Electrical Contacts for Off-Circuit Tap Changers for Oil Immersed Transformers

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Off-Circuit tapchanger Contact "coking" is a problem that increasingly plagues modern liquid filled transformers. Hydrogen gas formation is one of the first indicators. Industrial loads are particularly susceptible, especially when heavy motors are involved. Mineral oil is known to have susceptibility, but increasingly, silicon oil is particularly more acute. Electrical contact oxidation is the fundamental catalyst to said coking, with tin platings the most severe. This report presents an analysis of the cause, as well as steps that can be taken to avoid the problem.

Index Terms--

I. INTRODUCTION

Off-Circuit electrical tapchangers for liquid filled transformers have a particularly onerous service duty. These devices are universally constructed of a number of stationary contacts, which are electrically connected to the tapped winding elements as well as spring-loaded moving contacts that respectively bridge the appropriate stationary contacts. In almost every tapchanger installation, the tapchanger is set on position during the initial installation and rarely ever changed again. Service duty consists of decades of desired stable operation with full robustness for long life, short circuits, thermal storms, and over-voltage conditions. Such stable conditions will only happen if the electrical contacts are composed of stable materials and operated within their capabilities.

Temperature and time are the two most damaging factors that affect electrical contact life. The recognition that tapchangers are set in position and rarely moved to a new position means that little or no abrasive wiping action will ever be present to clean the contact surfaces. Hence, corrosion must not be allowed to occur to any significant degree throughout the full 30-year life of the transformer. Even minor contact oxidation results in large resistance increases and is likely to result in thermal runaway.

Accelerated aging tests are useful in predicting life if the test parameters and physical models are representative of service conditions, time factors are linear, and numbers of samples are sufficiently large to be credible.

In this paper, contact behavior is analyzed, an accelerated aging test is described and data is presented. Tin plated contacts are shown to be particularly prone to thermal runaway. By the same token, silver plated contacts are shown to be especially stable. Functional life testing is presented as the best design tool to assure long robust life. This test is recommended as a "design required type test" for all Off-Circuit tapchangers.

Background

Silver plated copper contacts for Off-Circuit tapchangers have long been recognized for their stable behavior and widely applied for use in liquid filled transformers. Through their use, high current ratings with small physical size have been achieved. However, the 1970's and 1980's were noted as the high inflation years, marked by oil embargoes and runaway commodity price increases. Silver hording and price tampering was so severe that the industry was forced to seek alternatives for electrical contacts. Tin was generally the selected plating to replace silver. The most common application was tin plated copper on the moving contacts against plain copper stationary contacts.

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The 1990’s have had increasing reports of transformer gassing. Industrial transformers that energize motors and welders often see high transient loads. The first reports of pending problems describe large amounts of hydrogen gas formation. In later stages, small amounts of ethylene and ethane gases are also reported. Toward the end of life, contact runaway is accompanied by small amounts of acetylene gas formation, as contacts become extremely oxidized and arcing occurs to reestablish conduction. This arcing often results in large gas bubbles being formed with the subsequent likelihood of high voltage flashovers to ground. These ground faults quickly result in total winding breakdowns.

Seemingly all reported cases of contact problems are associated with moderate to heavy industrial applications. Broadly diversified light commercial applications have not reported problems. This load-sensitive characteristic suggests that a properly designed accelerated life test could predict future performance.

Contact Aging Phenomenon.

Electrical contacts rarely touch in more than a few spots no matter what their initial shape. This results in nonuniform current density throughout the cross-section, with highest concentration and most of the heating occurring at the point or points of contact. The hot spots are locations where oxidation is likely. As it occurs, an insulating film forms and spreads into the contact zone, constricting the area for current flow. This activity may result in rapidly increasing resistance and thermal runaway. Unstable materials can go through two or more orders of magnitude of resistance increase before arcing sets in to reestablish conduction.

As oxidation sets in and contact resistance rises, temperature at the point of contact (the super temperature) shows the sharpest increase. Super temperature is not easily measured but is readily calculated by measuring bulk temperature of the contacts and the millivolts drop across the contact pair. Mathematically, per the Ney Contact Manual, contact super temperature is relatable to bulk temperature and voltage differential as follows:

$$V^2 = 4*L*(T_c^2-T_b^2) \qquad (1)$$

Where V = the voltage drop in volts

L = the Lorenz constant, $2.4*10^{-8}$ volts^2/degree K^2 (2)

T_c =the super temperature increment over bulk rise of the contacts in degree Kelvin = 273 + degree C (3)

T_b = the bulk temperature of the contacts in degree Kelvin, or 273 + degree C (4)

Super temperature increments over bulk temperature are typically in the order of a few degrees at rated current for new contacts, but may deteriorate to hundreds of degrees for badly oxidized contacts, even to the point of melting. Oxidation of the contact surface acts to further constrict or restrict the current-carrying metallic path beyond the natural constriction of the two mating surfaces. As the insulating oxidation film spreads, contact voltage rises such that the effective resistance increases. Tiny discharges break down the insulating film to restore conducting paths. These small bursts of energy are similar in nature to high voltage partial discharges and act to dissociate the oil, liberating significant quantities of hydrogen gas. Continued aging results in more intense discharges and more elevated super temperatures. Small amounts of ethylene and ethane gases are the second effect that is observable from such operation. When contact super temperature exceeds 300 degrees C, oil cracking occurs with small amounts of methane, and carbon monoxide. Finally, when the surface is thickly film coated, arc energy to reinitiate conduction becomes intense, and acetylene gas is liberated. This condition is the most vulnerable time for the transformer because the rising gas bubble has very low dielectric strength and may allow flashovers and ground-faults to occur. If ground-faults develop, telescoped windings are almost inevitable.

Assumptions

The following assumptions are used to derive a model and suitable life test for Off-Circuit tapchangers in liquid-filled transformers:

1. A 200-amp tapchanger is modeled, as it is typical of many applications.
2. Transformer windings are designed for a rated winding rise of 65 C over outside ambient.
3. Mineral oil and silicon oil are fluids to be examined
4. Contacts are composed of copper but are plated as follows:

Moving Contact	**Stationary Contact**
Plain copper	Plain copper
Tin Plate	Plain copper
Silver Plate	Plain copper
Nickel Plate	Plain copper

5. 30-year expected life
6. 30-day functional life test
7. Arrhenius linear life relationship exists with half the life expectancy for each 10 degree C higher in contact peak (Super) temperature.

Analytical Model - The Contact Pair

Figure 1 below shows a typical contact pair. These contacts are represented by a pair of spheres of radius, R, that make single point contact at location, P. A spring of force F applies squeezing pressure to maintain contact.

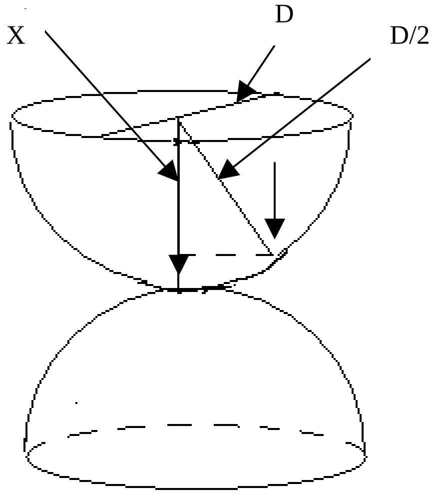


Figure 1 Equivalent Contact Shape

The general expression for resistance is as follows:

$$R = \rho * X/A \qquad (5)$$

Where ρ= the contact material resistivity (6)
Note for copper, $\rho = 0.679 * 10^{-6}$ ohm-inch at 20 C (7)
X = the length in inches (8)
A = the cross-sectional area in inches (9)

Here, *A* can be expressed in terms of depth *X* and the contact diameter *D* as:

$$A = \pi * ((D/2)^2 - X^2) \qquad (10)$$

Then the resistance between the two contacts can be expressed as:

$$R = 2\int \rho/\pi((D/2)^2 - X^2)dX \qquad (11)$$

The integral is carried over a pathlength, X from X=0 to X= D/2. However, it must be noted that a practical limit is less than D/2 from the realization that the contact point will not tolerate mechanical stress much in excess of 30,000 psi. For a 200 amp tapchanger and a 5 lb spring force, this would be reached with a contact area of about $166\mu\text{-in}^2$. For a contact of diameter, 0.312 inches, this translates to an upper length of 0.155843 inches. Hence, the integral reduces to the following:

$$R = -2\rho/(\pi D)\ln \left|(D/2-X)/(D/2+X)\right| \qquad (12)$$

Since D = 0.312 inches (13)

$$R = -2\rho/(\pi 0.312)\ln \left|(0.156-X)/(0.156+X)\right|_{X=0 \text{ to } X=0.155843} = 10.5\mu \text{ ohm at 20 C} \qquad (14)$$

This theoretical resistance would exist if there was no film of contaminant and all of the contact surface was making perfect contact. Practical experience for copper contacts shows an as-built resistance closer to 50 or 60 μ ohm suggesting that true contact is not achieved uniformly over the surface.

