

# Oil Soluble Contaminants from Materials Used in Electrical Equipment

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# OIL SOLUBLE CONTAMINANTS FROM MATERIALS USED IN ELECTRICAL EQUIPMENT

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## Abstract

Elevated oil power factor has been observed in a small number of relatively young power transformers in recent years. This phenomenon is characterized by an initial low power factor that increases over a brief 1-3 years for some transformers and then returns to normal over the next several years. While oil power factor is dynamically changing, critical oil properties like dielectric strength and interfacial tension remain largely unchanged. Investigation of this power factor phenomenon has provided a new insight into the dynamics of oil aging in electrical equipment. It has been assumed that the materials used in electrical equipment are stable on exposure to oil over time. This is a very reasonable assumption based on the fact that these materials exhibit very little change over years of service in the field. New materials are tested in accordance with ASTM D3455-95, which has been assumed to be a reasonable accelerated aging test. However, recent transformer tests have suggested that there are other considerations. Residual chemical compounds in some materials are extracted by the oil without significantly changing the physical properties of the materials but that do affect the electrical performance of the system as a whole. This is the first paper by the authors that documents the unexpected impact, on the performance of electrical equipment, of subtle chemical interactions between the oil and other materials present. This paper documents the presence of extractable contaminants in transformer components and some of the conditions that result in the extraction of these contaminants from the components into the oil.

## Introduction

The design of electrical power equipment is a mature technology. The performance of specific equipment has been confidently predicted based on established mathematical and engineering models. These theoretical models assume that we understand the properties of the materials used in these systems and that these properties don't significantly modify the physical model upon which equipment designs rely. It has been further assumed that the oil, though it changes with time, will not affect the performance of the equipment. These assumptions are now being challenged based on test results from the field and laboratory tests of materials that are consistent with those field tests. Some materials are now found to be dynamic and interactive and some chemical interactions are in fact, found to impact equipment performance.

In the early Fall of 2004 field data from a utility in the southern US indicated a slight unexpected increase in the winding power factor tests for a transformer that had been in service for only a few years. When the oil was tested all results were nominal (interfacial surface tension with respect to water (D971), dissipation factor (D924), acid acceptance (D974), dielectric breakdown voltage (D877), dielectric constant (D924), and color (D1500)) except the power factor at 100° Celsius. The power factor at 100° Celsius was 16%, while the preferred value would be less than 1%. This discovery initiated the testing of the oil in a large number of relatively new transformers in order to assess the frequency of this phenomenon. A small number of other transformers were found to have similar power factors, nearly all in the southern half of the US. One utility had noticed this phenomenon in two of its newer transformers and had run the oil through Fuller's Earth. The power factor of the oil dropped to less than 1% but a year later it was climbing again. The investigation that followed demonstrated that this was a relatively short term phenomenon of 1 to 3 years that occurred under certain conditions of external and internal temperature for the transformer in question. The oil then dropped back below 1%. In the process of this investigation a new perspective was gained regarding the interaction between the oil and other materials in the equipment.

## Observations

### *Infrared Analysis*

Fuller's Earth was known to remove the responsible agent from the high power factor oil. In the laboratory the equivalent to Fuller's Earth is silica gel. A silica gel column was prepared and some of the high power factor oils were passed through the silica. The silica was washed with hexane to remove residual oil. The silica was then flushed with methylene chloride and acetone. The solvent was evaporated and the residue was analyzed using infrared spectrophotometry. Figure #1 (attached) shows the resulting spectra for three of the high power factor oils. All three had the same combination of chemical compounds as shown by the similarity of the spectra.

A methylene chloride extract of two cured paints commonly used in electrical equipment was then examined using infrared analysis. The result is shown in Figure #2. Many of the peaks seen in Figure #1 were also present in these spectra. The difference in preparation was important. Some of the compounds absorbed by the silica were not extracted by the methylene chloride and acetone rinse. When a copper plate was set in with one of the high power factor oils and then rinsed with hexane, a film remained on the copper. This film was removed by the methylene chloride. Its spectrum was compared to one of the paint



Photograph #1: MicroCell Used to Test Oils for Film-Forming Compounds

The cell is about an inch and a quarter in diameter and designed to fit on the stage of a microscope. The center bar is a copper plated heating element on which the film is deposited as the oil flows through the cell.

extracts and found to match almost identically (see Figure #3). There was a good reason to examine the film that formed on the copper. It was discovered early in the investigation that these high power factor oils quickly cast a film on heated copper and that after a three hour exposure to a copper rod heated to 120° Celsius the power factor dropped to about 1%. The agent causing the high power factor was in the film on the copper. It was also trapped by the silica but it could not be completely recovered from the silica by methylene chloride and acetone. This tendency to cast films on copper was discovered using a device called a MicroCell. The MicroCell has become a way of rapidly concentrating foreign compounds from oil used in electrical equipment.

**MicroCell Testing**

Two of the authors (Crutcher and Warner) had been working with TJH2b Analytical Associates Inc. on an EPRI supported research project<sup>1</sup> focused on the formation of films on copper surfaces in load tap changers. In the course of this research a special test called the MicroCell (see Photograph 1) test<sup>2</sup> was developed for detecting the presence of the film-producing chemicals. When this test was applied to one of the high power factor oils, an unusual film was quickly formed on the heated copper element. At low temperatures the spectrum of the films formed from the high power factor oil matched that from the methylene chloride extract of the cured paint. An examination was made of a number of oils from load tap changers that generated films in this apparatus. Only one of the eight oils tested matched the paint spectrum (see Figure #4). That indicated that this material was not only seen in transformers but could also be found in oil from load tap changers. It also indicated that other materials were more common in the oil that also formed films but were not associated with high power factor. The LTC oil samples were from a number of different types of LTC’s and represented multiple manufacturers.

The striking similarity of the spectra seen in Figures #3 and #4 suggests a cause and effect relationship between the extractable compounds from some paints, elevated power factor, and film formation on copper.

