Transformer Load Tap Changer Management

Diagnostics, Contact Coking, and On-line Oil Filtration

Technical Report

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Diagnostics, Contact Coking, and On-line Oil Filtration

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REPORT SUMMARY

On-load tap changers (LTC) are the single biggest contributor to transformer problems. Their failure modes may be mechanical, electrical, or related to the quality of oil and contacts. Utilities are seeking new strategies regarding LTC maintenance to minimize these problems and, at the same time, reduce maintenance costs. EPRI has initiated several projects with a goal towards a "Maintenance-Free LTC." This report summarizes work to date under EPRI/BC Hydro sponsorship to address some of these concerns.

Background

LTCs play a major role in the reliable delivery of electric power. According to recent studies, they are the single biggest contributors to transformer problems, responsible for over 30% of all forced transformer outages. Common LTC failures result from any of the following: mechanical malfunction, increased contact resistance, localized thermal stress, material failure, breakdown of insulating oil, contact coking, contact wear, improper design, or high loads. It is quite common to find that these are interrelated. Increased contact resistance leads to thermal stress, which results in breakdown of insulating oil, onset of coking, and, finally, mechanical failure. Improper design, application, and/or high loads may initiate or aggravate failure mechanisms.

Utilities are adopting proactive operating and maintenance practices, using monitoring devices, and seeking new diagnostic techniques to improve reliability, extend LTC service interval, avert catastrophic failures, reduce maintenance costs, and improve reliability of power delivery and distribution. Diagnostic tools used previously have had limited success in accurately diagnosing incipient faults. In recent years, use of dissolved gas-in-oil analysis, oil quality analysis, and differential temperature has gained popularity as a noninvasive means of fault detection and condition assessment. However, because of numerous LTC configurations, designs, manufacturers, and models, use of these tools requires a great deal of expert knowledge and experience with the particular LTC under consideration.

Objective

To develop and evaluate new diagnostic and condition monitoring techniques, to investigate causes of contact coking and methods to reduce it, and to evaluate merits of on-line filtration to extend maintenance intervals.

Approach

Based on literature review and previous work, the research team focused on three areas of study: (1) Laboratory studies—Laboratory investigations were designed to simulate normal and abnormal thermal and electrical stresses encountered in LTCs and to identify chemical markers for development of diagnostic tools. Thermal and electrical stresses were simulated using specially designed laboratory apparatus. (2) Field case studies—The team modified a voltage regulator at a BC Hydro substation to simulate high tap-change operations under accelerated conditions to correlate the laboratory findings with operating conditions. One of two identical LTCs was equipped with an on-line filtration system and operated under similar conditions to the sister unit. (3) Database analysis of oil test results from in-service LTCs—Oil samples from approximately 100 in-service LTCs were subjected to comprehensive analysis. Results and operating conditions were recorded in a relational database. Knowledge gained during laboratory work and field study was used to interpret the data.

Results

The laboratory investigations have shown that thermal breakdown of oil produces a multitude of gases, unsaturated hydrocarbons, and aromatic compounds whose carbon to hydrogen ratio increases with temperature. Coke formation is dependent on the contact material, the nature of the oil, the presence of contaminants, and oil breakdown products. Arcing produced acetylene, hydrogen, carbon, and a variety of highly unsaturated, aromatic, and polyaromatic compounds suspected of being precursors to coking. Marker compounds specific to thermal or arcing conditions were identified. Results of the field study showed that under normal operating conditions, combustible gases, carbon, and suspended metals increased with increasing switch operations, but the ratio of arcing to thermal markers remained constant. On-line filtration helps reduce sludge and coke formation but does not remove soluble coking precursors. To date, the merits of on-line oil filtration remain inconclusive. The survey of in-service LTCs at BC Hydro was successful in identifying several LTCs in imminent fault mode.

EPRI Perspective

Transformer LTC management is one of the most critical issues facing today’s substation engineers. LTCs are the biggest single maintenance item in a substation. EPRI will continue to study new technologies that improve LTC reliability and reduce maintenance. This investigation has contributed to a new approach for effective LTC management. It will be used for further studies to develop early warning monitoring techniques.

Keywords

Transformer
Load tap changer
Coking
Diagnostics
Filtration
Monitoring
Maintenance

ABSTRACT

LTCs are recognized as the single biggest contributors to transformer outages. Research was undertaken to develop and evaluate new diagnostic techniques, investigate the causes of coking and methods to reduce it and evaluate the merits of on-line oil filtration. The results of laboratory studies simulating LTC thermal and electrical stresses, accelerated LTC field conditions and database analysis of many in-service LTCs have shown the presence of marker compounds specific to thermal or arcing conditions. The ratio of arcing to thermal marker compounds was used to identify several LTCs in fault mode. In addition to acetylene, hydrogen and carbon, arcing produced a variety of highly unsaturated, aromatic and polyaromatic compounds suspected of being precursors to coking.

These reactive compounds are formed during normal arcing and thermal fault modes and are useful as thermal fault indicators.

This first, comprehensive report is based on findings resulting from: applied laboratory work, a field-case-study ("Kent Substation") of nine months duration, the field testing of on-line filtration ("Mission Substation"), and a limited survey of about 100 LTCs ("B.C. Hydro").

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INTRODUCTION/BACKGROUND

Introduction

The usual maintenance interval for LTCs depends on make, model and load and is typically, for older designs, in the range of 50, 000 to 100, 000 switch operations and/or after four to seven years in-service [5]. In a review of on-line diagnosis and monitoring of switching equipment, other than LTCs, researchers [6] make a point for future integrated electrical switch equipment that provides full diagnostic readouts for all components. They see the need for on-line diagnostics that applies itself to:

- Existing, older electrical equipment and
- Present day switching equipment.

We believe the same point is also valid for LTCs. The results and consequences displayed in Tables 1-1 and 1-2 describe very well the motivation behind this study.

With the increasing demand on transformer equipment and their reliability utilities have shifted from time-based maintenance to predictive maintenance, with its cost/benefit analysis. Predictive maintenance demands the successful monitoring of equipment health, and equipment performance.

The engineers have to come to terms with the issues of "reliability improvement/ preventive maintenance reduction" and "reliability improvements/insurance cost reductions" [7]. The driving force is the same throughout the industry- the effect on the company's bottom line.

From 1994 to 1996 there was an increase in awareness for "hot spot detection" in LTCs, and important papers were presented at DOBLE and CIGRÉ Conferences [8,9,10] to name just two well-known utility forums. "Methane, ethane and ethylene were chosen as the key gases to use ---" and coking was discussed [8,13]. Gas-in-oil analysis and the measurement of contact resistance in the context of local overheating were investigated and reviewed. "The development of tarnish or its presence on the contacts of LTCs represents the first stage of the build-up of oil carbon (heavy layers)" [9]. Other chemical compounds, than those detected by DGA, were suggested to be of additional diagnostic value such as benzene, toluene, ethyl-benzene and xylene (BTEX) [10].

This was essentially the state-of-the-art prior to the inception of this series of projects, which are sponsored by the electrical utility industry and the Electrical Power Research Institute (EPRI).

Recently other methods for the monitoring and diagnosis for LTCs, aside from DGA and related methods, have been suggested. Additional diagnostic tools are under development, such as: LTC-vibration monitoring [2], Acoustic Monitoring [4]. These different approaches compete and the most economic and successful tool will succeed.

Since the 1980's there is also a move, if it was not for the costs involved, to solid-state tap-changer technology.