With theoretical and practical resistance established, we are ready to consider accelerating factors for life test.

The Thermal Environment

Tapchangers in liquid-filled transformers are normally mounted above the core clamp in or near the top oil, where the hottest spot of their contacts see a temperature that is the sum of several elements as follows:

Tsc = Ta +To/a + Tb/o + Ts/b (15)

Where

Tsc = Contact super temperature (16)
Ta = Ambient temperature outside of the transformer (17)
To/a = Oil rise over ambient (18)
Tb/a = Contact bulk conductor rise over oil temperature (19)
Ts/b = Contact super temperature rise over bulk temperature (20)

Most liquid-filled transformers in use today are insulated with thermally upgraded Kraft paper and are designed to operate at an average winding rise of 65 C over ambient in accordance with ANSI C57.12.00. Normal service conditions are defined assuming a 20 C ambient average temperature. Long life in the order of 30 years is typical of these transformers under normal loading and with the typical ambient of 20 C. Normal loading is less than rated load, and in fact is probably closer to 50% of nameplate as is documented in NEMA TP-1 efficiency standards. However, it would seem reasonable to require the tapchanger to have a 30-year average life expectancy under rated load conditions to provide long and reliable field performance. Hence, rated load and 30 year life are the chosen parameters to define a suitable functional life test. The following parameters are typical of modern transformers and form the basis for the thermal model:

Rated current	200 amp	(21)
Ta	20 C	(22)
To/a	55 C	(23)
Tb/o	17 C	(24)
Ts/b	8 C	(25)
Ts	100 C	(26)

Accelerating Relationship for Life Test

Assumption 5 desires a 30-year product life at rated load. Assumption 6 also desires a 30-day functional life test. If we further define the functional life test as 30 days of an “8-hr on period” of twice load current in a hot oil bath, and a “16 hr off-period” with no load and allow the oil bath to cool, then the total available aging on-hours are

Aging hours = 8hrs/day*30days = 240 hours (27)

Now, over a 30-year life, the total life-hours is:

Life hours = 30 years*8760 hours/yr = 262800 hours (28)

Hence, the accelerating factor from eq 27 and 28 is:

Accelerating factor = life-hrs/aging-hrs = 262800/240 = 1095 (29)

Derivation for Aging Temperature

From assumption 7, the 10 degree C arrhenius aging relationship results in half the life for each 10 degree C higher temperature. This relationship may be related to the aging factor as follows:

2^n = Aging Factor = 1095 (30)

n = ln(1095)/ln (2) = 10.09 or about 10 (31)

But 10 ten degree increments is 100 degree C (32)

Hence the life test needs to operate at 100 degree C higher than the temperature at rated load as described in equation (26). Therefore, combining equations (26) and (32), the life test needs to operate at or a little above 200 degree C to achieve the desired accelerating factor.

Selection of Life Test Parameters

Load Current: 2 times rated current (2XN), is a good choice, since it is representative of cold-load pickup for many types of transformer installations, and yet low enough that linear aging performance can be expected.

Oil Bath Temperature: The oil bath temperature is derived by subtracting the load related super temperature and bulk temperature rises from the selected aging temperature. Mathematically, the relationship is as follows:

$T_o = T_{aging} – Tb/o2xn-Ts/b2xn$ (33)
Here, To= oil temperature, the unknown (34)
T_{aging}= 200 C (35)
Tb/o2xn = 2^1.6 *Tb/o rated (36)

Where 2 is from 2XN load current
But Tb/o rated = 17 C from equation (24)

Therefore Tb/o2xn= 2^1.6*17 = 51.5 (37)

Now the super temperature increment at twice-rated current, Ts/b2XN is material dependent, but for clean unoxidized copper contacts in hot oil with 400-amp current is approximately 25 C.

Therefore, To = 200-51.5-25 = 123.5 C (38)

For the life tests, the authors chose a nominal oil bath temperature of 130 C.

Super temperature is calculated from a range of contact voltage drops for several oil and bulk temperature conditions in Table 1 to follow. From the data, one can see that 200 millivolts results in extremely high contact super temperatures, hovering on the melting temperature of the metals.

Selection of Criteria for Life Test

Since contact super temperature is the most important parameter that determines life performance, and since it is reflective of contact resistance, then it stands to reason that contact resistance should be the measure of stability. For all calculations, resistance is a derived parameter, calculated as follows:

R = V/I (39)

Where, R is the calculated contact resistance (40)
V is the voltage measured across the contact pair (41)
I is the measured current through the contacts (42)

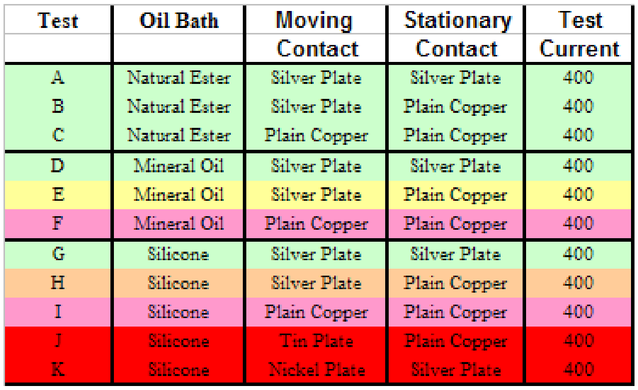
A contact pair will have been deemed successful if the following criteria are met

1. Resistance change after the 30-day test is less than 25%.
2. Resistance change has stabilized and is not continuing to rise.

The Functional Life Test Setup

Figure 2 below shows a test tank and a three-phase tapswitch. A single-phase power source supplies current to the switch. All three phases of the switch are connected in series, such that 6 contact-pairs are on-test simultaneously. Thermocouples are embedded in the stationary contacts of each switch, close to the point of contact. Voltage probes are also located close to the point of contact for each contact pair. The tank has a heater that is thermo-off-circuit controlled to within 2 degrees, plus and minus of the set point.

Combinations OF Test Samples



Test	Oil Bath	Moving Contact	Stationary Contact	Test Current
A	Natural Ester	Silver Plate	Silver Plate	400
B	Natural Ester	Silver Plate	Plain Copper	400
C	Natural Ester	Plain Copper	Plain Copper	400
D	Mineral Oil	Silver Plate	Silver Plate	400
E	Mineral Oil	Silver Plate	Plain Copper	400
F	Mineral Oil	Plain Copper	Plain Copper	400
G	Silicone	Silver Plate	Silver Plate	400
H	Silicone	Silver Plate	Plain Copper	400
I	Silicone	Plain Copper	Plain Copper	400
J	Silicone	Tin Plate	Plain Copper	400
K	Silicone	Nickel Plate	Silver Plate	400

Conclusions

1. The most stable fluid tested was Natural Ester. It was stable with all contacts tested. Natural ester fluid has a unique capability of absorbing large quantities of water and reacting with it. With water out of the fluid, contact oxidation is minimized. The result is that it remained stable with all contact pairs tested.
2. Mineral oil is moderately stable. However, it is not capable of absorbing much moisture and does not readily react with it, resulting in contact oxidation for all but the most stable types of contacts.
3. Silicone is the least stable fluid. It readily holds water and oxygen, and does not react with either, resulting in the greatest exposure of the contact metals to oxidation. Only the most stable contacts work in silicone.
4. Silver-Plated copper on both the moving and stationary contacts is the best combination of contact materials. These contacts had almost no resistance change from the "new" value. In fact, the exceptional stability suggests that they would be capable of even higher current ratings. This is attributable to the fact that silver-oxides have the exceptional capability to revert back to the parent metal when at elevated temperatures, more specifically, greater than 300ºC. However, the silver-silver combination may only be useable on tapchangers with rotating contacts because sliding contacts can readily cold-weld, preventing a successful tap-change. Some contact shapes and hardness variations with sliding contacts may not cold-weld, but this will take some experimental work to verify.
5. Silver-Plated copper on the moving contact against plain copper stationary contacts was the second most stable combination. This contact-pair still has the ability to form copper-oxides, but silver both provides low initial resistance for low super temperature and migrates into the copper to help maintain a low resistance over time. Furthermore, silver-plate on only the moving contact places dissimilar metals in contact such that cold-welding does not occur for sliding contacts.
6. Tin plated contacts were a poor performer. With a conductivity of 15%, tin places a high resistance film in series with the plain copper contact to cause super-temperatures to run considerably higher than copper-copper or silver plated contacts. The quick thermal runaway that was observed with tin plating relates directly with field experience.
7. Nickel plate was the worst performer, with performance similar to tin but at a faster pace.

Discussion of Results

One obvious result of life testing was the understanding of the relative performance of the various contact materials. This knowledge is especially useful when designing new applications. However, an equally important consideration revolves around what to do about existing installations. If left unchecked, copper-tin contact applications that are heavily loaded could rapidly oxidize and deteriorate. For such applications, a routine exercise program could avoid messy changeouts. The purpose of the exercise program would be to sufficiently rotate the tapchanger such that heavily oxidized contact points are scrubbed clean. This should be possible by simply rotating the tapchanger through the range of extreme positions after which it may be returned to the original setting. The frequency for exercise will vary directly, with the load current to which the tapchanger is exposed. Rolling mills for steel plants, having large starting currents will have the most severe duty and will require the most frequent exercise programs. Conversely, light commercial applications may never need attention. Gas in oil analysis will be a pretty good predictor of the frequency for such exercise programs. If hydrogen gas evolution is low or non-existent, no exercise will be needed. If hydrogen gas is of the order of 200 ppm or higher, then exercise yearly or every six months may be needed. Some experimentation will help sort this out.

