cycle defined by 8 hours with heated ambient fluid and with load current followed by 16 hours without load and with unheated fluid each day for 30 consecutive days (cycles) of testing. Considering the effect of thermal lags both in heating and in cooling, it is reasonable to think of an equivalent 8 hours of heated service each day. Since there are 8,760 hours in a year, the desired acceleration is 8760/8 or 1095. Applying the 10ºC rule, the search is to determine the number of additive 10ºC temperatures to produce such acceleration. If x is the number of 10ºC increments, then

$$2^X = 1095 \qquad (1)$$

$$\text{Therefore, } X \approx 10 \quad (2)$$

This means that there are approximately (10) multiples of 10ºC that must be added to the 50% equivalent average load contact temperatures in order to reach the desired daily aging cycle, such that one day of test equals one year of expected service. However, at 50% load, the average oil temperature inside of the transformer will be approximately 26ºC above ambient. Assuming a 20ºC ambient, a 5ºC conductor rise over oil, and a 4ºC super temperature increment at the point of contact, suggests an equivalent real service starting temperature of approximately 55ºC. Hence, a desirable aging temperature can be thought of as 55ºC plus 100ºC for acceleration or a net 155ºC aging temperature.

This temperature of 155ºC is the contact super temperature or the temperature of the hottest point at the actual spots of contact.

$$\text{Super temperature} = T_{oil} + T_{bulk/oil} + T_{super/bulk} \quad (3)$$

Where,

T_{oil} = the fluid temperature in ºC

$T_{bulk/oil}$ = the bulk temperature rise of contact/oil in ºC, and is generally measured by thermocouple.

$T_{super/bulk}$ = the hottest spot rise of the point of contact over the bulk contact in ºC and is a calculated number, based on the measured voltage drop between the contact pair.

Note that for stable contact pairs, the following relationships generally hold:

$T_{bulk/oil}$ is generally in the range of 20ºC at 2 times load.

$T_{super/bulk}$ is in the range of 5ºC at 2 times load.

Hence, if the desired aging temperature is 155ºC then the fluid temperature by equation (3) above must be 130ºC. It is interesting to note that the 130ºC is the upper limit temperature that over current temperature devices would generally permit in distribution transformers.

The aging cycle is thus established as 2 times rated load current in a 130ºC fluid bath for 8 hours on followed by 16 hours with no load and with no heat applied to the bath. A total of 30 replications of this cycle constitute the life test.

E. Functional Life Test Pass/Fail Criteria

Electrical contact resistance is considered the best measure of contact performance. Contact resistance is calculated by the ratio of the measured voltage drop across the contact pair divided by the load current in the test. Two criteria have been established for successful completion of the functional life test:

1. Contact resistance must not increase by more than 25% during the test.
2. Contact resistance must remain stable in the test.

This test and these acceptance criteria have been applied by one major manufacturer of circuit interrupters and tapchangers for nearly 40 years, with such success that there is no recorded incident of contact systems that have passed the test showing field problems.

F. Contacts and fluids in the test

Three popular contact pairs and three fluids were subjected to the functional life test. The contact pairs were as follows:

1. Silver plated copper mated against silver plated copper.
2. Silver plated copper mated to plain copper.
3. Plain copper mated to plain copper.
4. Tin plated copper mated to plain copper.

The three fluids tested were:

1. Natural ester fluid
2. Mineral oil
3. Silicone

For each tested combination, 3 phases of one tapchanger were connected in series, providing (6) contact pairs. The following plots compare the average result of all 6 contacts in one chart. For each tested combination, super temperatures and contact resistances are shown.

G. Test results of silver versus silver

Slade remarked that "silver is unique among the materials of contact technology. One virtue of silver is that for practical purposes it does not form oxide films as do other materials such as copper and nickel. In fact its oxide tends to decompose above about 150ºC in air." Even though this test was conducted in fluid and not in air, clearly the same oxidation resistance is present. Figure 1 below shows contact super temperatures for silver-silver in natural ester and in silicone. This combination was not tested in mineral oil because it proved so stable in silicone (the most aggressive fluid of the group). It is believed to be as stable as other tapchangers with silver-silver contacts that have been successfully tested by the same supplier in mineral oil.

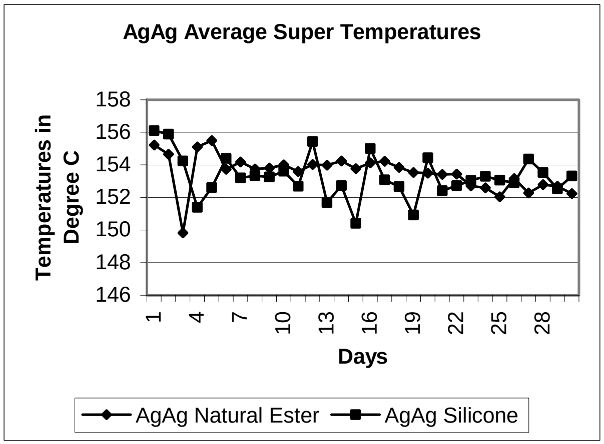

Figure 1 shows the average super temperature of all 6 silver-silver contacts for natural ester and silicone. Both tests were stable.