Background

Surveys conducted in the United Kingdom, in Australia and internationally (CIGRE) [1,2,3] agree that LTCs cause more outages and failures than any other 'sub-component' of power transformers. This is put in perspective in the following Table 1-1 by the National Grid Company plc, an English source [1] and an Australian study [2] (Queensland), which details the major failure modes in LTCs for that part of the world, supplementing and supporting the previous findings, as presented in Table 1-2:

Table 1-1
A Survey of LTC Failures and Causes (National Grid plc)

Defect Type	Base Cause	Result	Consequence
Mechanical failure of shaft couplings, drives, components and fixings. Contact support component failures.	Inadequate design; poor quality control in manufacture or site assembly: component ageing or fatigue:	Loss of drive and synchronisation between diverter and selector. Loss of contact	Arcing faults in selector and/or diverter. Major failure of tap-changer/ transformer
Diverter operation. Slow or incomplete	Inadequate design or quality control: component deterioration:	Slow or incomplete operation of diverter	Arcing fault in diverter. Major failure of tap-changer/ transformer
Pyrolytic carbon growth	Inadequate design and/or infrequent use of tap-changer:	Selector drive failure or misalignment	Gassing in selector and/or arcing fault. Possible major failure.
Barrier failures	Maintenance induced:	Cracked barrier	Major failure of tap-changer or transformer
Tie-in or transition resistors	Inadequate design, application or ageing:	Overheating or gassing faults	Unplanned outages for inspection
Miscellaneous minor defects: fixing failures; seal failures; Contact erosion and failure; current carrying joints;	Inadequate design: ageing of components: Inappropriate maintenance:	Oil leakage or water ingress: overheating	General nuisance: overheating: gassing: Unplanned outages

Table 1-2
Major Failure Modes of LTCs in Service (Australia/Queensland) [2]

Driving mechanism	Contacts	Insulation	Others
• Tap changer stopping off position (8%) • Loose fastener (1.3%) • Improper operation of tap selector (9.4%) • Problematic operation of changeover selector (2.5%) • Damaged shafts (5.7%) • Damaged reduction gears (1.9%) • Weak springs (1.3%) • Mechanical failure of inter phase drive shaft (0.6%) • Geneva wheel out of adjustment (1.3%)	• Loose couplings or inter phase drive connection failure (1.9%) • Arc erosion on stationary and moveable arcing contacts (6.9%) • Excessive wear on fixed or moving contacts (5.7%) • Transitional impedance burnout (9.4%)	• Moisture ingress contamination (3.2%) • Barrier board tracking and cracking (3.1%) • Flash-over between phases (2.5%) • Internal arcing (7.5%) • Inter phase drive insulation breakdown (3.1%)	• Loss of mechanical integrity such as loose mechanical parts (7.5%) • Limit switch inoperative (3.1%) mechanical stop absence/failure (LTC drives beyond bottom tap) (3.1%)

Other international publications point in the same direction [3]. Arcing, gassing and overheating are associated with all of these defects, and can thus be monitored chemically by dissolved gas analysis (DGA). In fact the UK put to practice this method as early as in the mid 1980s, "---, when a short period of poor operating experience led to a drive to improve designs, type test specifications and quality standards for new tap-changers" [1]. This work, indeed, resulted in improved tap-changer designs (conforming with the IEC214 standard).

Project Motivation

In the case of power transformers, it was said at an international presentation (1996): "Several diagnostic techniques have been developed to obtain information about their internal condition. Though, very little information is available in this area concerning transformer accessories" [10].

Currently, most LTCs are an expensive and maintenance-intensive option on power transformer. Some transmission autotransformer and most step-down power transformer in the United States, Canada, Mexico and Europe are equipped with LTCs.

At this junction in time EPRI initiated projects with a number of companies towards: "Maintenance-free LTC".

Fault-mode operation of LTC equipment remains a major cause of power transformer failure, while a significant percentage of these failures are related to the quality of the oil and contacts, the majority of failures are due to mechanical problems, such as loose bolting, lack of contact pressure etc. LTCs capable of handling 250,000 to 500,000 power-adjustments are the goal by present industrial standards.

Preventive maintenance at B.C. Hydro, as was previously stated, is conducted every 5 to 8 years or every 50,000 to 80,000 operations and includes:

- Removal of oil
- Removal of access covers
- Removal of all carbon, metal particles and other contaminants
- Inspection
- Replacement, repair of defective components
- Replacement of oil
- Continuity and ratio tests
- LTC will either be back to service or the equipment reached its end of life
- Introduction of on-line filtration systems is viewed to improve maintenance.

Nevertheless, it is estimated that a substantial portion of transformer maintenance requirements and costly substation failures are due to faulty operation of LTCs. Aside from mechanical malfunction, local overheating from increased contact resistance due to coking and excessive contact wear resulting from improper design or high loads. Utilities and EPRI are seeking new ways of lowering associated outages and costs by increasing their reliability. New techniques have been developed and are introduced to the power industry, but new approaches are still needed.

2
OBJECTIVES AND SCOPE

Objectives

The project had three main objectives.

i) To develop and evaluate (new) diagnostic and condition monitoring techniques for LTCs

ii) To investigate the causes of coking and methods to reduce it

iii) To evaluate the merits of on-line filtration and the objective to extend the maintenance interval of LTCs

It is the first objective, which is of key-importance to this report. Thermal- as well as electrical stress, especially arcing result in gaseous but also in non-gaseous products. Non-gaseous products are attractive for the purpose of predictive maintenance as they may accumulate in the oil; thus perhaps providing a better record of LTC performance [10]. This knowledge in return may provide the tools to evaluate the performance of LTCs and help, perhaps, in the design of LTCs.

Scope

To understand sudden sludge formation and coking is an important objective and should help to explain much of the chemistry for oil-filled switchgear, such as LTCs. Loss in oil quality in LTCs is in many ways distinct and different from what happens in transformers under normal operating conditions. The scope of the work covered the following areas: 1) New diagnostic and monitoring methods; 2) Coking mechanisms; and 3) Merits of on-line filtration.

New Diagnostic and Monitoring Methods

The scope for new diagnostic and monitoring methods provides, ideally, answers to the following questions:

- What constitutes a normally operating LTC, if judged by applicable analytical tools like ‘gas-in-oil’ (DGA)
- What signatures, if any, as provided by DGA and other analytical tools, are indicative of incipient or severe fault mode (prior to failure)
- Which new analytical tools are available to predict LTC-fault modes

- What tests can be applied to predict the advent of severe sludge formation or coking of transformer oil
- Is it possible to provide an algorithm based on a comprehensive LTC database to recognize fault modes for LTCs
- Is it possible to enhance on-line filtration, so as to extend the service life of the LTC transformer oil
- Does the collective knowledge gained provide for the design of successful on-line monitoring and diagnostics

We have collected encouraging results, which are based on our laboratory findings and both types of field investigations. These will go a far way to address the above questions.

Coking Mechanism

Transformer oils are just one of a number of cuts, or "mineral oil fractions", during the distillation and fractionation of crude oil. Once this oil fraction has been obtained it is subjected, as previously mentioned, to special "refining" methods resulting in transformer oil. Transformer oil has many properties in common with another middle distillate "diesel", especially if of high quality. Thus the methodology and techniques applied in this study is not unique, and it should be familiar to those readers who have a background in petroleum technology. New, perhaps, is the application of certain analytical tools, which help to shed light on some of the chemical transformations that take place during the operation of LTCs and which might be useful in LTC-diagnostics.