Future Direction

The life test methods that were used in this experiment are an excellent means of determining contact stability. IEEE C57.131 currently describes On-Load Tapchangers. Tapchangers for de-energized operation should be added to describe the contact stability issues and to add type test requirements for stable contact life. Once this is completed, reference material will be available to tapchanger manufacturers that should help to improve their respective product designs. In addition, the author plans to encourage IEC TC 14 to adopt similar methodology for the international market.

References

Holm, R. - Electrical Contacts Theory and Application, Fourth Edition (1967). Reprinted by Permission of Springer-Verlag, New York

NEMA TP-1 (1996) National Electrical Manufacturers Association

Pitney, Kenneth E. Ney Contact Manual, (1973) The J.M. Ney Company

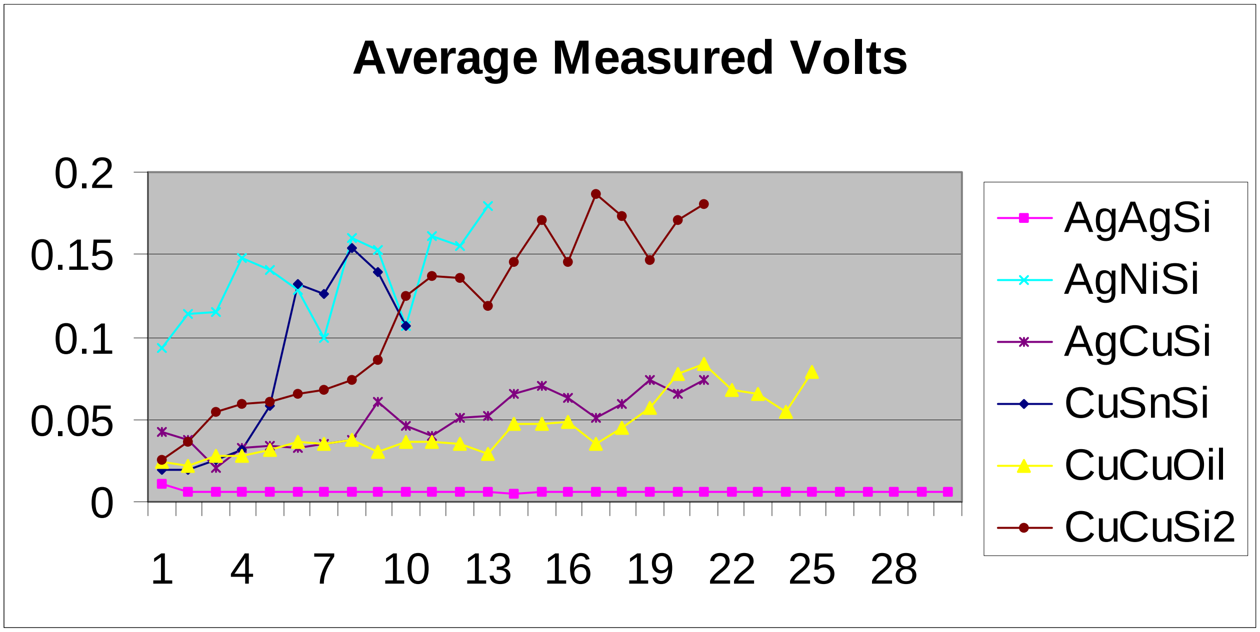
TABLE 1 Electrical Contact Super Temperature

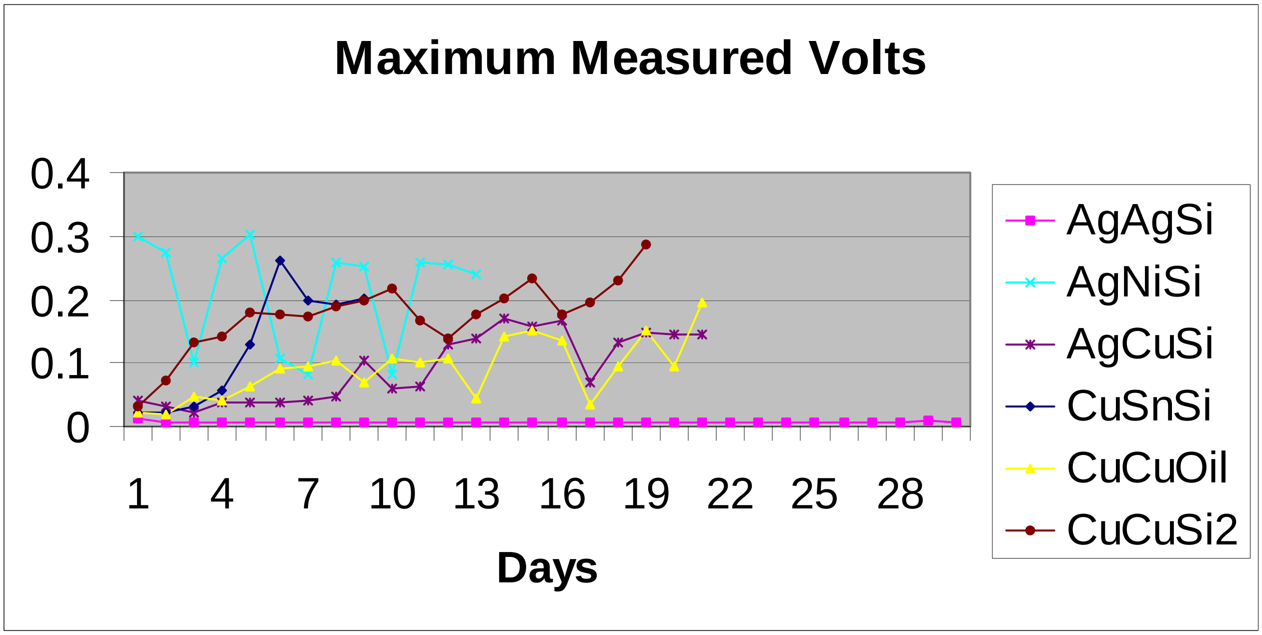
Super Temp = $\mathrm{SQRT}((Ta+To+Tb+273)^{2}+((A3*0.001)^{2})/(4*2.4*10^{-8}))-273$

Ta = Ambient	20	20	20	20
To = Oil Rise	50	110	110	110
Tb = Bulk Rise	20	40	60	20
Bulk Temp	90	170	190	150

Millivolts	**Super Rise**	**Super Temp**	**Super Rise**	**Super Temp**	**Super Rise**	**Super Temp**	**Super Rise**	**Super Temp**	**Condition**
10	1.4	91.4	1.2	171.2	1.1	191.1	1.2	151.2	Good
20	5.7	95.7	4.7	174.7	4.5	194.5	4.9	154.9	
30	12.7	102.7	10.5	180.5	10.0	200.0	10.9	160.9	
40	22.3	112.3	18.4	188.4	17.7	207.7	19.3	169.3	Marginal
50	34.3	124.3	28.5	198.5	27.3	217.3	29.7	179.7	
60	48.4	138.4	40.5	210.5	38.9	228.9	42.2	192.2	
70	64.6	154.6	54.3	224.3	52.2	242.2	56.6	206.6	Unstable
80	82.5	172.5	69.8	239.8	67.1	257.1	72.6	222.6	
90	101.9	191.9	86.7	256.7	83.6	273.6	90.1	240.1	
100	122.7	212.7	105.1	275.1	101.4	291.4	109.1	259.1	
110	144.8	234.8	124.7	294.7	120.4	310.4	129.2	279.2	Thermal Run-A-Way
120	167.8	257.8	145.4	315.4	140.6	330.6	150.5	300.5	
130	191.8	281.8	167.2	337.2	161.8	351.8	172.8	322.8	
140	216.6	306.6	189.8	359.8	183.9	373.9	195.9	345.9	
150	242.1	332.1	213.2	383.2	206.9	396.9	219.9	369.9	
160	268.2	358.2	237.4	407.4	230.6	420.6	244.5	394.5	
170	294.9	384.9	262.2	432.2	254.9	444.9	269.8	419.8	
180	322.0	412.0	287.6	457.6	279.9	469.9	295.6	445.6	
190	349.6	439.6	313.5	483.5	305.4	495.4	322.0	472.0	
200	377.6	467.6	339.9	509.9	331.4	521.4	348.7	498.7	