**Paint Extraction Tests**

A series of tests was then conducted using oil from a three year old transformer that had a low power factor at 100° Celsius of 0.9%. Fully cured paint samples were added to both new transformer oil and to the aged oil. The samples in the new oil were tested per ASTM D3455-95. The paint panels in the aged oil were tested at 80° Celsius, 20° Celsius lower than required by ASTM D3455-95, and for 120 hours rather than the 164 hours prescribed by ASTM D3455-95. The results are shown in Table #1. Paints #1 and #2 were the two paints extracted with methylene chloride whose infrared spectra are shown in Figure #2. As can be seen, the paints easily pass

Sample	New Oil PF	Aged Oil PF
Paint #1	No Change	+1.2
Paint #2	No Change	+0.2
Paint #3	+0.1	+0.6

Table #1: Change in Power Factor at 100 C

The new oil exposure was for 164 hours in oil at 100° Celsius (ASTM D3455-95). The Aged oil test was for about 120 hours at 80° Celsius.

the ASTM D3455-95 test but are extracted by the aged oil under much milder environmental conditions of both a shorter time and a lower temperature.

The aged oils exposed to these paints were exposed to heated copper and the resulting film on the copper was examined using infrared spectrophotometry. The infrared spectrum was nearly identical to the methylene chloride extract from the cured paint (see Figure #3). The collection of the film also dropped the power factor of the oil back to its value prior to exposure to the cured paint.

It is evident from these tests that the ability of aged oil to withdraw chemicals from cured paint is comparable to that of methylene chloride. The aged oil may not be nearly as efficient. A drop of aged oil on the cured paint would not produce the same results as seen with methylene chloride, but at elevated temperature, 80° Celsius, for five days, the same chemicals are extracted in the same proportion.

## Discussion

The oil in electrical systems has long been known to be chemically very complex. An accommodation of this fact can be found in the way transformer oil is specified per ASTM D3487. There is no precise chemical definition nor any chemical constraints on the oil other than limiting the amount of “reactive sulfur”. The oil is controlled by its performance in specific electrical and physical environments. The interfacial surface tension with respect to water (D971), dissipation factor (D924), acid acceptance (D974), dielectric breakdown voltage (D877 and D1816), dielectric constant (D924), and color (D1500) are all tests specified to monitor changes in the oil with exposure to the equipment and the operational environment over time. These tests provide all the information required to know if the oil will perform adequately. All of these values degrade with time, generally at different rates. Degraded properties can often be recovered by drying, filtering, or treating with Fuller’s Earth. Each of these operations removes chemical entities and/or particles from the oil.

The change in transformer oil over time has always been acknowledged as a chemical process but the nature of the process is very poorly understood and has been assumed to involve the composition of the oil alone as acted upon by the heat, copper catalysis, moisture, and oxygen typical of the operating environment. In load tap changers and oil filled circuit breakers arcing is another process that has added complexity to the composition of the oil. Oxidation, polymerization, and “reverse refining” are terms that have been applied to the composite process. These are different aspects of the aging process that have been viewed as largely beyond our control due to the chaotic and complex nature of the reactions involved. Recent research funded by EPRI<sup>3</sup> and independently by Kuhlman Electric Corporation<sup>4</sup> and TJH2b<sup>5</sup> has begun to open a new window into the mystery of “aging” oil in electrical equipment. Important additional parts of that process seem to be related to **solubility, solubilization, and solvolysis**<sup>6,7,8,9</sup>.

**Solubility** is the extent to which a substance can be mixed with a solvent to produce a homogeneous system. **Solubilization** is a process by which the ability of a solvent to carry a substance is enhanced by the addition of another substance. **Solvolysis** is a term indicating the formation of new chemical species in the solution as a result of dissolving the solute in the solvent. Solubility, solubilization, and solvolysis are processes that can be evaluated in the laboratory. They can be used to evaluate the performance of materials over time and to control the precise chemical composition of materials to be used in electrical equipment. They offer a key to understanding many of the processes that impact the performance of equipment in the field. More importantly, they provide a key to controlling those processes.

### ***Transformer Oil as a Solvent***

A solvent can be simply defined as a liquid that dissolves another substance without any change in the liquid's molecular structure. Its properties as a solvent can be expressed in a variety of ways. With respect to a single solute it can be expressed as the quantity of that solute per unit volume of the solvent that will form a solution at a given temperature. These values are listed in various standard handbooks of chemistry and physics. Unfortunately, these tables are largely limited to a few common solvents and a relatively few organic compounds. There are many theoretical models that can be used to predict the solubility of a solute in a solvent or blend of solvents. These include the "regular solution theory (RST) of Hilderbrand and Scott, the "Hansen Model", the "universal functional activity coefficient" (UNIFAC) model, and the "modified separation of cohesive energy density" (MOSCED) model. The difficulty with all of these models is that they require knowledge of the compounds that constitute the solvent blend and the identity of the compound that would be taken into solution<sup>10</sup>. Most transformer oils are a complex mixture of organic compounds derived from different crude oils and having different fundamental constituents that can only be empirically modeled. This situation is briefly described by Joone in relation to using mineral oils in the formulation of inks<sup>11</sup>. Similarly, the compounds that may be taken into solution are diverse and are often unexpected products of curing side reactions, trace additives to coatings, polymers, or composite components. The knowledge necessary to usefully apply any of these models is not yet available. The models do provide insight into trends that may be applicable.

The Hansen model would suggest that mineral oil, the most common transformer oil, is a very poor solvent. It further suggests that mineral oil is relatively incompatible with most common solvents<sup>12</sup>. By implication, transformer oil would not be expected to dissolve or extract compounds that are difficult to keep in solution even when very effective solvents are used. Mineral oil does have a reasonable capacity for holding gases in solution. Though the composition by weight of a gas in a saturated solution is not very high, when viewed as a composition by volume it can be impressive. The volume percent for a saturated transformer oil containing hydrogen is 7% at 25 Celsius and about 10% at 80 Celsius. Hydrogen values as high as a tenth of a percent are not unusual in transformer oil at ambient temperatures. Other gases present in transformer oil include nitrogen, oxygen, methane, ethane, ethylene, acetylene, carbon dioxide, and carbon monoxide. The presence of these gases in solution may have an important effect on the solubility of other foreign compounds in the oil.