Based on our present understanding of oil chemistry, we can see the following scenarios and factors, which may lead to the coking-up of LTCs and their different switches like: reversing-switch, diverter-switch and selector-switch plus other hardware.

The scenarios are:

- The possible formation of coke-like deposits at low to intermediate temperatures of about 200°C to 400°C
- Coking on surfaces of intermediate to high temperatures of 400°C to 800°C
- Coking between contact surfaces, such as in the interface: "metal-oil-metal". (We have good reasons to assume that the ‘interface’ temperatures can be very high.)

Some of the contributing factors are:

i. Contact temperature

ii. Contact type and alloy composition

iii. Contact pressure

iv. Current loading

v. Number of switch operations

vi. Status of the oil: new transformer oil, reconditioned transformer oil, filtered transformer oil, old transformer oil and type:

  - Oil composition (paraffinic, naphthenic, etc.)
  - Oil additives and impurities
  - Moisture and oxygen content
  - Oil decomposition products as a result of normal fault-stress
  - Duration of: arcing, partial discharge and oil temperature

The power equipment and utility industry has neither standards for LTC oils nor do they have specific tests that are developed for the effective monitoring of such LTC oils.

Coking and the associated increase in the carbon/hydrogen ratio resulting in the subsequent formation of graphite like deposits, necessitates high temperatures. Our experience with LTCs in normal, fault and failure mode favors a chemical mechanism, which was reported for the first time in detail, according to our knowledge, by the "Hebei" Institute of Technology [16].

On-Line Filtration

If "---the analysis of the dielectric properties reveals that an ageing of carbonized oil samples leads to a faster and more intensive degradation of the fluid, compared to uncarbonized oil" [11, 23,], then perhaps filtration might help in extending the inspection interval for LTCs.

This does not mean that filtration will prevent failure due to:

i) Material or mechanical fault that might result in excessive heating of metallic surfaces in the switch equipment

or stop the development of:

ii) Poor oil quality due to dissolved contaminants, oxidation and/or detrimental oil degradation products ("reverse refining")

The second cause is sometimes the result of the first, and/or the lack of adequate maintenance or overloading. Simple filtration will remove particular matter above a prescribed particle size, and possibly will also absorb dissolved materials, but there is no proof as of yet for this to happen. Presently we have to assume that simple filtration will remove certain particulate matter and in addition it may dry the oil, if designed to do so, but usually it will not remove colloids and dissolved degradation and/or oxidation products.

We found in the literature reference to a relationship between the carbonization of transformer oil, ageing and the dielectric properties [11] and the effects of particulate matter, especially of oils at an operating temperature at or greater than 50°C [12].

Two of B.C. Hydro's LTCs of the same age, the same make and design, same maintenance schedule were evaluated over a four-year period. One unit was equipped with on-line filtration and the other unit was left without filtration.

3
APPROACH

Introduction

In Figure 3-1 we show the conceptual schematic, which served us well in approaching the task of explaining LTC failures.

Our current thinking about the "coking mechanism" in LTCs is based on the experimental work done at Powertech Labs Inc on the background of related studies, which address coke formation by using gaseous hydrocarbons as experimental feedstock. This type of work was completed at various international universities and R&D institutes in recent years.

The mechanism leading to coke formation depends on the starting materials, which undergo "coking". The catalytic conversion of hydrocarbons is a mature subject and came into it’s own especially during and after World War II. The starting materials, in the gaseous, liquid or solid state are affected by variables such as: pressure, temperature, surfaces and catalysts if present.

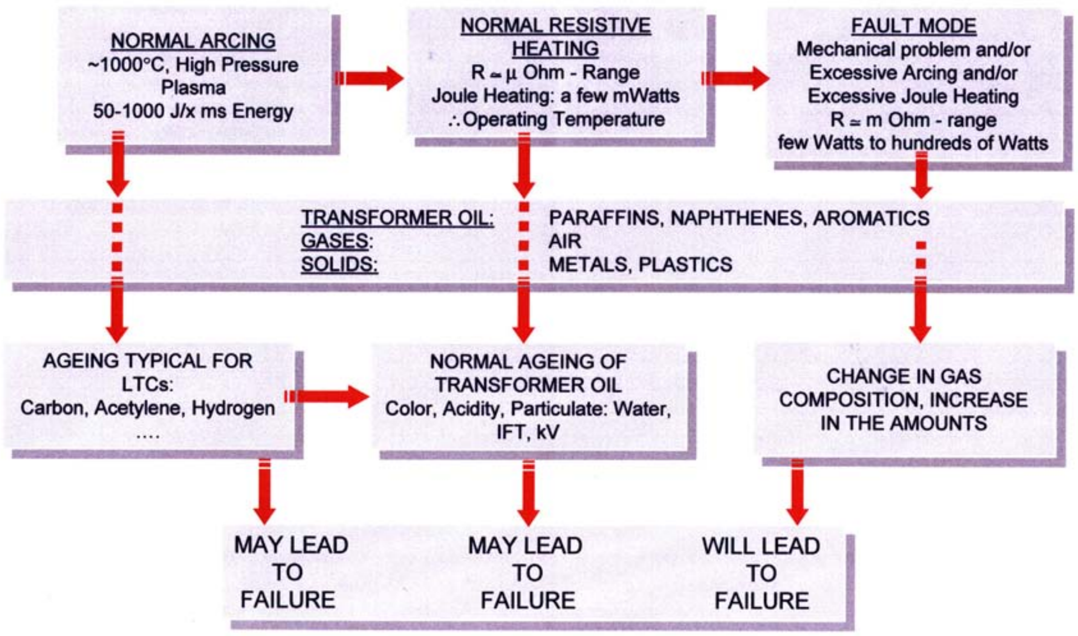

Figure 3-1
LTC Stresses

Thermal Model

Low to medium temperatures in combination with low pressures (typically: •300°C and •1 atm) favor the dehydrogenation of hydrocarbons (HC), and these conditions apply to mineral-based transformer oils (mixtures of HCs) in LTCs.

Cracking reactions of hydrocarbons such as C-C bond ruptures, are endothermic and thus thermodynamically favored reactions at medium to higher temperatures. They are depicted below.

<u>Cracking of paraffins (alkanes)</u>

$$C_nH_{2n+2} \rightarrow C_pH_{2p+2} \quad n = m+p \qquad \textbf{Equ. 3-1}$$

<u>Cracking of paraffins (alkenes)</u>

$$C_nH_{2n} \rightarrow C_mH_{2m} + C_pH_{2p} \quad n = m+p \qquad \textbf{Equ. 3-2}$$

<u>Cracking of aromatic hydrocarbons (benzene etc.)</u>

$$Ar - C_nH_{2n+1} \rightarrow ArH + C_nH_{2n} \qquad \textbf{Equ. 3-3}$$

These basic cracking reactions may be accompanied by side-reactions such as hydrogen transfer, the formation of free hydrogen, the formation of free carbon, the isomerization, the trans-alkylation of aromatics and cyclization processes. At medium to higher temperatures exothermic *alkylation* reactions will occur.

<u>Inversion temperatures are around 400°C. Olefins will polymerize</u>:

$$2\,C_2H_4 = C_4H_8 \quad Ti = 527°C \qquad \textbf{Equ. 3-4}$$

A great number of other reactions are possible, for example "free radical initiated" processes like aromatization and the formation of poly-aromatic compounds [19].