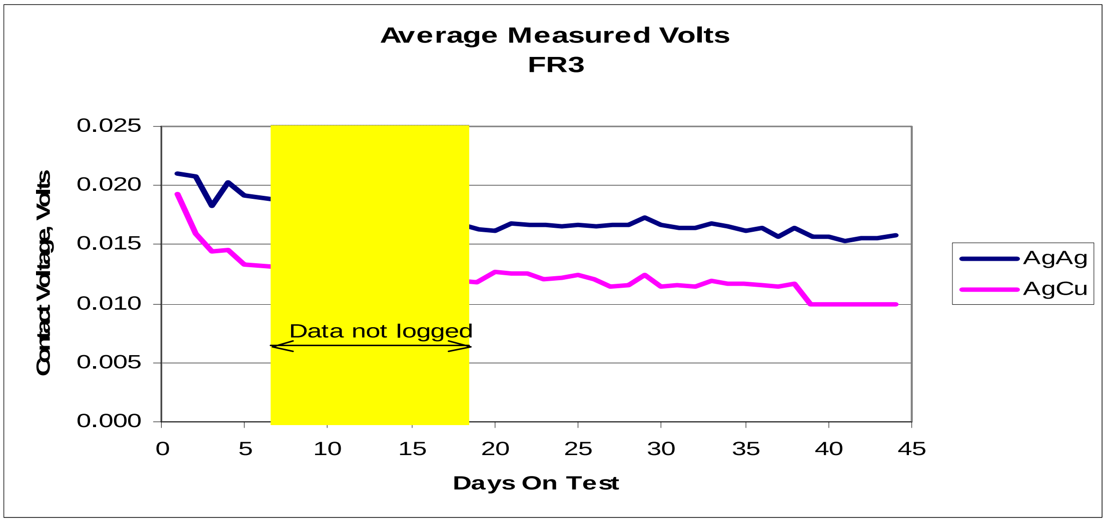
Results of Life Tests: Part 1. Voltage across contact pairs

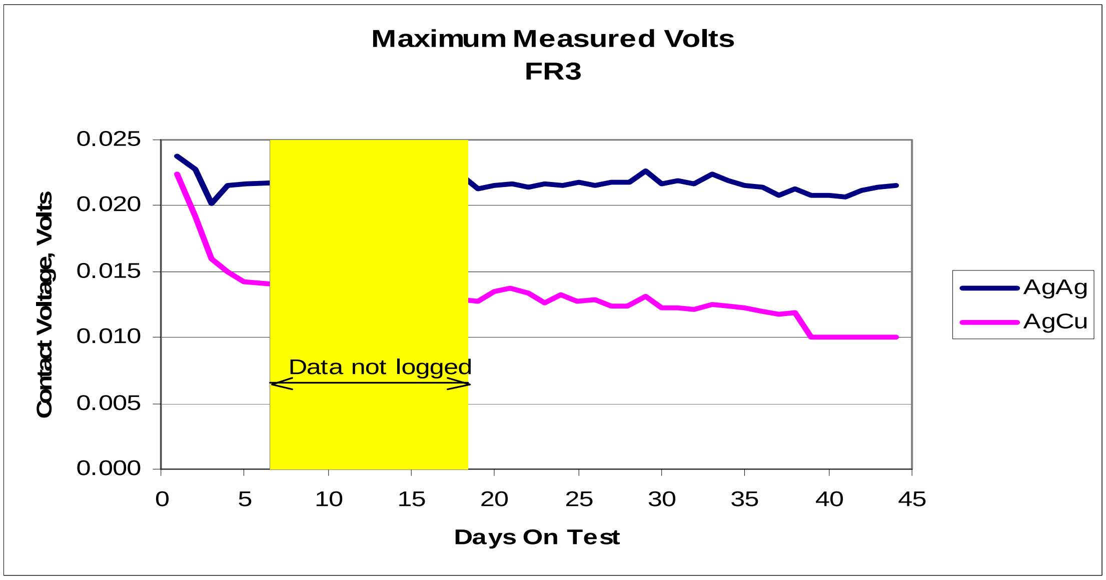


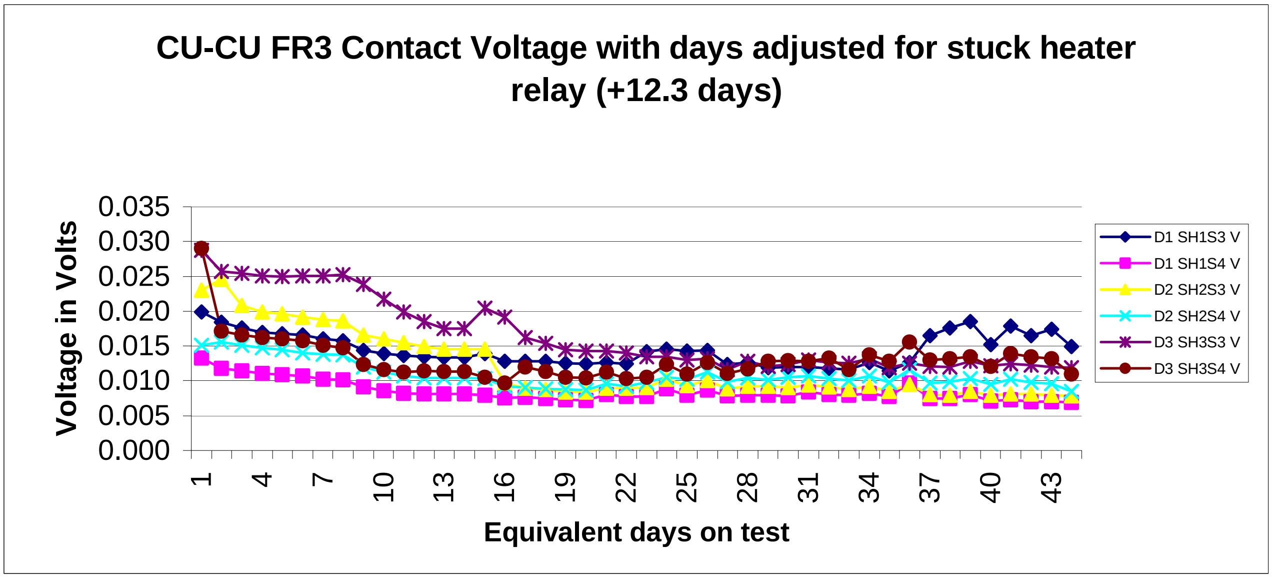


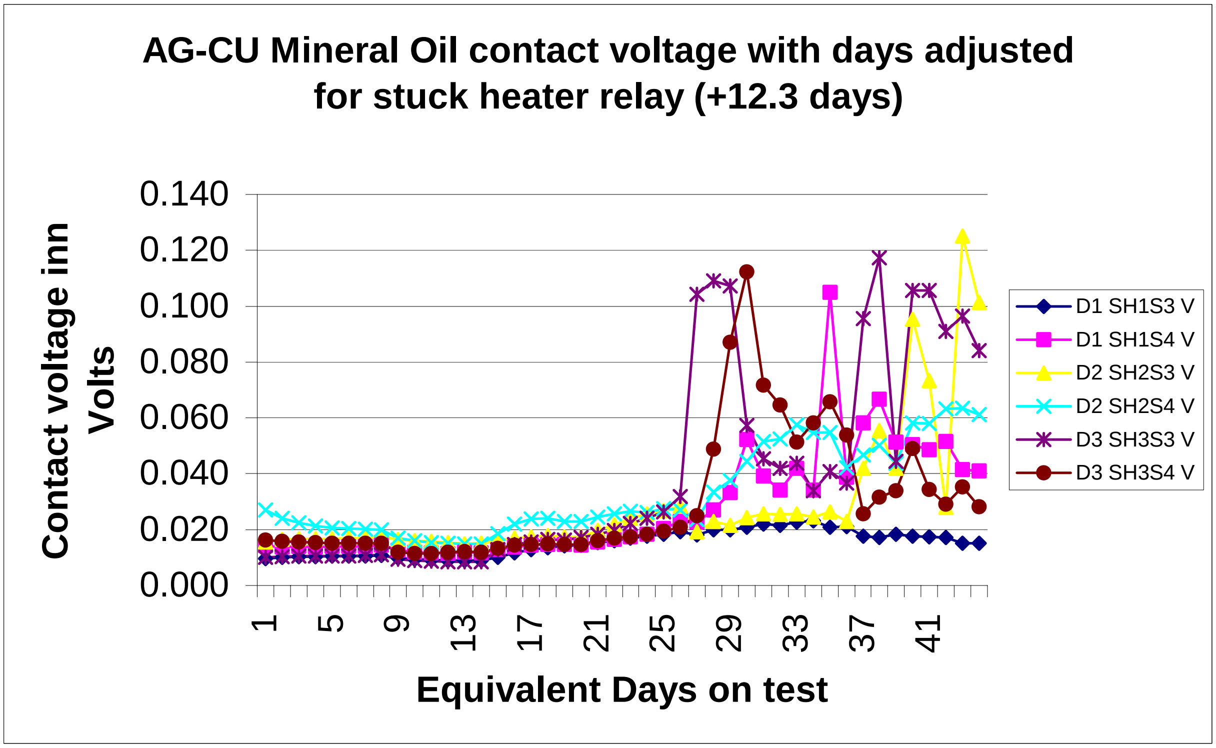
Voltage is measured between the two mating contacts under test.