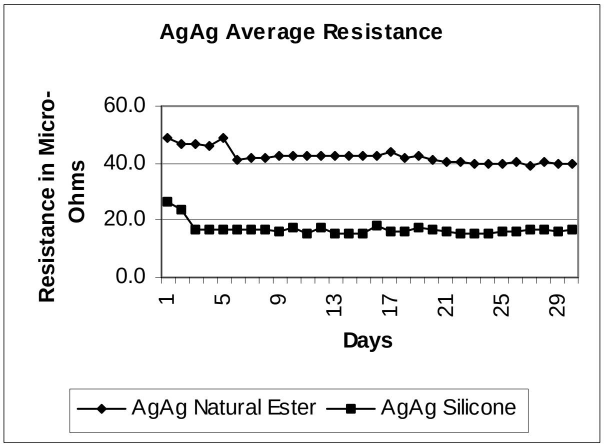

Figure 2 shows the average resistance of all 6 silver-silver contacts for natural ester and silicone. Both test groups passed and were stable.

H. Test results of silver-copper

Silver-plated copper contacts mated to plain copper contacts are less stable than silver-silver, and more likely to overheat due to oxidation of the copper. For these contacts, tests were conducted in natural ester, in mineral oil and in silicone. Note that super temperature and resistance rose with time for all but the natural ester fluid tests, which remained absolutely stable.

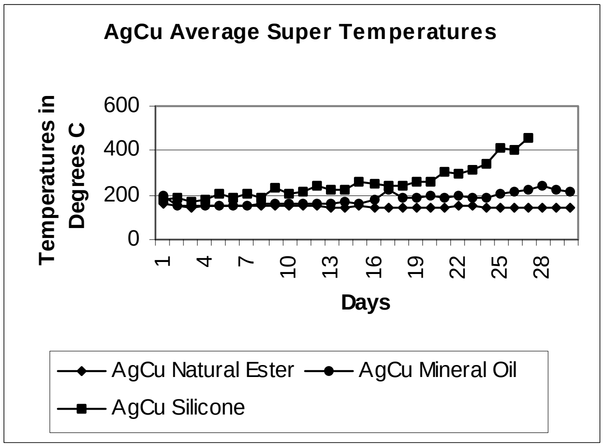

Figure 3 shows the average super temperature of all 6 silver-copper contacts for natural ester, mineral oil, and silicone. Only natural ester was stable.

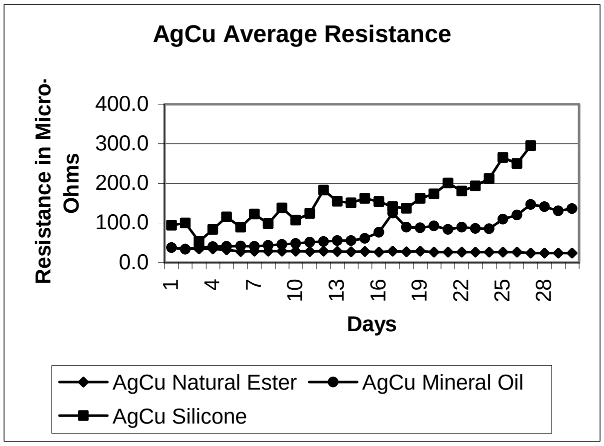

Figure 4 shows the average resistance of all 6 silver-copper contacts for natural ester, mineral oil, and silicone. Only natural ester passed the test.

I. Test results of copper-copper

Plain copper contacts mated to plain copper contacts were the least stable of the three types tested in all three fluids and in that comparison the most likely to oxidize. Note that only tin-plated copper on plain copper was more unstable but that contact pair was only tested in silicone and in natural ester. For the copper-copper contacts, tests were conducted in natural ester, in mineral oil and in silicone. Note that super temperature and resistance rose with time for all but the natural ester fluid tests, which remained stable and passed the test for each of the contact pairs.

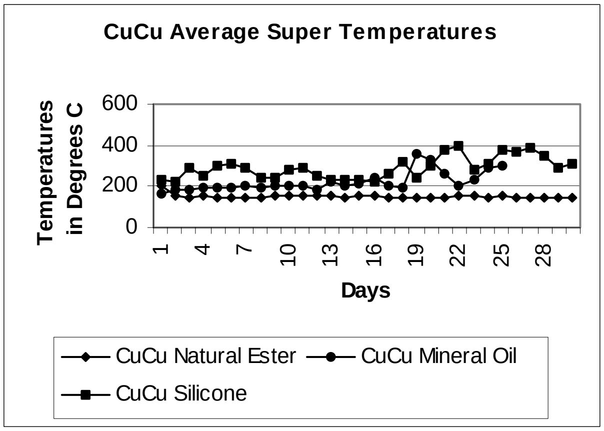

Figure 5 shows the average super temperature of all 6 copper-copper contacts for natural ester, mineral oil, and silicone. Only natural ester was stable.