Indeed all of these reactions can occur in a LTC, if the equipment goes into fault or failure mode. We conducted temperature controlled furnace experiments at Powertech Labs Inc. Insulating fluids, indeed, undergo under simulated and field conditions these chemical changes.

Proposed Coking Mechanism

Coking at low and intermediate temperatures, according to the evidence from the field, appears to be a possibility. We would assume, for this to happen, the transformer oil in the LTC is either in an advanced state of ageing or generally it is outside the quality specifications for transformer oils (new or recycled). It is of interest to find out whether this applies mainly to reused old transformer oil, regenerated insulating oil, and/or transformer oil where the oil quality deteriorated while in service. Different scenarios should be considered.

First Scenario "Normal Ageing via Oxidation"'

For this case to occur the transformer oil is in the acceleration or saturation period of aging [18]. This oil would have no inhibitor protection, natural or otherwise and would rapidly deteriorate to a state, where the formation of sludge is natural. We are essentially concerned with the oxidation of oil via oxygen uptake and the formation of peroxides. This might lead to the build-up of alcohols, ketones and carboxilic acids. The presence of copper, and perhaps water, will accelerate this process significantly. We observe a rapid decrease of interfacial tension (IFT) and a major increase in the neutralization number and water content (Figure 3-2: Phase II and III).

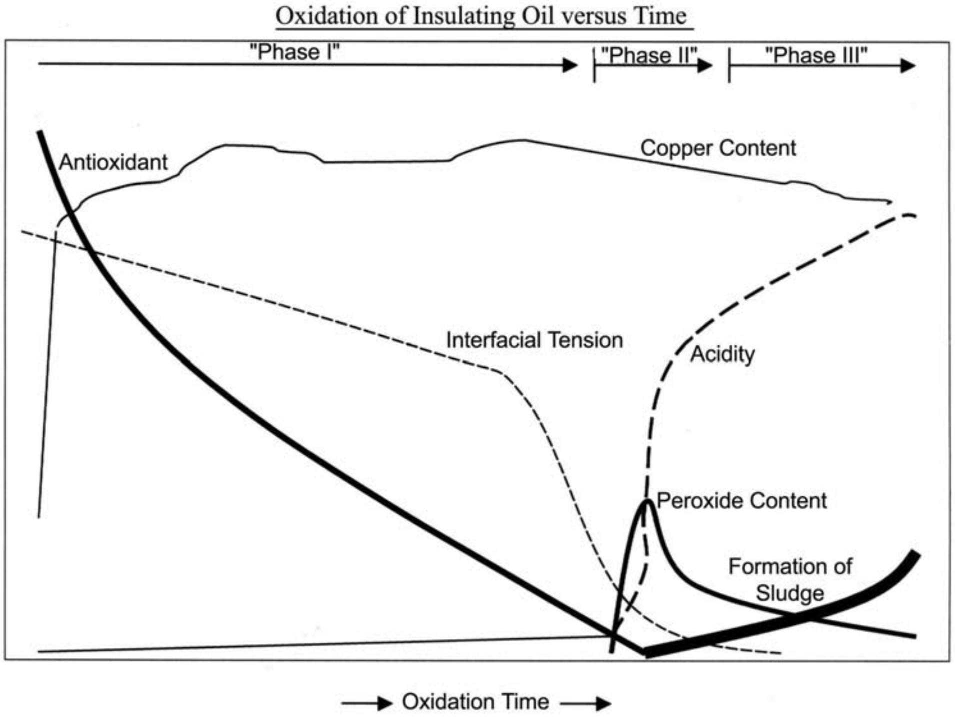

Figure 3-2
Oxidation of Insulating Oil versus Time

To detect this occurrence chemically, the focus is on the changes to interfacial tension, acidity, non-gaseous products, and dissolved-gas-in-oil (DGA). This is most likely to occur in free-breathing transformers.

We suggest, for most "sudden" sludge or coke formations in LTCs, another setting:

Second Scenario "Reverse Refining"

We have experimental evidence to formulate another mode of ageing, which we call for a lack of a better term *reverse refining*. The previous Figure 3-2 does not describe this ageing process. This mode of ageing is common to electrical equipment such as oil-filled switchgear, especially LTCs. Reverse refining occurs when both arcing and high temperature persist, as is the case in

LTCs. It is, to express it in a somewhat "pointed form", the reversal of the refining process. Refining is a string of chemical conversions and treatments, which converts a middle distillate fraction of mineral oil into the sophisticated refinery product labeled ‘insulating oil’. For many years the refining of mineral oil and its process-chemistry consisted of the removal of unsaturated compounds including olefins (alkenes) and acetylenes (alkynes). The detrimental chemistry, which these compounds impose on the finished products, is well documented and understood. Their presence in mineral oil-based transformer oils results in fluids, which are lacking storage stability and resistance to thermal and other stresses. They promote the formation of ‘tacky’ deposits, lacquer-like coatings and can lead to the slow or sudden formation of sludge. Their presence in finished petroleum products is not desired. Their chemistry is akin to self-drying or polymerizing paints.

Third Scenario

We suspect that pyrolytic processes as described under "two" might be accompanied and are accelerated by ageing processes according to "one". The presence of oxygen (and/or water) facilitates. In fact the deterioration of the reverse re-fined transformer oil will be accelerated and/or promoted, since oxygen in oil is a potent, natural "free radical", which has a tendency to react with the compounds mentioned. These compounds are prone to attach to metallic surfaces, polymerize and/or react with any suitable agent.

Powertech Labs Inc. addresses in this study the effects of arcing, partial discharge and gross overheating on the chemistry of insulating oils in oil-filled switchgear.

The preoccupation with:

- The pyrolysis of transformer oil
- The elucidation of the conditions leading to the formation of sludge and / or deposit, and
- The applicable diagnostics,

resulted in simple, yet essential designs of specific laboratory equipment and reinforced the need for field studies that simulate stresses in live LTCs. There existed also a need for a limited LTC survey, which would put the results from the laboratory and the field case-study in perspective. This reference to a database of working LTCs would force us to assure that our work on diagnostic tools does indeed address the practical requirements of engineering and substations personnel.

So far, the results of this study helped us to identify correctly, and with factual conviction, several LTCs in fault mode. We are prepared to state that this EPRI-sponsored study provided a positive cost/benefit ratio to our sponsor B.C. Hydro at this stage of the investigations and will result in additional maintenance guidelines.

Researchers at Hebei [16] suggested a sequence of events, which is depicted in Figure 3-3. They studied the effects of pretreated surfaces, possible mechanisms, and the kinetics of coke deposition (800°C) and coke precursors. Zou Renjun et al studied in great detail the pyrolysis of propane and presented their findings as a model for the pyrolysis of hydrocarbon feedstock in general.

POSSIBLE MECHANISM OF COKE FORMATION

[1] Olefins (Alkenes), Alkynes are easier adsorbed on surfaces (metals) than paraffins due to π-electrons

For Example:

Coke precursors for the pyrolysis of propane are ethylene and propylene. At the "Hebei Institute" (Peoples Republic of China) the sequence leading to coke formation has been described thus:

1. Ethylene, propylene
2. Cyclo olefins
3. Benzene, Alkylbenzene, (Aromatics)
4. Nuclear Condensed Aromatics
5. Coke

Figure 3-3
Proposed Mechanism of Coke Formation (Hebei)

The chemical sequence leading to the formation of coke, as suggested by the researchers agrees with our experimental findings, as well as our field observations, and thus the given sequence of precursors appears to apply also to the process of coking in LTCs. The only difference is in the starting materials: insulating oil instead of propane.