New transformer oil is not a very good solvent but it doesn't have to be. The quantity of oil is large, temperatures are often elevated, and the gas phase constituents and/or the compounds formed by the reactions that release the gas, that begin forming immediately after the oil is added to the equipment,<sup>13</sup> may significantly increase the solubilization for some materials. Tests based on the changes in a material, such as a paint, or changes in the properties of new transformer oil after a material and the oil have been interacting together for 164 hours at 100 Celsius (ASTM D3455-95) may not be the best way to evaluate the potential impact of the material on the electrical performance of a system containing large volumes of both oil and that material over many years of exposure. In tests conducted by the authors, there was a significant difference in the electrical properties of "aged" oil after exposure to some materials compared to the changes seen in new oil exposed under the same conditions to the same material. As already reported here, the electric properties of aged oil change on exposure to some paints that have no apparent effect on new oil.

The oil may not always be affected in ways detected by the standard set of physical tests. That doesn't mean that there is no extraction of foreign chemical compounds into the oil. Figure #5 shows the extractable compounds from a crepe paper used in transformers. Many common materials used in electrical equipment contribute foreign chemicals compounds to the oil contained in that equipment. The identity of these compounds is difficult to determine and their presence in a given material is often not well documented because these chemical compounds are not part of the principal composition of the material. They are essentially "ghost" or nascent compounds in the materials. More work needs to be done to evaluate the relationship between extractable compounds from a variety of materials and their possible effects on electrical equipment over time.

### ***Nascent Compounds in Materials***

A nascent compound in this application refers to chemical compounds that facilitate a process or that are a trace product of the process but do not become a functional component of the final material. They are residual compounds that may or may not be mobile in the final material and whose removal from that material will not affect the properties of the final material. Their presence in transformer oil may change or facilitate change in the electrical performance of the system. Paper and paint are two



Photograph #2: Gas Released by Sulfites in Paper Insulation

Sodium azide in solution with iodine is catalyzed by the presence of reduced sulfur (reactive sulfur) to release nitrogen gas and form sodium iodide. This simple test demonstrates the presence of sulfites throughout paper insulation.

examples of materials that contain nascent compounds. Significant quantities of both are used in large transformers.

Paper is primarily a product of the processing of wood and is one of the primary insulating materials used in the transformer. Paper is basically a cellulose product but its chemistry is far more complex. Wood is only about 65% cellulose. Paper is about 95% cellulose<sup>14</sup>. In order to produce paper from wood the wood must go through a number of chemical processes. The goal of these processes is to remove the lignin “glue” from the wood and thereby release the cellulose fibers and improve the cellulose content of the wood pulp. The lignin is removed through a digestive process involving the use of sulfur containing compounds. Care must be taken in this process not to degrade the physical properties of the cellulose fiber. There is a balance between the damage done to the cellulose polymer chain by removing the last traces of the lignin and the quality of the paper with residual lignin. The balance selected for use in transformers is what is called a Kraft paper. The nascent compounds in Kraft paper include sulfites and other sulfur containing compounds (see Photograph #3), lignin, and a variety of degraded hemi-cellulose products. Some of these materials are soluble at low levels in the oil. The effects that the soluble compounds may have on the performance of the equipment have not been identified but they are part of the difference between “aged” oil and new oil in transformers.

Paper naturally degrades over time. That degradation takes many forms depending on the environment in which the paper is used. In a transformer or similar electrical equipment the degradation is thermal, mechanical, and/or hydrothermal. Hydrothermal degradation is the most common and it produces a variety of chemicals in the process. Carbon dioxide, carbon monoxide, water, furans, and a variety of hemi-cellulosic products are produced. All of these become part of the complex solution that is aged transformer oil.

Paint is a material that contains a wide variety of chemical compounds from the polymer itself to the pigments, fillers, opacifiers, curing agents, driers, and other chemical residues, such as tin and aluminum organic compounds, to additives used to process the major constituents<sup>15,16</sup>. Most of the curing agents and driers are metal organic compounds. The most common metals are calcium, nickel, cobalt, iron, copper, and other transition elements. Tin organics are used as catalysts in the production of some resins used in paints. Aluminum organics are used as anti-caking agents for the titanium dioxide pigment of white or light colored paints. The elements calcium, nickel, tin, and aluminum have been detected in films intentionally grown on heated copper ribbons (MicroCell test) from transformer oil exposed to paint and in oil exposed to paint. These materials are at trace levels in the paint and some are unknown and unexpected by the paint manufacturers. They are certainly unexpected by manufacturers of electrical equipment who simply want paints that are “stable” in transformer or other electrical equipment oil. The paint is “stable” but that doesn’t mean that it has no effect on the performance of the equipment.

Driers, curing agents, anti-caking agents, and reaction catalysts play no role in the cured paint and are simply locked physically in place by the polymer they help form without becoming part of the polymer. Over time these metal-organic compounds can move into the oil where they may have a

significant impact on the power factor of the oil and may affect other performance characteristics of the equipment. A detailed examination of a specific power factor phenomenon will be the subject of a subsequent paper in the near future by the authors. Leaching of chemical agents from paints, even two part epoxies, is a common complaint in many commercial or industrial applications of paints or coatings.

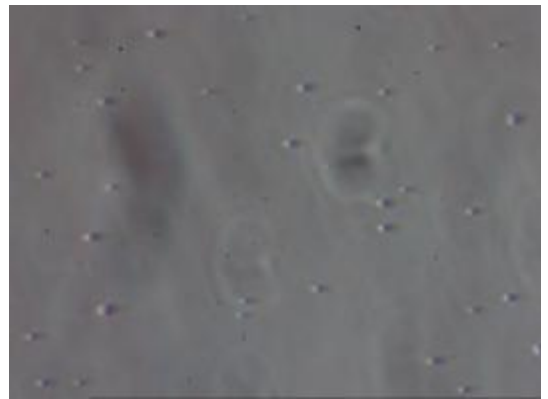
Most non-metallic materials used in electrical equipment can be evaluated the same way and will be found to contribute some chemical compound to the mixture that is “aged” oil. This is not necessarily bad, it’s just a fact to be considered by designers. These extractable compounds will change with time because these materials change as time goes on. Suppliers are constantly changing their products as a part of process improvement. The end user is normally not informed of these changes. As a result, new chemical compounds may be extracted from what the end user believes is the same old material. Understanding how these compounds can affect the performance of electrical equipment and developing the tools to detect them will minimize their impact.