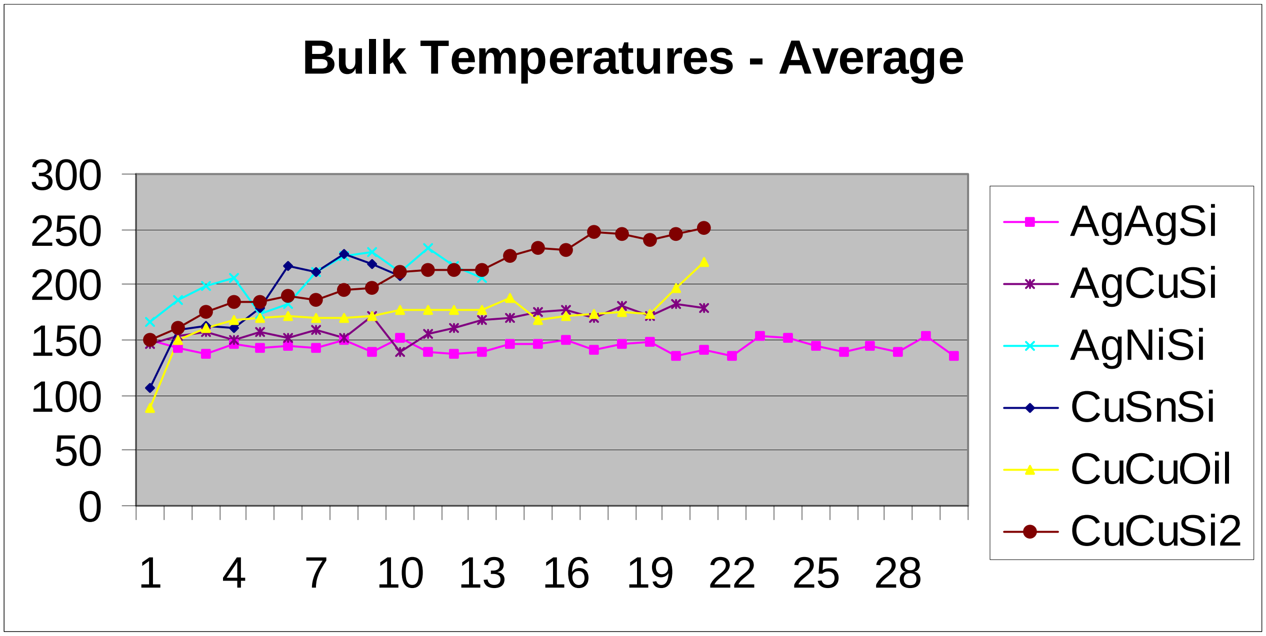
Work with Natural Ester FR3 Fluid:

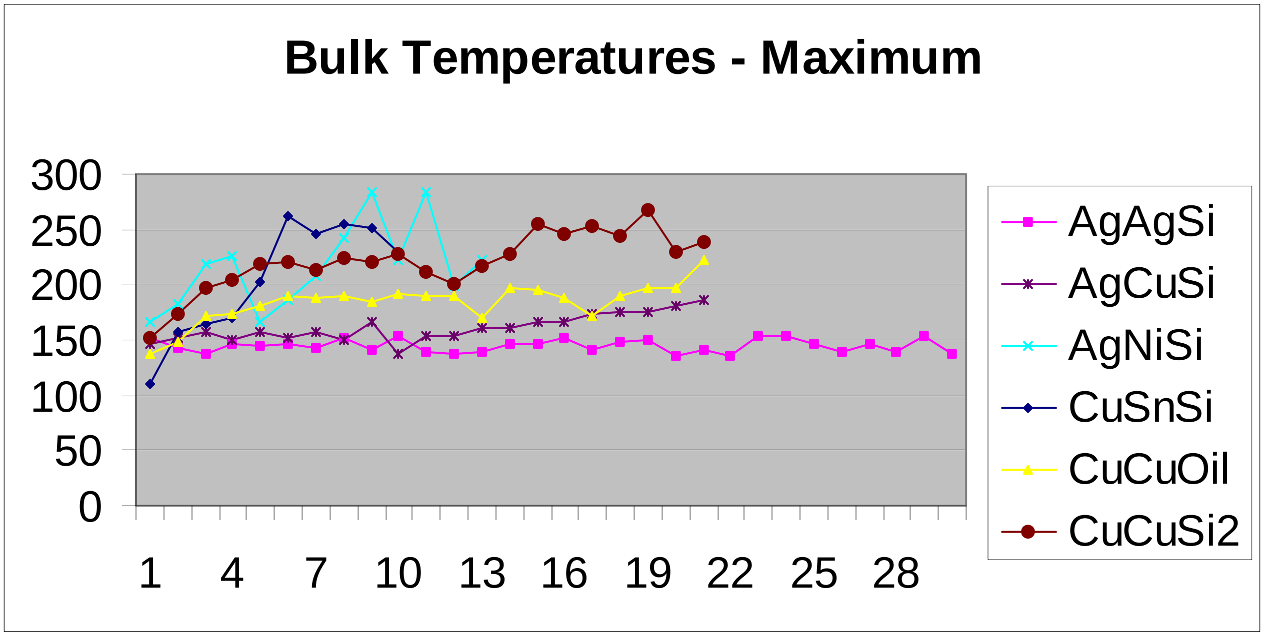




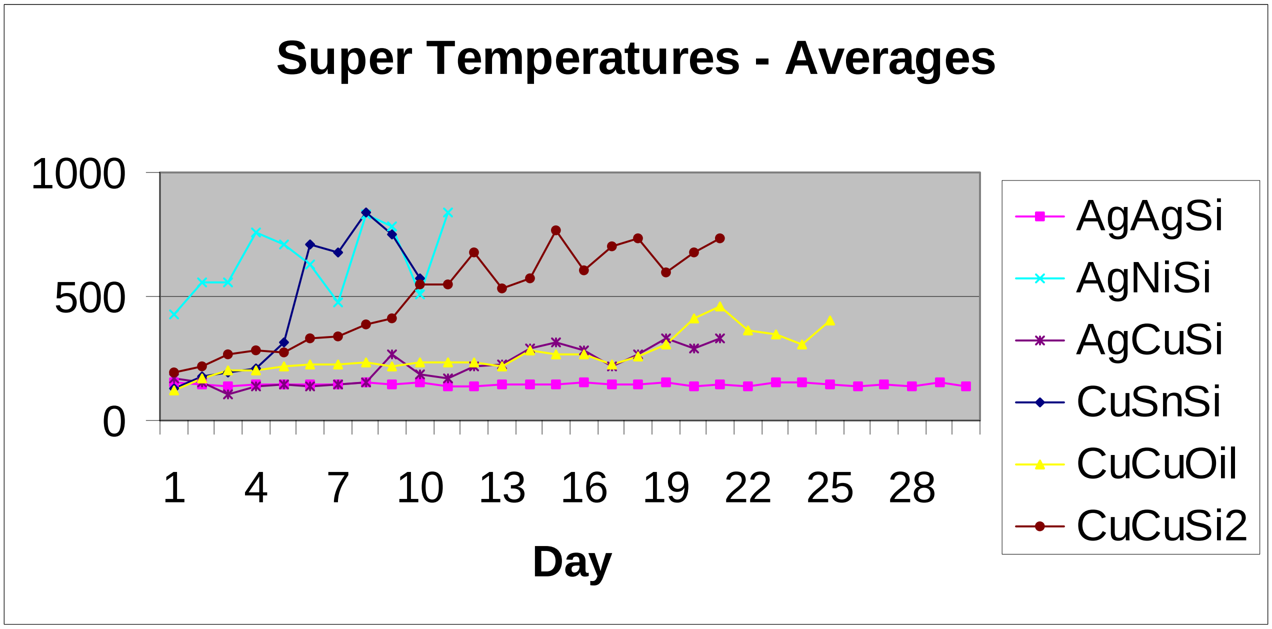

CU-CU FR3 Contact Voltage with days adjusted for stuck heater relay (+12.3 days)
Voltage in Volts
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
Equivalent days on test
D1 SH1S3 V
D1 SH1S4 V
D2 SH2S3 V
D2 SH2S4 V
D3 SH3S3 V
D3 SH3S4 V