This mechanism, which might be called loosely the <u>ethylene mechanism for coke formation</u>, does not imply that ethylene is necessarily the starting material in the chain of events leading to the coking of LTCs. This only implies that the chain of events is thought to be correct and applicable, but that any of several of the precursors listed in the mechanism might be the starting material for coke formation in LTCs.

The unsaturated hydrocarbons of Step 2 to Step 4 in Figure 3-3 are the critical compounds, which are available in severe thermally treated and/or transformer oil, which suffered arcing stress. The coke-precursors can be derived from both sources: gaseous hydrocarbons and mineral oil-based transformer oil with equal ease.

Powertech Labs Inc. presents in this report such evidence, based on our experimental work as shown in the schematic Figure 4-3.

The physical/chemical process of gum and sediment formation can be found in more detail in the literature [25,26]. Olefines as components of cracked distillate fuels have been recognized early on to participate in the formation of gums or tacky deposits. The previously described process of ‘reverse refining’ includes ‘cracking’ of transformer oil (equation: 3-1 to 3-3).

Historically the addition of oxygen to diolefins was one of the first mechanisms to be elucidated, the oxygen adds to the hydrocarbon forming a peroxy radical, which then can further react to form either a hydroperoxide or a dialkylperoxide. This is a typical starting sequence for fuel degradation as shown in the following sketch of four to five crucial mechanisms:

i) Oxidation/autooxidation

ii) Acid/Base reactions

iii) Condensation

iv) Polymerization: Free radical and ionic addition and condensation

v) Hydrogen bonding leading to

nucleation or agglomeration. These latter processes lead under storage conditions to the formation of sediments, but under thermal conditions result in migration to hot surfaces, adherence and the formation of surface deposits. Olefins in combination with oxygen are excellent starting materials. "For example, complete removal of dissolved molecular oxygen eliminates surface deposits until relatively high temperatures are encountered" [26].

Electrical Stress Model

Arcing in Oil

A simplified view of an arc is shown in the following diagram (Figure 3-4):

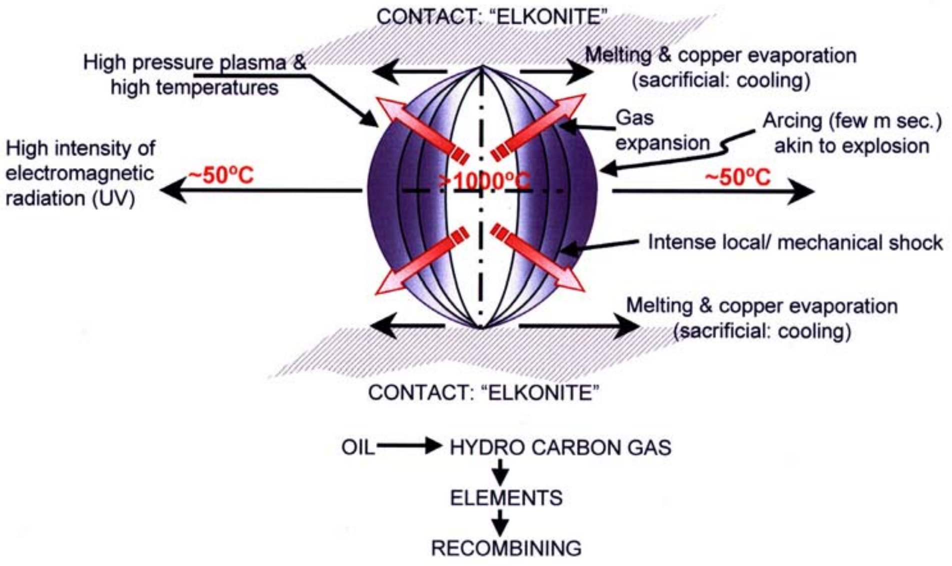

Figure 3-4
Conceptual Model of an Electric Arc

During the operation of a large number of LTCs, especially of the older vintage LTCs, certain switching contacts are subjected to incipient and breaking arcs of high energy. These result in arc stress of contacts and oil. This type of electrical stress is usually accompanied by Joule heating of the contact material, associated hardware and oil leading to the thermal breakdown of the oil. The temperatures can be quite high - as all know, who inspected visually the scarred surfaces of Elkonite or similar copper / tungsten composite alloys. Welding occurs and is usually indicated by small spheres of molten metal and by contact-surface ablation.

The result of all of this will be accelerated sludge deposition, the coating of contacts, which is followed by Joule heating; not to mention the catalytic effects of real and colloidal dissolved copper. These actions are followed by baking of deposits, coke formation and finally, perhaps, LTC failure.

The formation of the arc products is related to arc energy, which in turn depends on the number of switch operations of the LTC [10]:

$$W = \int u \cdot i \cdot dt$$

with

W = the arc energy, u = voltage, i = current, t = time

The time dependent arc-energy depends only on N•I, in which N is the number of operations of the LTC. In modern LTCs the arc quenching can be achieved in a few milliseconds. According to this paper the LTC's arcing contacts are designed for about 200,000 operations at full load. These authors relate, similar to Powertech's understanding and observations of LTCs, (N•I) to the concentration of specific gases:

$C_{cc} = K_{cc} \cdot (N \cdot I)$

with

C_{cc} = Concentration of chemical compound X,

K_{cc} = a collective constant, which is among other things equipment specific.

At Powertech Labs Inc. we are less inclined to correlate C_{cc} to benzene or toluene concentrations.

Coking of Contact Surfaces

During the operation of LTCs the thermal and electrical models apply simultaneously. The contact surfaces of all switches in the normal, operating mode of the LTC, which are: reversing switch, diverter switch, or selector switch assembly function as conductors of electric current (amps). Coating with transformer oil will occur at the interfacial layer of the contacting surfaces: 'contact metal-transformer oil-contact metal'. The applied EMF (voltage) will impress a current via the organic interface and contacting islands of metal. The scenario in this microenvironment during contact making and breaking will display arcing and partial discharge, accompanied by Joule heating. The temperatures in this organic interface, initially transformer oil, will be very high resulting in hydrogen loss (dehydrogenation). The driving force is Le Chatelier's Principle: "Every system in equilibrium is conservative, and tends to resist the changes upon it by reacting in such a way as to help nullify the imposed change."

Laboratory Simulations

It was decided to simulate the stresses, which are observed in the field, in the laboratory. The oil was analyzed by headspace and dissolved gas-in-oil (DGA) chromatography, supplemented by gas chromatography/mass spectrometry (GC/MS) and high performance liquid chromatography (HPLC). The feedstock for most experiments was Voltesso-35, degassed to utility standards with a water content well below 10 ppm. The feedstock was stored under a nitrogen blanket.

Field Simulations

BC Hydro Engineering provided an LTC/Voltage Regulator at one of their substations (Kent Substation, Figures 5-1 to 5-4). The LTC was modified to simulate high tap-change operations under accelerated conditions. The changes in oil, gas phase and contact material were analytically monitored.