The compounds that are extracted are not passive over time but will participate in secondary reactions. The sequence of reactions that take place in the oil in electrical equipment can be characterized in general even though the specifics of the reactions are not known. These subsequent reactions can be a guide to techniques for the removal of chemical contaminants from the oil or keys to how they may affect the performance of the equipment over time.

## Reactions

As soon as oil is added to new equipment, hydrogen begins to be released<sup>13</sup>. The hydrogen released tends to stay in solution. The presence of hydrogen in solution is a slight modification of the chemistry of the oil. A more significant result chemically is the change of the molecule that lost hydrogen. The release of hydrogen leaves behind free radicals, unsaturated hydrocarbons, and other reaction products that were not part of the original oil. The release of hydrogen has been well documented but the new compounds left behind have not been documented or even considered in terms of how they change the chemical nature of the oil.

The reactions that release the hydrogen are known in part to be due to catalytic reactions as a result of the copper, silver, and other metal surfaces that are present in the equipment. Other reactions may be the result of special micro-environments in the equipment that promote specific types of reactions. The micro-



Photograph #3: Suspended Liquid Droplets In Transformer Oil Exposed to a Commonly Used Paint

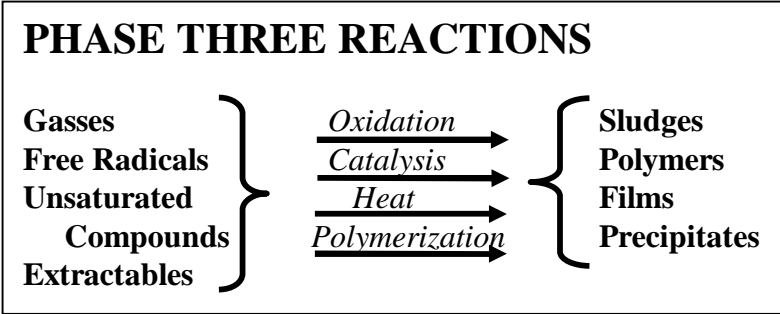
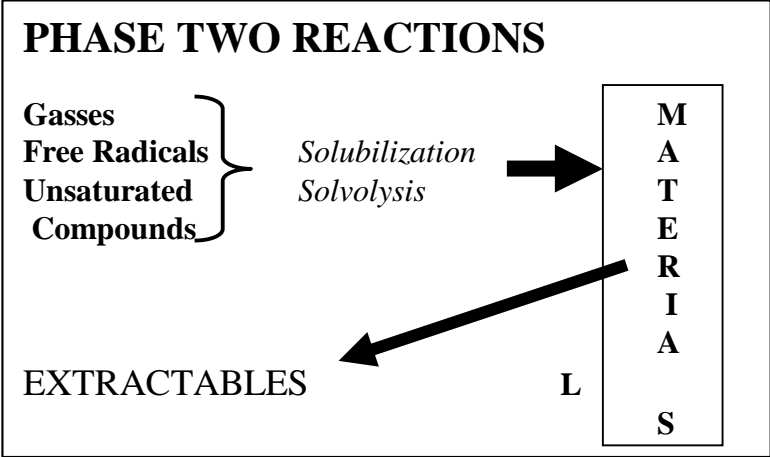
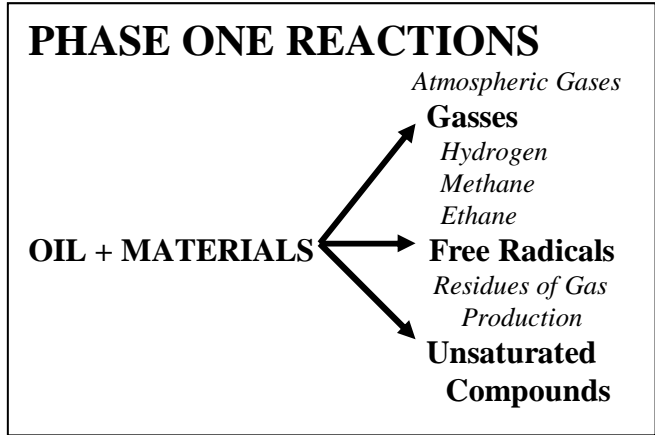
This insoluble phase disappears at 80° Celsius. The shading on the right side of the droplets indicates that they have a higher refractive index than the oil. That implies a more complex chemical composition.

environments within electrical equipment include activation sites on metals, tightly wrapped paper on copper, strong electrical and magnetic fields, and dissimilar metals in contact. Surface oxide or sulfide films on copper or silver provide another microenvironment. All of these areas are areas of special potential for chemical reactions. The reaction products may be solids, such as polymers or sludges, or they may be liquids in solution or in suspension as fine droplets in the oil (see Photograph #3). Their suspension as fine droplets indicates that at one time they were in solution. These chemicals drop out of solution either by virtue of a decrease of their solubility in the oil, often a result of a change in temperature, or by becoming associated with another chemical compound that decreases their solubility. An example might be a polar compound associating with an aromatic compound in the oil and thereby pulling both of them out of solution from the main body of the oil.

These initial reactions create the potential for solubilization and solvolysis, which is the next phase in the extraction of compounds from the materials used in electrical equipment. The removal of hydrogen from a simple long chain

alkane tends to create a molecule that to some degree is polar or has a polar functional group attached to the main chain hydrocarbon. Such a compound exerts more force on a polar compound or ion that may be available in one or more of the materials used in the equipment. It may also facilitate catalytic reactions that would not take place in its absence. The simple act of orienting another molecule, such as a gas in solution, to react with an active site could result in a reaction that otherwise would be unexpected.

These reactions progress to solvolysis and solubilization. Solvolysis and solubilization then begin extracting chemical compounds from materials used in the equipment that were inert in the original new oil. This is the second phase of the process leading to aged oil. This phase will continue



until nothing remains to extract. For some materials that time period may be fairly short, measured in months. For other materials the time period may be measured in years.