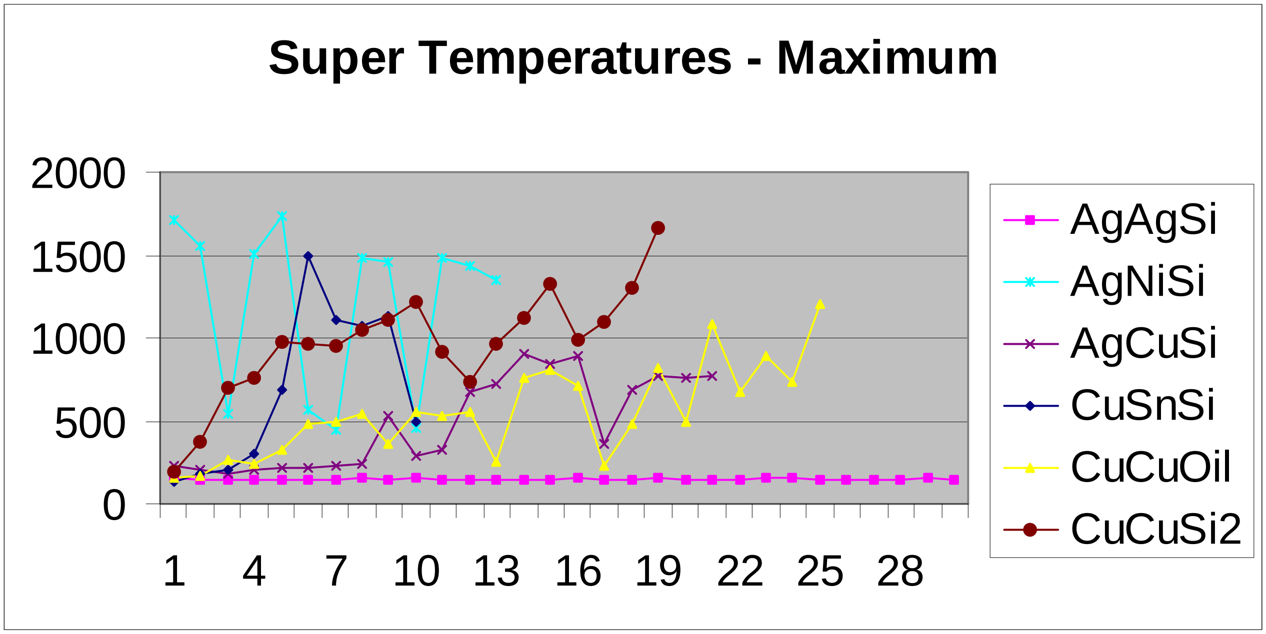

AG-CU Mineral Oil contact voltage with days adjusted for stuck heater relay (+12.3 days)
Contact voltage inn Volts
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
1
5
9
13
17
21
25
29
33
37
41
Equivalent Days on test
D1 SH1S3 V
D1 SH1S4 V
D2 SH2S3 V
D2 SH2S4 V
D3 SH3S3 V
D3 SH3S4 V





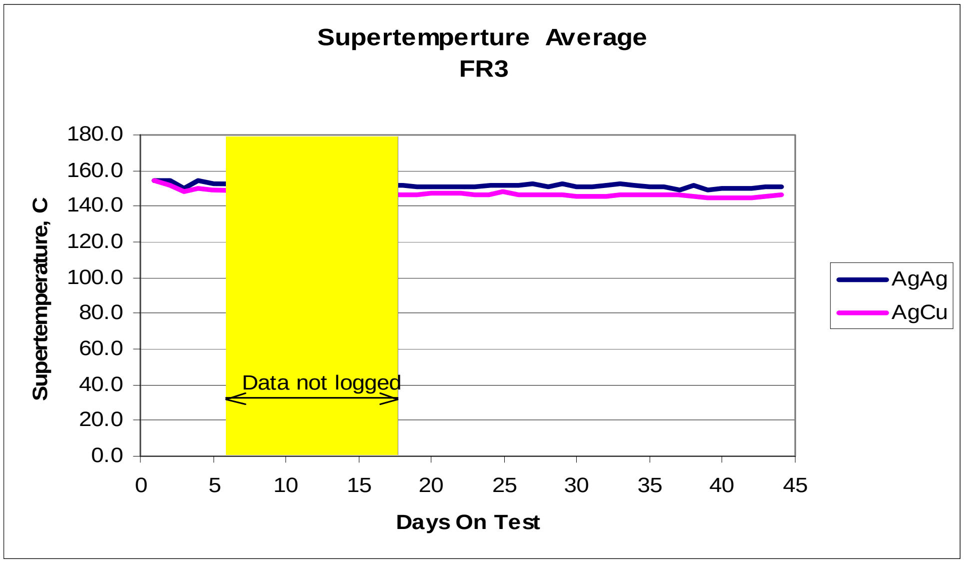
Bulk temperature in degrees C is the average temperature of the two mating contacts under test measured by thermocouple.

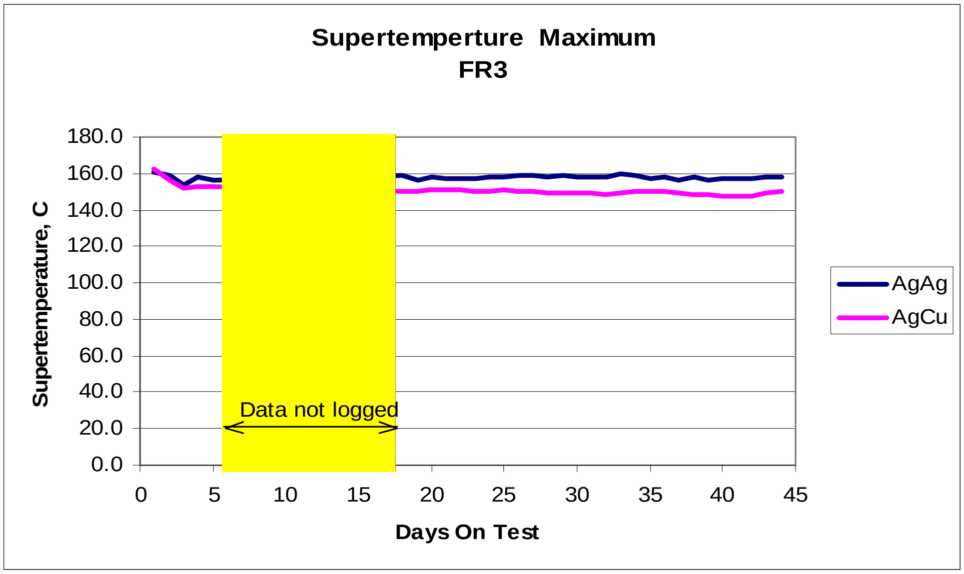


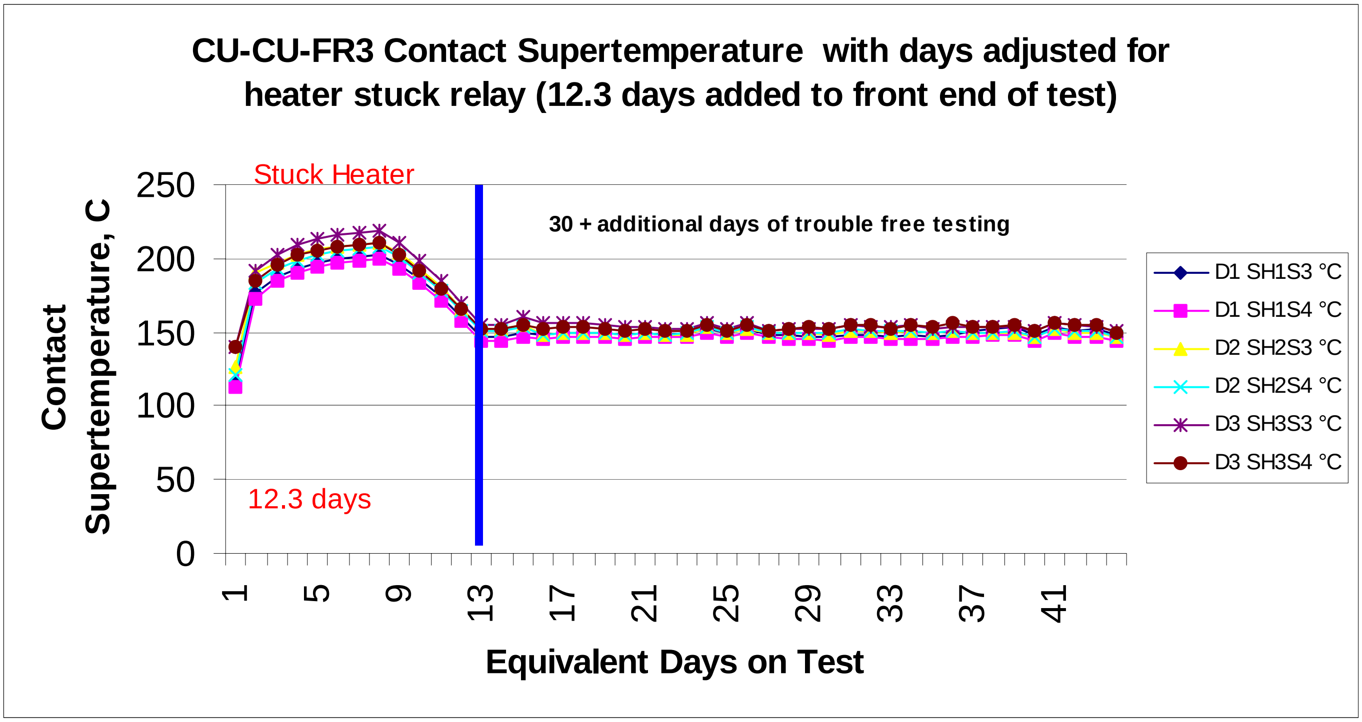


Super temperature is a calculated parameter in degrees C and refers to the temperature of the point of contact of the two mating contacts under test.