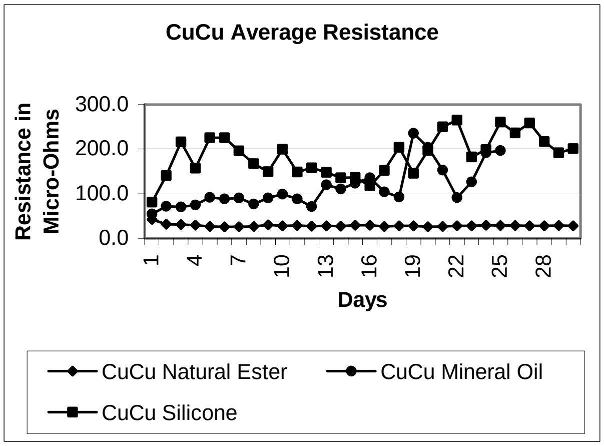

Figure 6 shows the average resistance of all 6 copper-copper contacts for natural ester, mineral oil, and silicone. Only natural ester passed the test.

J. Test results of tin-copper

Plain copper contacts mated to tin plated contacts have been used in the industry for many years. Our previous work indicated that contact pairs in silicone, if problematic, tended to deteriorate faster than the identical contact pairs in oil and faster than every other contact pair investigated. Therefore, only silicone and natural ester fluids were used in the testing of the tin-copper contacts. Once again, the contact pair was not stable in silicone but remained stable in natural ester fluid.

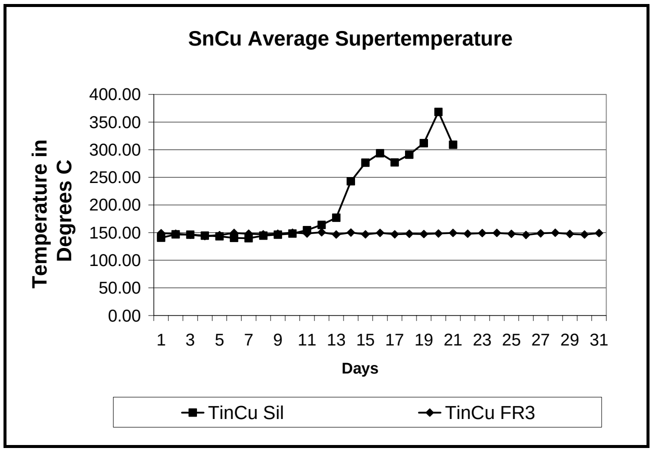

Figure 7 shows the average super temperature of all 6 tin-copper contacts for natural ester and silicone. Natural ester was stable.

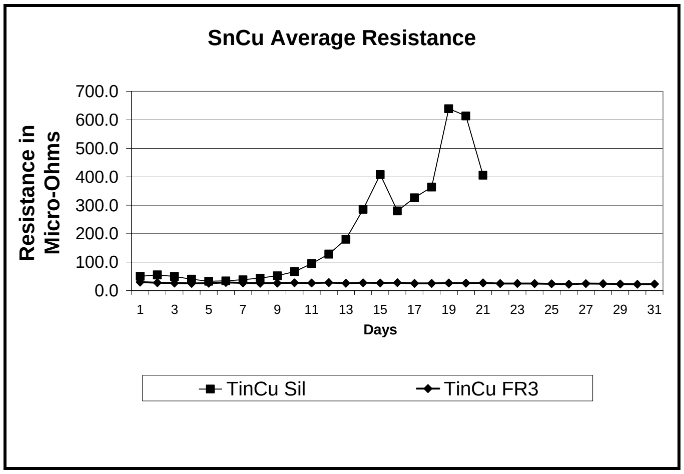

Figure 8 shows the average resistance of all 6 tin-copper contacts for natural ester and silicone. Natural ester was stable

K. Conclusions from Tests

Several conclusions can be drawn from the work in this test series:

1. Contacts in natural ester fluid are the most stable, followed by contacts in mineral oil with contacts in silicone being the least stable.
2. Silver-plated copper contacts mated to silver plated copper contacts are the most stable contact materials

regardless of fluid type, followed by silver-copper contacts, copper-copper contacts and finally tin-plated copper –plain copper contacts.

3. All four contact groups were stable in natural ester and passed the tests, while only silver-silver are stable enough to project a 30-year life expectancy in mineral oil and in silicone.