The impact that the extracted compounds may have on the equipment's performance may be a function of the concentration of that compound in solution or of the total amount of compound that may be extracted. For example, the effect on oil power factor will be proportional to the concentration of the compound in solution but there may be a limit to that compounds solubility. That would limit the power factor excursion. If the compound were to be removed by some process, filtration by Fullers Earth for example, then the power factor would drop but then begin to increase again as more compound was extracted from the material. This would continue until the compound was completely removed from the material.

The third phase of the process is the reaction of the compounds in the oil with each other and with the surfaces inside the equipment that remove them from the oil. These reactions include polymerization, oxidation, sludge formation, film formation, and precipitation. All of these processes are different chemically and may be different in terms of their relative effect on equipment performance. These are the removal processes that draw reaction products and foreign materials out of solution from the oil. They may result in a colloidal suspension of fine particles in the oil, films on metal surfaces, or in the formation of a layer of viscous "sludge" on surfaces in the equipment. No detrimental effects have been seen in transformers as a result of the films generated by the compounds from paint that had caused the increase in power factor.

The first phase continues at some rate, possibly much slower, as time goes on and surfaces and micro-environments become saturated or passivated. The second and third phases take place together. The concentration of any compound in the oil will be controlled by the balance between the rate of its generation and the rate of its removal from the oil. How the equipment is affected will depend upon the specific operational environment of that equipment, the chemistry taking place in the oil, and the materials used in that equipment.

## **Future Work**

There are a number of specific investigations that could provide useful information and design improvements in the near term. The adverse effect of paints on power factor in the oil is another area that could provide a way to optimize equipment performance in the near term. Optimal formulations for the paints used in the equipment could be identified and things to avoid could be specified. Ways to control the rates of generation/extraction and the rates of removal from the oil for specific types of compounds could provide mechanisms to remove problem compounds before placing equipment in the field or for the removal of these compounds from the oil in equipment operating in the field. These are just a few areas now open to immediate investigation. The approach presented here opens a new way of thinking about the materials that are used in electrical equipment. It is the beginning of a more sophisticated way of evaluating and selecting materials to optimize the design of electrical equipment.

## Conclusion

As documented here, “aged” oil extracts chemical compounds from paints and other non-metallic materials commonly used in electrical equipment and previously considered “inert” in that environment based on tests with new oil. Some of these chemical compounds have been shown to affect power factor. There is a balance between the rate of the reactions that extract these chemicals and the reactions that remove them from the oil, the “Phase Two” and “Phase three” reactions. The conditions that control those rates are affected by the pattern of use, the specific design, and the exterior environment of the equipment.

Additional papers will follow shortly by the authors discussing some specific effects that extractables have on equipment performance. As this body of information grows materials can be selected that will optimize performance and extend the useful life of that equipment. Further progress in equipment design and in the selection of new oils for use in electrical equipment requires tighter control of materials and a better understanding of how the chemical properties of the oil change as a result of the chemical interaction between the solid materials, the chemicals in the oil, and the gases created within the oil over time. Tools have been developed now to track these compounds over time and to assess their impact on equipment performance. There will be fewer things we have to learn by trial and error, or unexpected performance. We are at the beginning of a new era of product improvement.

## References

1. Hanson, D, T. Hauptert, Leo Savio, and R. Crutcher, *Mechanism of Coking Technical Report*, EPRI Report EP-P5779-C2903, December 2001.
2. Crutcher, E. R., Ken Warner, Leo Savio, and Dave Hanson, “*LTC’s with high cholesterol: coking potential testing*”, TechCon US, San Diego, CA, 2005
3. Crutcher, Russ, Dave Hanson, and Leo Savio, “*Mechanism of coking in load tap changers: a progress report*”, EPRI Substation Equipment Diagnostics Conference XII, February 15-18, 2004.
4. Kuhlman Electric Corp, Internal Documentation.
5. Work Partially Reported Here
6. Kaufman, Samuel, “*Solubilization*”, in Considine, Douglas M. and Glenn D. Considine (eds) Van Nostrand Reinhold Encyclopedia of Chemistry, 1984, pp. 870-871.
7. Hilderbrand, Joel H., “*Solutions*”, in Considine, Douglas M. and Glenn D. Considine (eds) Van Nostrand Reinhold Encyclopedia of Chemistry, 1984, pp. 871-875.

8. Considine, Douglas M. and Glenn D. Considine (eds), “*Solvolysis*”, Van Nostrand Reinhold Encyclopedia of Chemistry, 1984, p. 875.
9. Hammel, H. T., “*Colligative properties of a solution*”, Science, vol. 192, pp. 748-756, 1976.
10. Lazzaroni, Michael J., *Optimizing Solvent Selection for Separation and Reaction*, PhD Thesis, Georgia Institute of Technology, July, 2004.
11. Joone, Marika, “*Solubility the most important property—but difficult to measure*”, Naphthenics Magazine, #2, 2000.
12. DuPont and Company, “*Hansen solubility parameter system*”, on line at [www.dbe.dupont.com](http://www.dbe.dupont.com).
13. Sundkvist, Kjell, “*Oil dependent gas formation in transformer oil*”, Naphthenics Magazine, #1, 2003.
14. Ott, Emil, Harold M. Spurlin, and Mildred W. Grafflin, *Cellulose and Cellulose Derivatives: Part I*, Interscience Publ. Inc., NY, 1954.
15. Crown, David A., *The Forensic Examination of Paints and Pigments*, Charles C. Thomas Publ., Springfield, IL, 1968.
16. van Gorkum, Remy and Elisabeth Bouwman, “*The oxidative drying of alkyd paint catalysed by metal complexes*”, Coordination Chemistry Reviews, Vol. 249, Issues 17-18, pp. 1709-1728, Sept. 2005.