A Federal Pioneer (1975 vintage), 33-step voltage regulator was used to model LTC switching. This unit was set up to cycle through one thousand tap change operations per day. A temperature monitor was installed to continuously monitor the switch tank temperature. Oil samples were taken periodically and analyzed for: particulate type, metals, moisture, dielectric strength, dissolved gases, and non-gaseous pyrolysis products. The results of analysis were related to the number of operations and condition of contacts following inspection. Gas-in-oil analysis is an important tool for monitoring the condition of power transformers and oil filled sub equipment. BC Hydro has also used this method for investigative work on other types of substation apparatus, including instrument transformers. Gases are produced by the dissipation of energy in the oil. This energy can come from electrical discharges, dielectric losses, resistive and eddy current heating, mechanical vibrations, friction, and chemical reactions (rusting, electrolysis, oxidation, etc.).

The primary sources of energy in the most common LTCs are arcing at the diverter switch and low-level heating at the selector and reversing switch contacts, at least that is the current thinking. Other sources may be current-limiting resistors and reactors, actuators, etc. depending on the design.

Statistical Approach – Data Base Analyses

The survey as conducted by Powertech Labs Inc. and the fieldwork sponsored by EPRI and BC Hydro incorporated originally fifty-five, randomly selected LTCs and included as many makes/models as possible (Table 3-1).

In the end about one hundred LTCs, as many makes/models as the survey could accommodate, were sampled and the full set of analytical tools: traditional and non-traditional methods were applied to gain information for the database. Factual insight, which was gained during the laboratory work and the case study at Kent Substation, was applied to interpret the database and reach some generalizations concerning LTCs. This limited survey was applied to predictive maintenance at B.C. Hydro, was reasonably successful and prompted the utility to be supportive of the project.

LTCs are usually maintained by frequent external inspections and annual oil testing for dielectric strength, water content, color, and acidity. Internal inspections are scheduled every 5 - 10 years, or after 50, 000 to 100, 000 operations. Routine overhauls usually focus on the diverter switch, and typically involve removal of the mechanism, cleaning components and the oil compartment, changing the oil, measurement of contact wear and replacement of parts as required. The mechanical components, resistors, reactors, actuators, relays, and oil filters are also replaced, as required. Selector switches, if housed in a separate tank, are inspected less frequently, for example Reinhausen [32] suggests that one type of tap selector can be left alone for a far larger number of operations. The potential benefits of condition-based maintenance regimes for LTCs have been described elsewhere. There is a general consensus that effective monitoring is required.

Table 3-1
Survey of LTCs #1

Manufacturer/ Abbreviation	Manufacturer	No. of Models	No. of Units	Fingerprint (chemically)
ABB	ASEA Brown Boveri Inc.	2	4	4
ASA	ASEA	18	43	4
BBC	Brown Boveri Canada Inc.	3	5	2
CGE	Canadian General Electric	6	56	5
EEC	English Electric Company	2	2	2
FPD	Ferranti Packard	9	24	6
FPE	Federal Pioneer Limited	5	18	3
HSD	Hawker Siddeley Diesel	5	18	2
JZN	Janzen	1	3	2
MAR	Maschinenfabrik Reinhausen	37	97	14
MLY	MYL	1	1	1
OTC	Osaka Transformer Company Ltd.	1	5	2
REI	Reinhausen Dr. Jansen	4	6	2
SEA	Sears	1	2	2
TOS	Toshiba	2	2	2
WCL	Westinghouse Canada Limited	2	7	2
	TOTALS	99	283	55

Ideally, the assessments would be sufficiently accurate to reduce maintenance costs to the absolute minimum, while increasing reliability and providing advance warning of pending failures.

4

LABORATORY WORK

Introduction and Overview

The LTC environment is rich in sources of stress, which were simulated with the aid of:

- A thermal stress unit, which is essentially a micro furnace milled out of Elkonite 3W3, that can reach (oil flow dependent) temperatures of up to 800°C with an oil/surface contact time of about 30 seconds . The results for thermal stress are the result of single contact of the oil with the hot surface of the micro furnace unless stated otherwise
- A micro-coker, which permitted the even flow of oil across heated surfaces at precise temperatures
- An arc stress unit, with conic Elkonite 3W3 electrodes, at a gap of 0.7 mm, an applied voltage of about 12.5 kV and a current of about 30 mA of (magnetic stirring).
- Corona/Partial Discharge Stress using the "Gassing Tendency Apparatus (ASTM D2000)" and other equipment

Ideal conditions for chemical modification of transformer oils are found in LTCs. Dissolved gases, liquids, solids are formed, which are supplemented by colloidal dispersions of sludge, perhaps, containing inorganic materials such as copper that accelerate the aging of insulating oils. Large metallic surfaces exist, which act as reactive surfaces and/or heat sinks (Figure 5-3), where the plating-out of certain dissolved and/or colloidal materials take place.

The chemistry for thermal stress, when the temperatures are sufficiently high (Figure 4-3), is schematically shown (Figure 4-4) and explains the process of coking events in overheating (O)LTCs.

All the compounds as listed in the Hebei Mechanism (Figure 3-3), are also present if the oil was exposed sufficiently long to arcing and qualify as precursors to coking (Table 4-4). We have the experimental evidence to prove it (Powertech Labs Inc. un-published data).

Powertech Labs Inc. has shown, if used filtered (0.8µ) insulating oil from an LTC is passed over a hot surface (for 24 hours, at 225°C, and at 1 atmosphere), a substantial layer of a black coke precursor is deposited (Figure 4-25). This deposit usually forms due to thermal stress at higher temperatures, typically 350°C and higher. New Voltesso-35 will yield under the same conditions and with the same type of test coupon (milled, polished copper) a clean surface. We have demonstrated (un-published results), while this report is being written, that the formation of coke precursor as just described is also possible at surface temperatures of 225°C and is due to arc stress rather than thermal stress.

This deposition of black surface deposits (sludge) will occur when arc-stressed transformer oil is in contact with hotspots at temperatures of 225°C or higher. The LTC could sludge up within a few days and fail. This would be a low temperature failure, in reference to Figure 4-3.

Products and Parameters to Monitor

The samples were derived from the laboratory, the field-case study or the LTC-survey. Many of the following parameters were monitored: (Most samples were either transformer oils or headspace gases, and a few solids. The sampling schedule was kept flexible.)

Chemistry:

- Traditional oil quality data
- Gas-in-oil (DGA ASTM) analyses were performed
- Benzene, ethyl-benzene, toluene and xylenes by (BTEX) analysis
- Volatile organic compounds by gas chromatography/mass spectrometry (GC/MS)
- Poly-aromatic hydrocarbons by high performance liquid chromatography (HPLC)
- Free radicals by an in-house method (semi-quantitative)
- The amount of particulate matter by weight and also by particle size distribution
- Metals by inductively coupled plasma emission spectrometry (ICPA)

Metallurgy:

- Investigation of some contact samples by scanning electron microscopy and more traditional tests like hardness
- Analysis of some graphitic residues

The goal was to find non-invasive diagnostic techniques for the detection of unwarranted stress in LTCs. These two experimental set-ups were used to investigate hotspot chemistry between 50˚C and 800˚C.

Thermal Stress

The bench studies were designed to simulate both normal and abnormal thermal operating conditions as might be encountered by LTCs:

i) Insulating oil was passed at temperatures of 100°C to 800°C through an Elkonite furnace (Figures 4-1, 4-2). The product stream, containing gaseous and non-gaseous decomposition compounds, was analyzed by chromatography and by mass spectrometry.

ii) Similarly, in a micro-coker transformer oil was circulated at a constant rate and surface temperatures (±0.2°C) across metal coupons of copper, silver and Elkonite. These coupons had thermocouple implants at 0.5 mm below the specimen surface (Figures 4-21, 4-22).