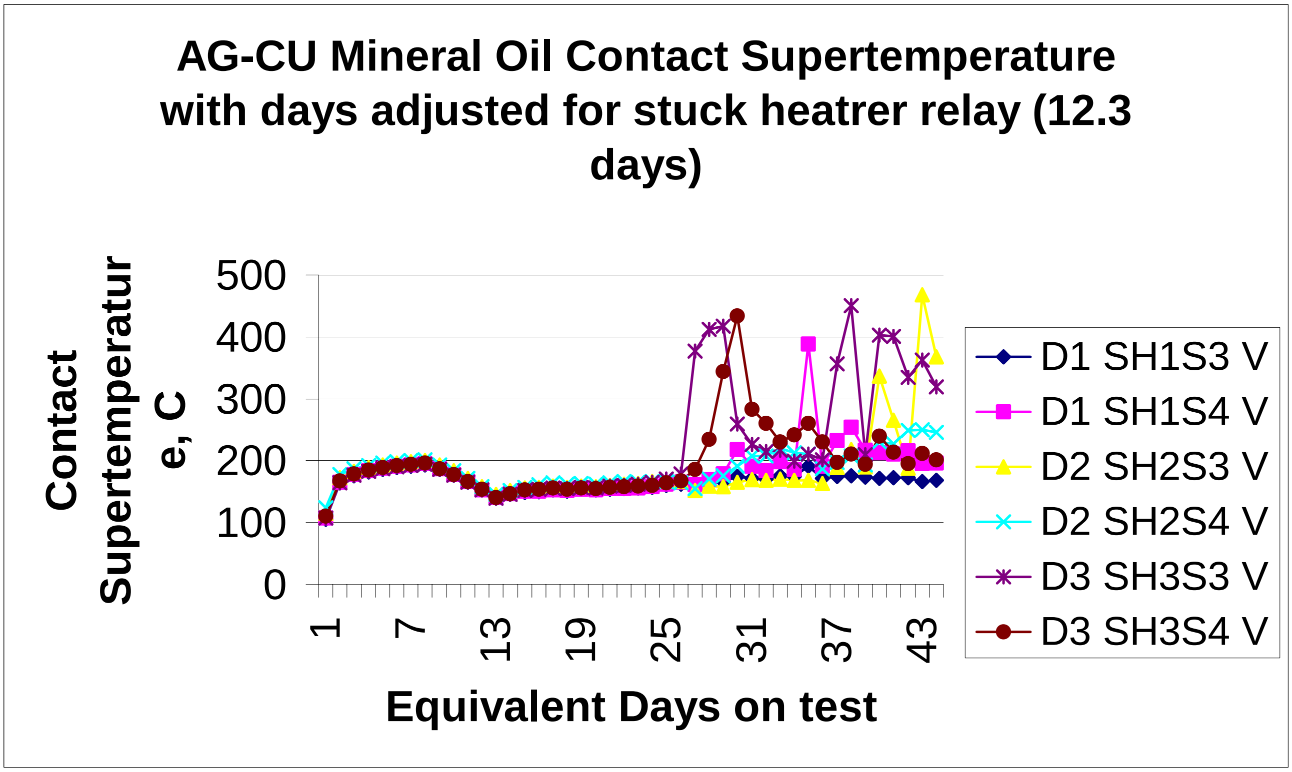
Super temperature for Natural Ester FR3 contacts is shown below:





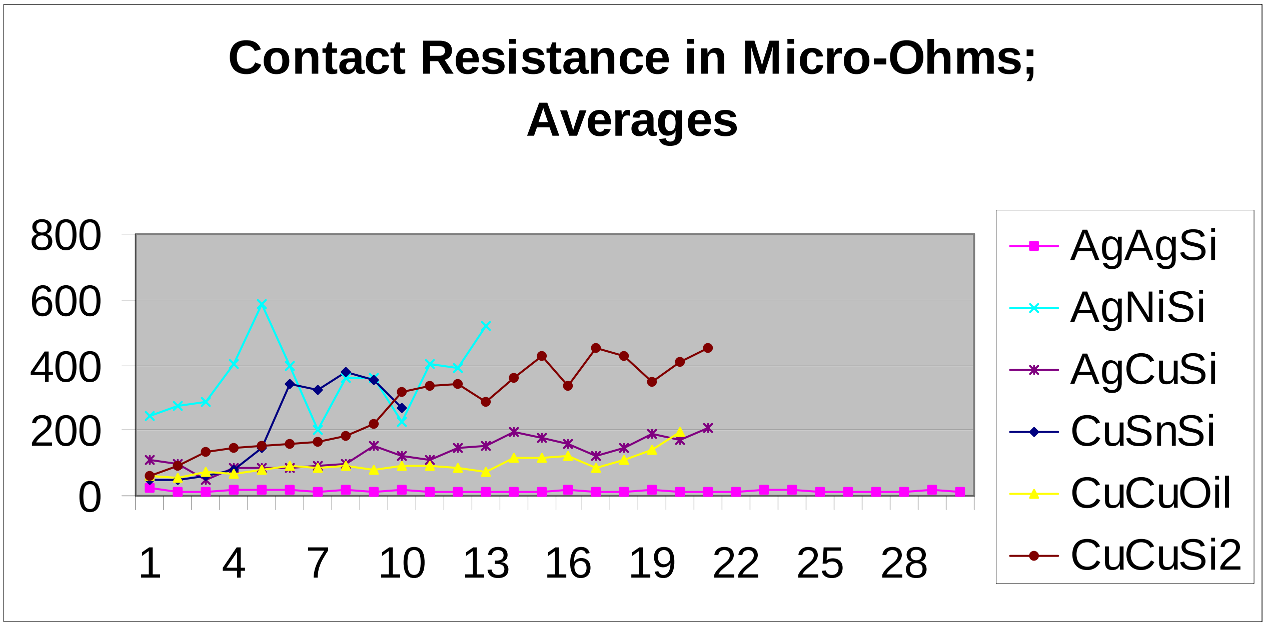


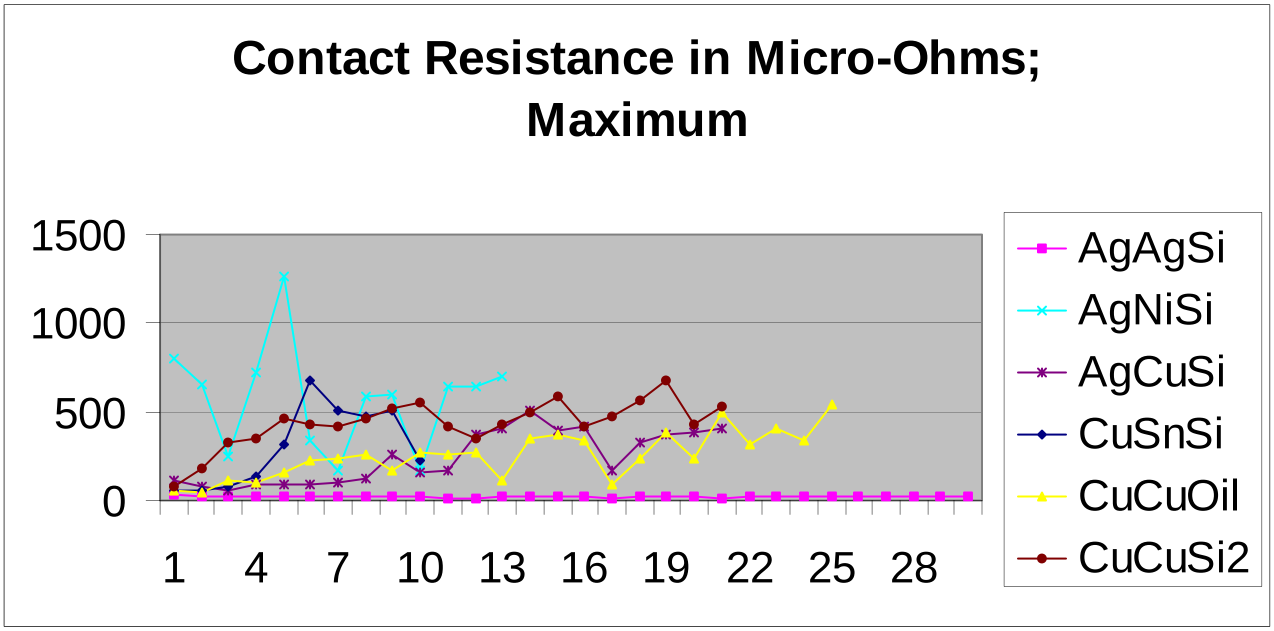
CU-CU-FR3 Contact Supertemperature with days adjusted for heater stuck relay (12.3 days added to front end of test)