## INFRARED SPECTRA REFERENCED IN THE TEXT

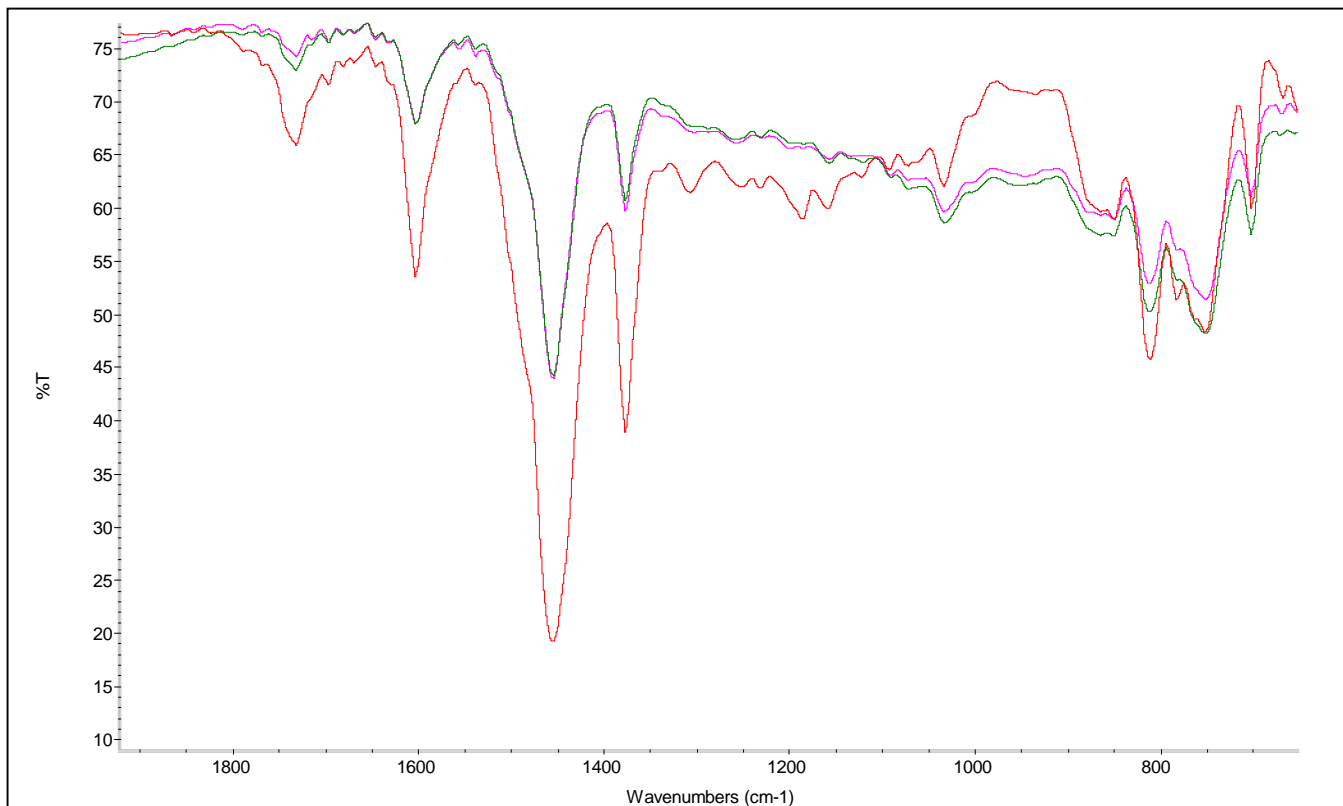


Figure #1: Material Rinsed from Silica Gel Columns With a Mixture of Methylene Chloride and Acetone.

The columns were loaded with 10 drops of oil and rinsed with hexane to remove the residual oil first. Each trace is a different transformer. The oil represented by the red trace had a power factor of over 60%. The power factor values for the other two oils were 14% and 9% respectively. The area scanned above is known as the “fingerprint” region of the infrared spectrum. This is the region that is most distinctive for most organic chemical compounds. The spectra above do not indicate a single organic compound but rather a mixture of different compounds in slightly different proportions. The mixture indicated is the same combination of compounds. This match is essentially identical other than the quantity of material in the beam path resulting in stronger absorption for the red trace.



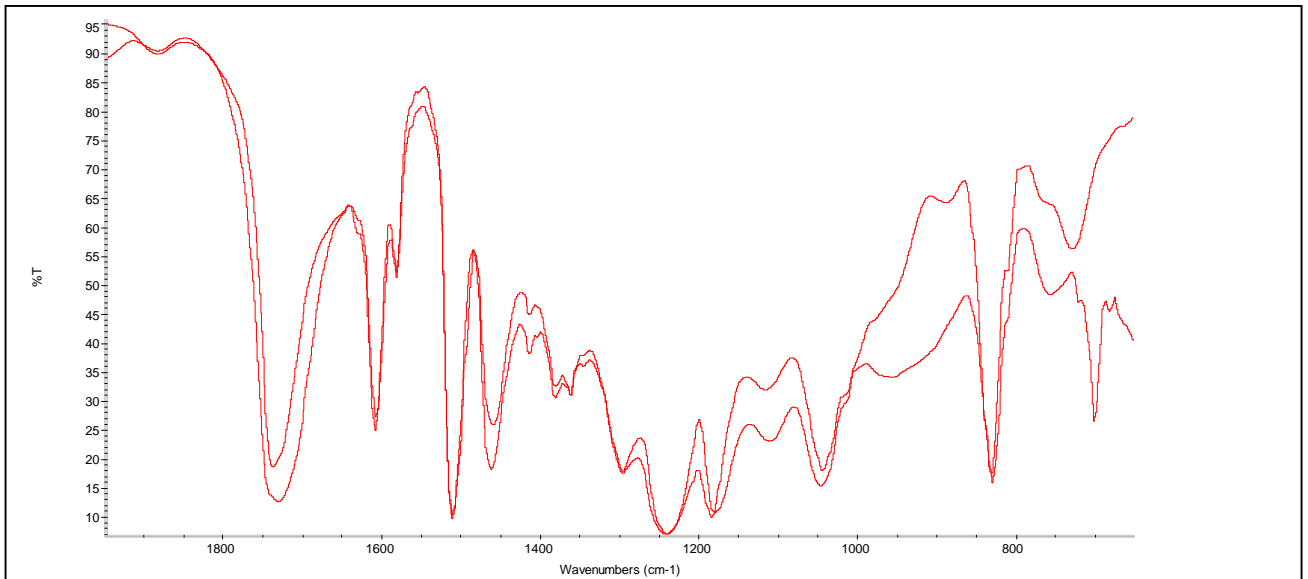


Figure #2: Overlay of the “Fingerprint” Region of the IR Spectra from Extracts from Two Paints of the Same General Type from Two Different Paint Companies

These spectra are methylene chloride extracts of two fully cured paints. The paints are of the same general type though they are produced by different companies and have slightly different compositions. The spectra are nearly identical down to 1000 wavenumbers, where they begin to show differences.