Elkonite Furnace

The copper heater blocks, cartridge heaters and Elkonite furnace were insulated with rock wool, while the cooling ribs and the exposed cartridge heaters and leads were cooled with forced air. This unit has a heat input capable of maintaining a constant temperature anywhere from 50°C to 800°C at a pumping speed of about 2.5 ml of oil/minute (not shown: magnetically driven micro-pump). The usual operation of this unit was single pass: the oil (degassed and under nitrogen blanket) would enter the furnace, move through a gas separator (quartz) and into a 50 ml capacity all-glass 'gas-in-oil' syringe (positive displacement); while the gas from the gas-separator collected in a gas-burette under slightly negative pressure (against mercury). The system was rinsed, prior to operation, with inert gas (nitrogen).

The Elkonite furnace permitted us to feed transformer oil (degassed Voltesso-35, nitrogen purged, 20 ppm H_2O) at a constant, slow stream through the heated furnace (Figure 4-2). The thermal runs from 100°C to 800°C were conducted at 50±0.2°C temperature intervals, 74 sec contact time and an effective fluid-film thickness of 2.4 mm. The maximum available heat input amounted to 400 watts and was supplied by two directionally opposed, thermally regulated cartridge heaters. The thermal/catalytic cracking of hydrocarbons at temperatures from 150°C to 800°C (endothermic processes, high entropy) favors the formation of methane, hydrogen, alkenes (olefins), alkanes and numerous other compounds. The reasons for the renewed experimental investigation of this well-known process are twofold:

i) inhibited petroleum-based insulating oils, although middle distillates, are not the usual feed-stocks for cracking

ii) Elkonite*, one of the common contact materials for LTCs, is not a typical cracking catalyst

Experiments

The temperature range of 150°C to 800°C, in our estimation, covers roughly the thermal environment encountered in LTCs under normal operating conditions. The melting point of brass, was assumed to lie anywhere between 800°C and the melting point of copper (1083°C). Old diverter switches typically show residues of molten copper; we concluded that a temperature of 800°C appeared to be a suitable, upper thermal limit to aim for.

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* This is a composite material of copper infused, sintered tungsten

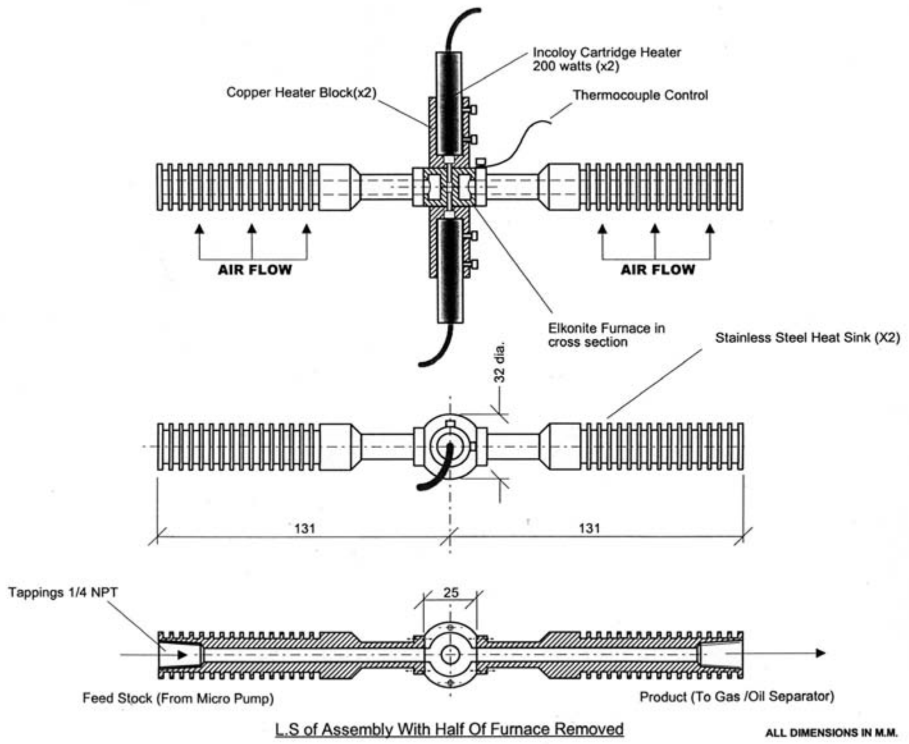

Figure 4-1
Schematic: "Elkonite" Micro Furnace

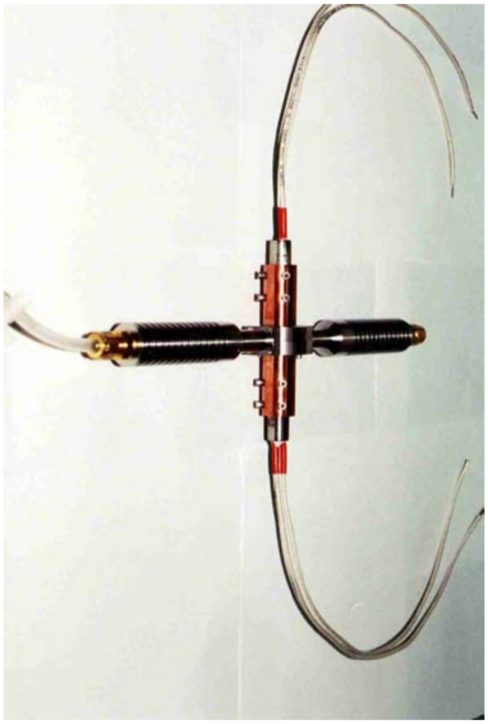

Figure 4-2
"Elkonite" Micro Furnace

This temperature – controlled furnace permitted the study of the catalytically promoted, thermal breakdown of insulating oil (Voltesso-35). The reaction products are mostly hydrocarbons of lower molecular weight than the starting material. In addition hydrogen, carbon and a host of other compounds of greater and lesser complexity are formed. The step-wise heating of mineral-based insulating oil (Voltesso–35, degassed, nitrogen purged) from 150°C to 800°C (at 50°C increments) permitted the observation of distinct thermal ranges as presented simplified in Table 4-3.

Results/Overview

The Formation Of Sludge Precursors

Thermal processes, especially catalyzed thermal processes, arcing and partial discharge, to name the most important stresses, contribute to the ageing of transformer oil. It is always problematic, if the insulating oil is left unchecked in the electrical equipment for a great length of time, especially at operating temperatures higher than usual (for example >60°C). The pre-stressed oil may have moved in its properties beyond the oxidation induction period, it might have entered the acceleration, or perhaps, the saturation period. (Bartnikas).

RELEVANCE OF THESE FINDINGS FOR OUR DATA

[3] Laboratory runs at Powertech Labs Inc.