Conclusions regarding the various contact pairs without respect to any particular fluid are in line with earlier works. These found that silver to silver contacts or a variable thereof (such as silver alloys) are generally superior to copper contacts. Copper contacts were noted by Hunt in "Electrical Contacts" to "suffer appreciable oxidation in service and develop contact resistances many times higher than those obtained with clean bright surfaces." The tests, as outlined, bear this out with the exception of those performed in the natural ester fluid. Thus, it would seem that the natural ester fluid introduces an exception to the normal rule with respect to contact materials.

It should also be noted that other variables involved with the stability of contacts are still under study. Contact geometry, contact pressures, and a myriad of contact material combinations warrant further investigation but in this study the effect of the contact environment, that is the fluid itself, was marked and substantial.

L. Discussion

In other work published by C.P. McShane and others, natural ester has been found to provide a 21ºC higher thermal index with cellulose insulation systems than with mineral oil. This higher thermal capability has been largely attributed to the unique ability of natural ester to remove moisture from the cellulose. In all likelihood, a similar mechanism is occurring with electrical contacts in natural ester. By removing moisture and oxygen, contact corrosion is largely prevented or minimized.

One caveat with respect to silver contacts would be in regard to fluids containing higher than normal sulfur content. Ag_2S (silver sulfide) grows steadily over time. However, it can be controlled by limiting exposure to active sulfur atoms. Thus specifications limiting the amount of sulfur products in oil along with careful selection of hoses (which may have residual sulfur from the vulcanizing process) used to fill transformers may need to be considered when using silver plated contacts. Tin does not react as readily to sulfur in oil and it is one possible reason that tin plating has been used in the past.

Books:

[1] P. G. Slade, *Electrical Contacts*, New York: Marcel Decker, 1999, pp. 1-140.

[2] Ragnar Holm, *Electric Contacts, Theory and Application,* 4th Ed, New York, Springer-Verlag, 1967 pg 112

[3] L. B. Hunt, *Electrical Contacts,* Johnson, Matthey and Co, 1946

Papers Presented at Conferences (Unpublished)

[4] P. J. Hopkinson, "Electrical Contacts for Off-Circuit Tap Changers for Oil Immersed Transformers" presented at the IEEE Transformers Committee. Fall 2000

Standards:

[5] *IEEE Draft Standard For Natural Ester Fluids*, IEEE Standard PC57.147, 2005.

IV. BIOGRAPHIES

Larry Dix holds a Bachelor of Engineering degree in Electrical Engineering from Youngstown State University. He has been involved in the electrical power industry for 29 years starting out designing medium power transformers for Standard Transformer. He has designed units up to 230 kV and also dry type transformers up to 34 kV. While with Square D Company he became involved in application engineering working directly with customers. Later, while with Square D Company he became Supervisor of Application Engineering with responsibilities for both liquid filled and cast coil transformers. Returning to Ohio, he worked for Ohio Transformer as a Utility Sales engineer responsible for transformer repairs up to 545 MVA and 230 kV. Following that he held a similar position with Eastern Electric. After a stint with Power Transformer Company as Vice President of Engineering he accepted the Vice President and General Manager position with Quality Switch. At Quality Switch he holds responsibility for manufacturing, engineering, and marketing. He is a Senior member of IEEE and has been a member of the IEEE Transformers Committee for the last 19 years. He has been an active member of the task force and working group for the IEEE Guide for Failure Investigation, Documentation, and Analysis for Power Transformers and Shunt Reactors (C57.125) and the working group for the American National Standard for Secondary Network Transformers - Subway and Vault Types (Liquid Immersed) (C57.12.40)

Phil Hopkinson is an IEEE Fellow and long service Transformer Engineer. He received his BS in EE from Worcester Polytechnic Institute in 1966. He also graduated from GE's Advanced Engineering Course in 1970 and simultaneously received his MS in System Science from Brooklyn Polytechnic Institute. From 1966 to 2002, Phil held numerous design and engineering management assignments in the transformer businesses of GE, Cooper Power Systems and Square D Co in liquid filled, dry, and cast resin transformers of all power ratings and voltage classes. In 2001, Phil formed a power transformer consulting company, called HVOLT Inc. and since 2002 has managed HVOLT full time. He currently holds 15 US patents, is a Registered Professional Engineer in North Carolina, and is Technical Advisor (TA) to the US National Committee for IEC TC14 for Power Transformers. He has authored IEEE Transactions papers on the effects of DBPC in Transformer Oil, on Low Voltage surge phenomena in Distribution Transformer windings, and has Chaired NEMA's activities and was primary author of NEMA TP-1 Guide for Energy Efficiency for Distribution Transformers. He has chaired numerous IEEE and NEMA Working Groups and from 2001-2003 was Chairman of IEEE's Policy Development Coordinating Committee.