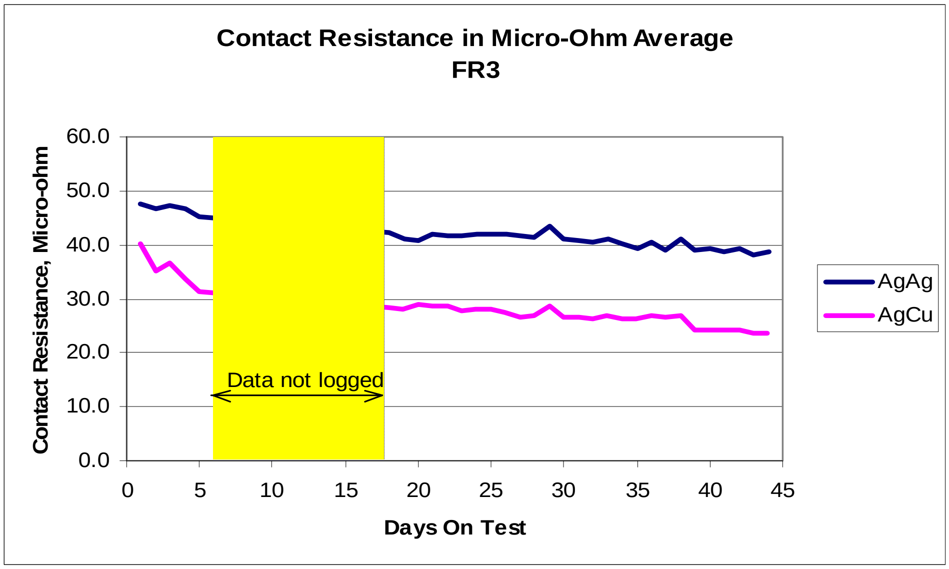
AG-CU Mineral Oil Contact Supertemperature with days adjusted for stuck heatrer relay (12.3 days)

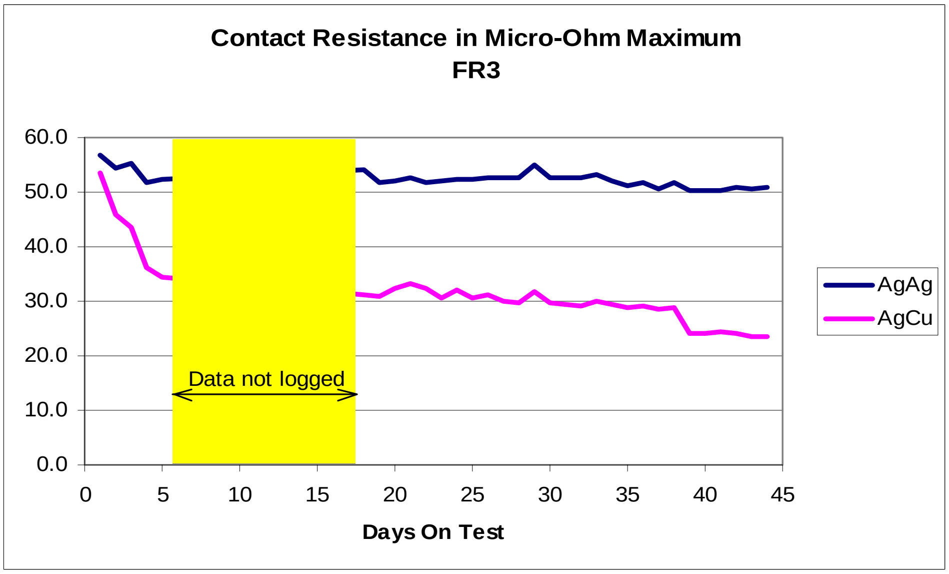
Contact resistance is measured by dividing the contact voltage under test by the test current.

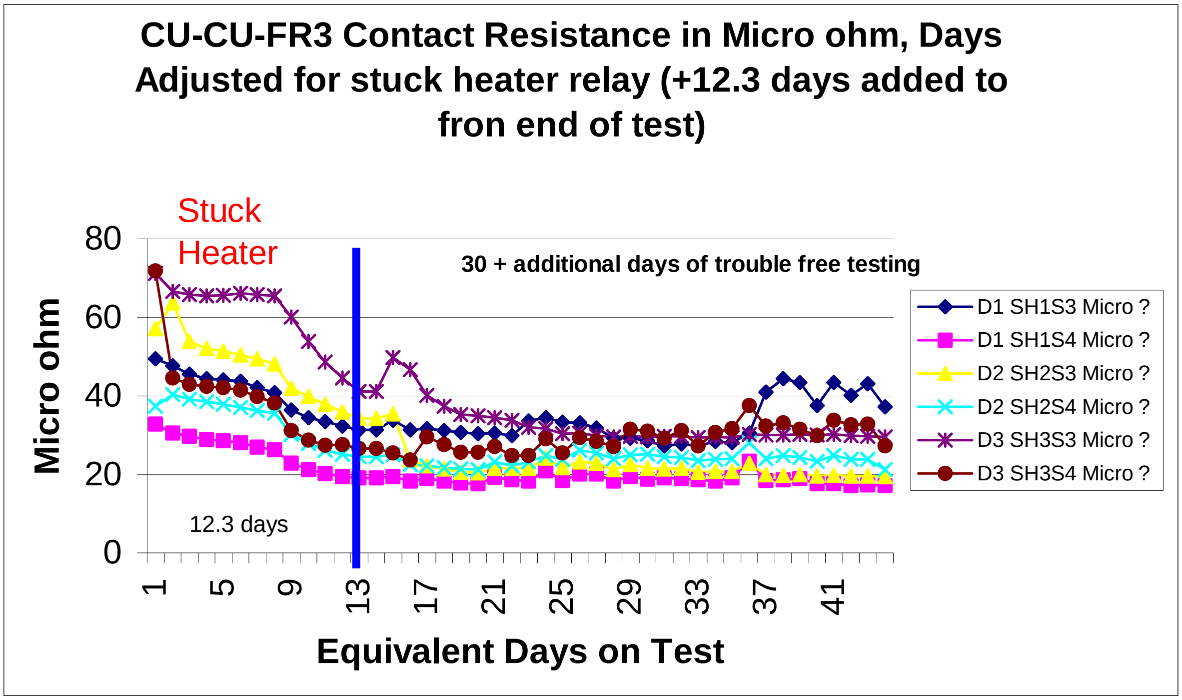




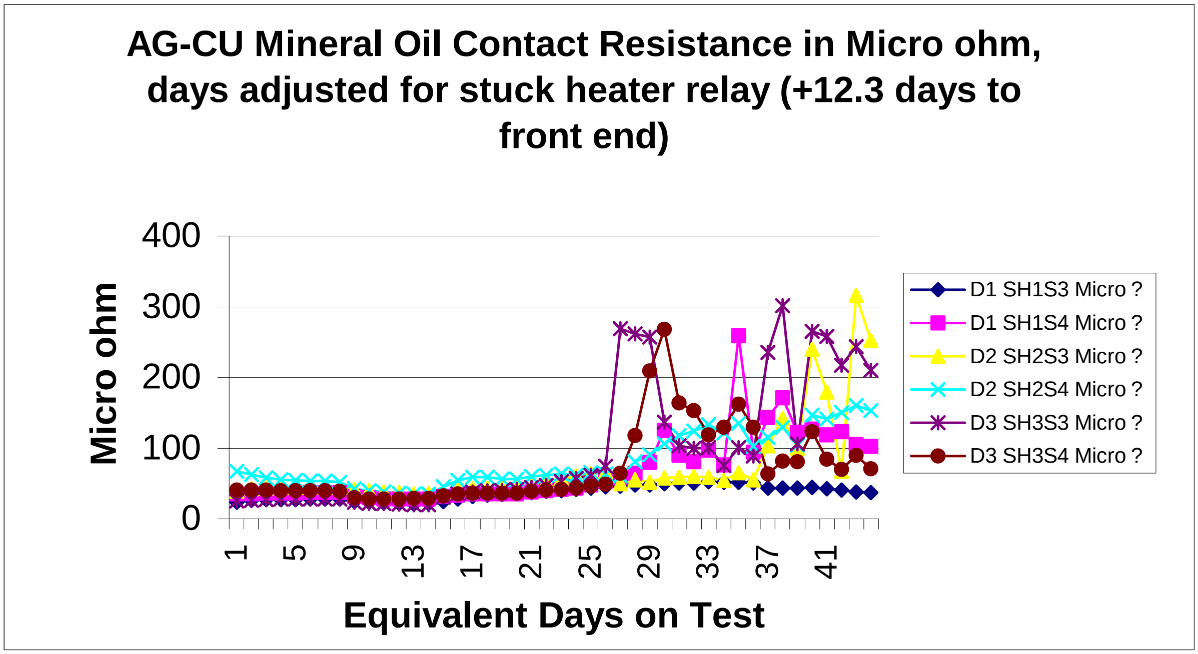
Contact resistance for Natural Ester FR3 contact pairs is shown below:







CU-CU-FR3 Contact Resistance in Micro ohm, Days Adjusted for stuck heater relay (+12.3 days added to fron end of test)



AG-CU Mineral Oil Contact Resistance in Micro ohm, days adjusted for stuck heater relay (+12.3 days to front end)