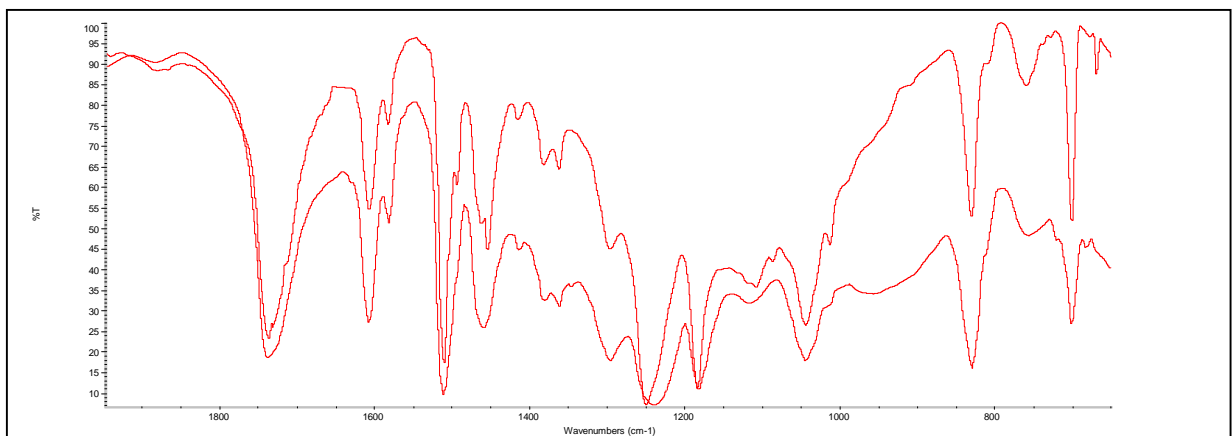


Figure #3: Overlay of the “Fingerprint” Region of the IR Spectra from a Film formed by an Aged Oil Exposed to a Paint (upper trace) and the Methylene Chloride Extract from that Paint

These spectra indicate that the film forming material is from the paint. These spectra represent a number of different compounds. The differences in amplitude suggest some compounds are leached less efficiently or the others are leached more efficiently by the oil than by methylene chloride. The aged oil prior to exposure to the copper had an elevated power factor. After forming this film it dropped below 1%.

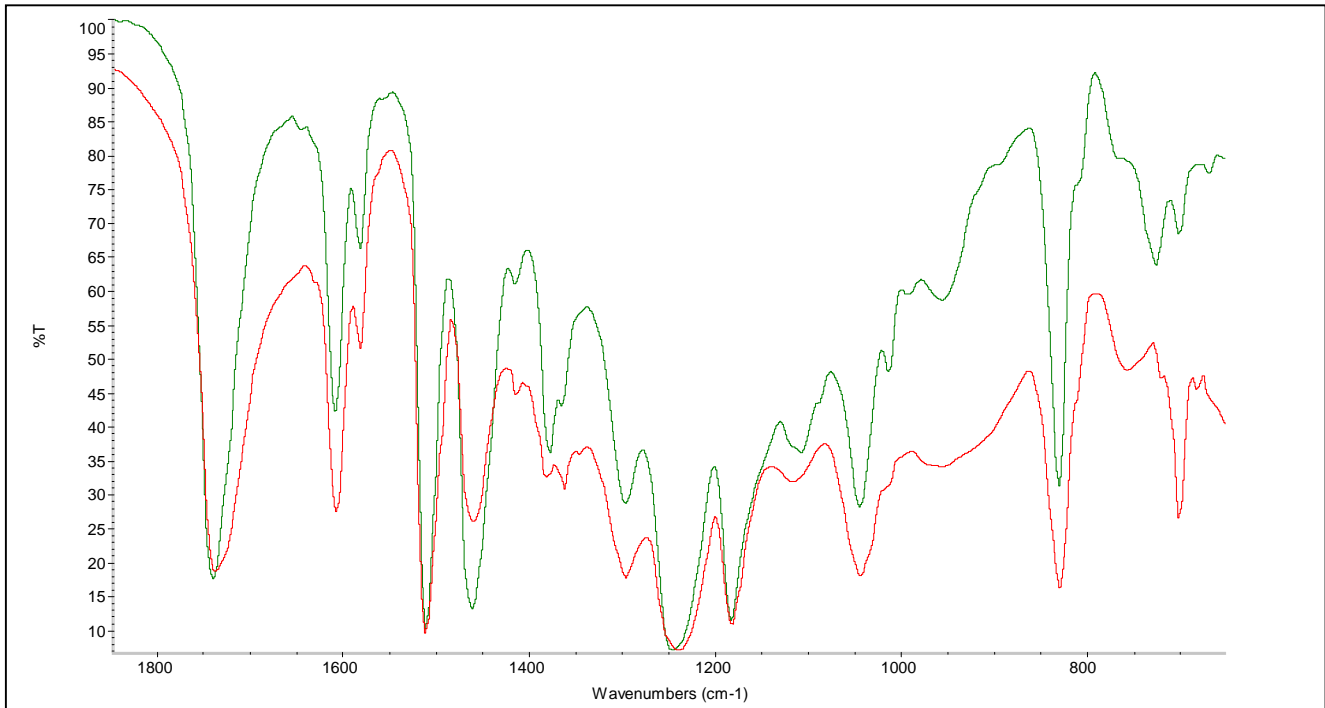


Figure #4: Overlay of the IR Spectra from a Methylene Chloride Extract of a Common Paint (lower trace) and a Film Cast on Copper by Oil from an LTC (upper Trace)

The remarkable similarity of these spectra would seem to implicate extractable compounds from the paint as the dominant film forming components seen in this LTC. There is some difference below 800 wavenumbers. This may indicate a different paint of basically the same formulation.

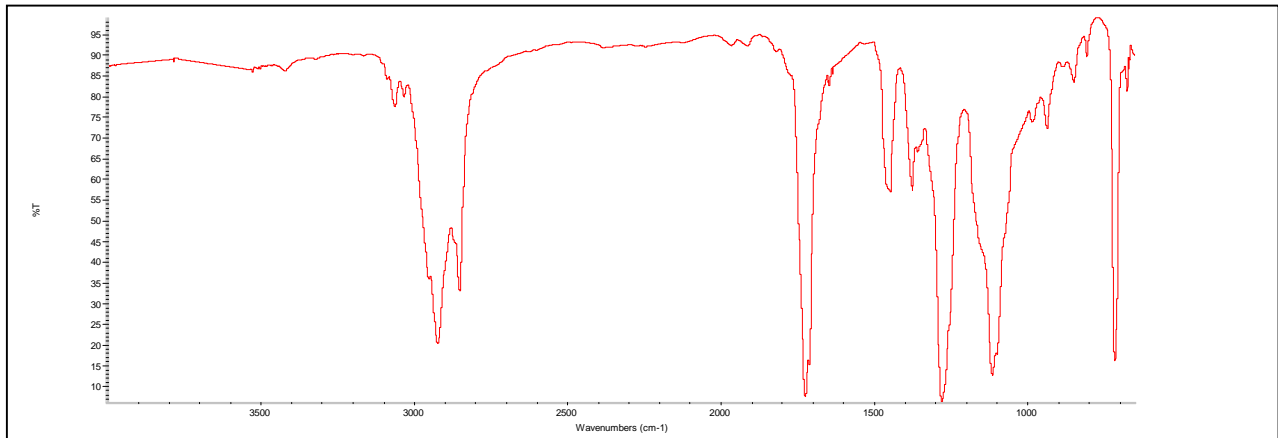


Figure #5: The Infrared Spectrum “Fingerprint” Region of a Hexane Extract from Colored Crepe Paper Used in a Transformer

This is include just as an example of extractable compounds from paper, resins, pressboards, plywood, plastics, and other non-metals used in electrical equipment.

## **Biography**

### ***Russ Crutcher***

Mr. Russ Crutcher is and has been the owner and principal scientist at Microlab Northwest in Redmond, Washington, USA since 1978. He has been involved in the contaminant and component failure analysis area for the Electrical Power Industry since about 1982. In 1999 he began researching the coking problems in LTC's along with TJH2b on a project funded through EPRI.

Mr. Crutcher was the lead scientist and principal investigator for the Special Materials and Contamination Analysis Laboratory of the Boeing Spacecraft Division from 1972 until he took early retirement in 2001. He taught at the University of Washington's School of Materials Sciences Engineering for 8 years while continuing to work for the Boeing Company from 1981 to 1989. In 1985 and again in 1987 he was invited as a Visiting Scholar to the Civil Engineering Division, Imperial College, London. His background includes working as a crime scene investigator and evidence analyst for the city of Bellevue, Washington from 1970 to 1972.

Russ Crutcher received a degree in Physical Anthropology with minors in Mathematics, Physics, and Chemistry from the University of Washington in 1970.

### ***Ken Warner***

Ken Warner has been associated with Microlab Northwest for five years. He is the principal Fourier Transform Infrared Microscope Spectrophotometer operator for Microlab Northwest and key research scientist. He helped develop the MicroCell for the evaluation of film growth in oil-filled electrical equipment.

Mr. Warner has worked as an analytical chemist for the Boeing Company, Monsanto Chemical Company, and the Inhalation Toxicology Research Institute. He taught classes on Infrared Spectroscopy at South Seattle Community College and was the Principal Analyst for Organic Films in Orbital Environments contract with NASA as part of the LDEF Program.

Ken Warner received a BS in Chemistry and Zoology from the University of Wyoming in 1972. He took additional classes in advanced chemistry at the University of New Mexico from 1974 to 1979.

### ***Ray Rettew***

Dr. Ray Rettew is a consultant in chemistry primarily for the solution of problems in the Electrical Power Industry. He is a major contributor to HVolt Inc. in the solution of materials problems.

Ray Rettew was the Director of Research and Development for the Square D Company Transformer Business Unit. In that capacity he directed the development of new epoxy resin

system to reduce costs for small power transformers. Prior to moving to the Square D Company in 1989 he worked as a group manager for General Electric in the materials development group. Until 1977, when he joined General Electric, was as a research scientist for W. R. Grace & Company developing specialty ceramics.

Ray Rettew received a BS in Chemistry from Clemson University in 1961 and a Ph.D in Chemistry from Emory University in 1966.

### **Steve Smith**

Steve Smith is Vice President of Engineering for Kuhlman Electric Corporation in Crystal Springs, MS where he is responsible for all Design Engineering, Quality, and Test at the Medium Power Transformer facility. He has been with Kuhlman Electric since 1990 and has been with the Medium Power Transformer operation since 1994.

Prior to joining Kuhlman he was Chief Engineer and Senior Staff Engineer for Cooper Power Systems in their Distribution Transformer Business where he held positions in Waukesha, WI; Nacogdoches, TX; and Zanesville, OH. Steve has also worked as a Plant Project Engineer and as a Technical College Instructor. He began his career as a transformer specialist for AEP in Canton, OH in 1972.

Steve is a 1972 Graduate of Ohio State University receiving both MSEE and BEE degrees with electric power systems as his specialty area of study.

### **Phil Hopkinson**

Phil Hopkinson is the owner of HVOLT, Inc., a power transformer consulting company that he formed in 2001. He is an IEEE Fellow and long service Transformer Engineer. He has chaired numerous IEEE and NEMA Working Groups and from 2001-2003 was Chairman of IEEE's Policy Development Coordinating Committee. 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.

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. 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.

Phil Hopkinson 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.