- [i] Thermal runs over Elkonite (furnace) (nitrogen saturated) to study "Gas in Oil" and "Gas Composition"
- [ii] Thermal runs over heated discs (recirculator)
- [iii] Unit to study arcing (use of Elkonite electrodes)

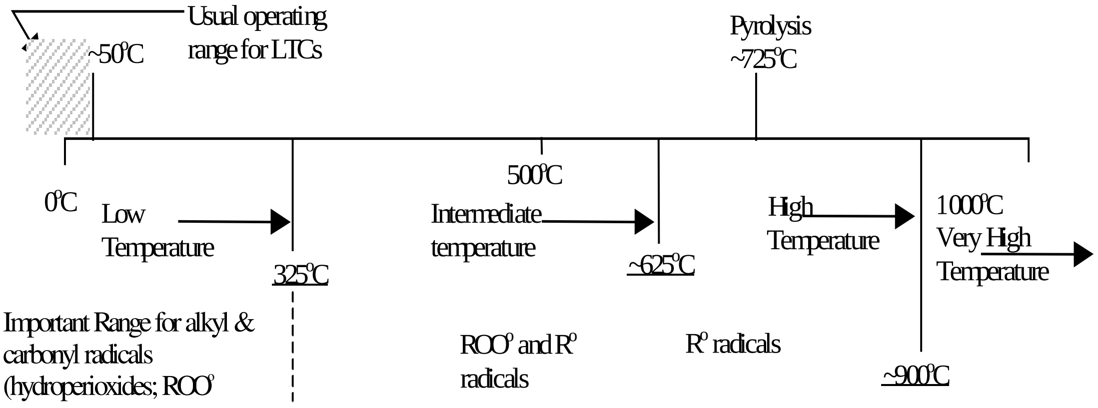

Figure 4-3
Powertech's Experimental Findings with Stressed Insulating Oil

Since the ageing of insulating oil, for most LTCs, takes place in the presence of dissolved oxygen, the sludge precursors described so far will have co-mingled oxidation products of same (alcohols, ketones, carboxylic acids, asphaltenes etc.). Usually this behavior coincides with other chemical changes, for example an increase in acidity and a sharp drop in interfacial tension.

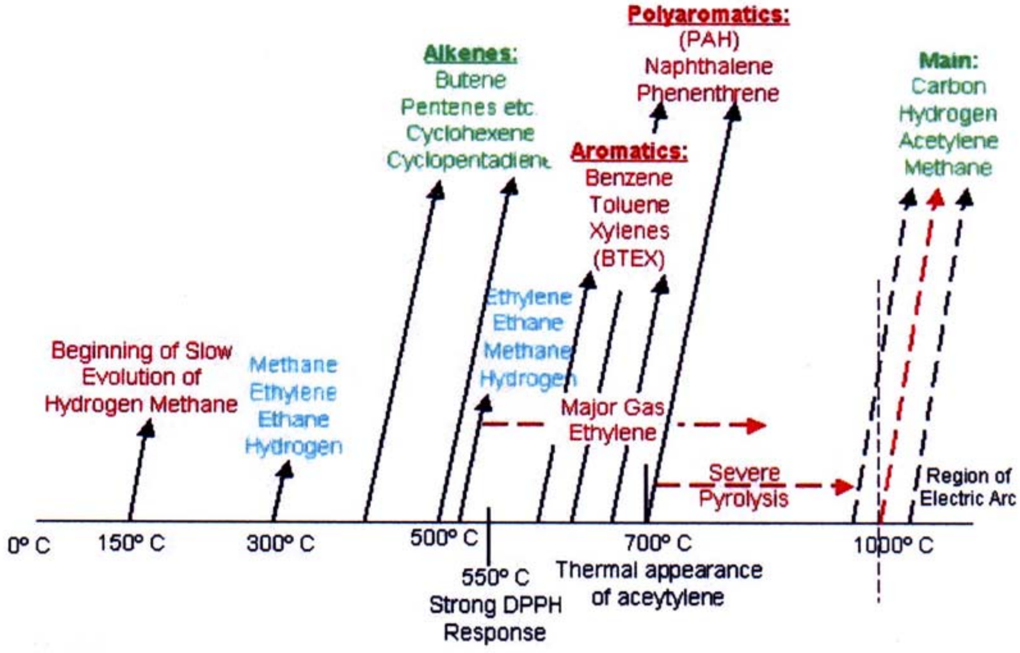

Figure 4-4
Graphical Presentation of Findings for Thermal Stressing of Mineral-Based Insulating Oil

The formation of sludge as well as of a black surface deposit is a function of oil aging, which we shall define as a depletion of the natural and man-made inhibitors (DBPC).

Aside from these processes, other changes take place, which result in oil deterioration and which are not the result of oxidation but rather a result of "reverse refining" (Section 3).

Thermal processes, catalyzed thermal processes, arcing and partial discharge, to name the most important ones, contribute to both ageing processes of transformer oil. It is always problematic if the insulating oil is left unchecked in the electrical equipment for a great length of time, especially at operating temperatures higher than usual (for example >60°C). The pre-stressed oil may have moved in its properties beyond the oxidation induction period, it might have entered the acceleration, or perhaps, the saturation period.

Worse from a maintenance point of view is the fact that simultaneously with normal ageing "reverse refining" may take place.

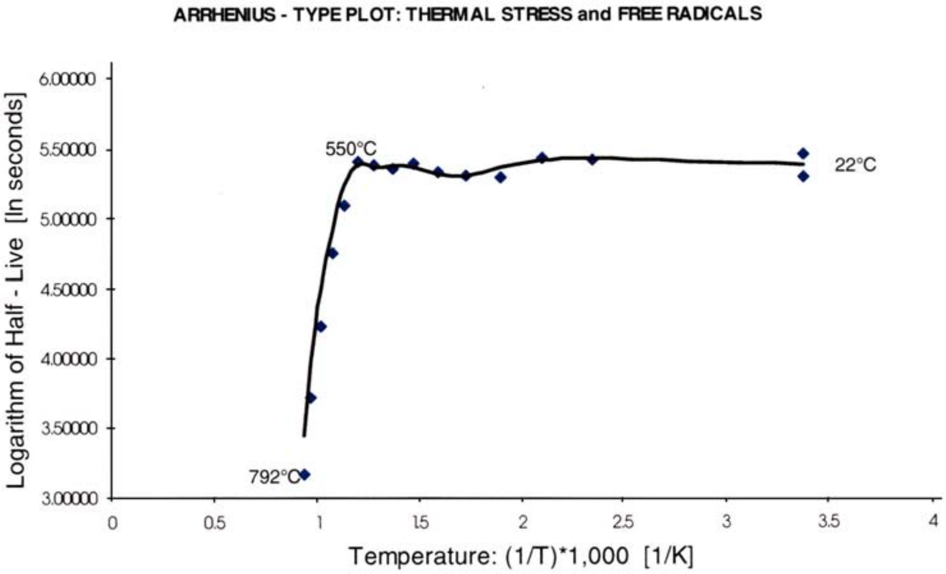

Figure 4-5
Appearance of Free Radical Scavengers and Tackiness

We made an interesting observation of practical implications. The onset of "threshold temperature" (Figure 4-5) is accompanied by a physical characteristic of the thermally stressed transformer oil, best described as tackiness.

This sudden change is accompanied by the production of a host of new compounds (Figure 4-4), especially alkenes (olefins), cyclic alkenes and alkynes, which easily adhere to metallic surfaces [16].

Coinciding with the appearance of this "threshold" (Figure 4-5) is the appearance of poly-aromatics (PAHs), a set of chemical compounds listed in the sequence for the formation of coke (Figure 3-3; step #4). We identified and measured by GC/MS some of these PAHs. The results are given as Arrhenius plots in Figure 4-6.

A review of the literature on transportation fuels (gasoline, middle distillates) reveals that early on the refining industry realized that olefines, among others, are responsible for the formation of sticky deposits on valves and other metallic surfaces [25,26]. These in turn lead to the formation of varnishes, petroleum resins and coke. The bromine number is traditionally used to quantify olefins (ASTM D1159).

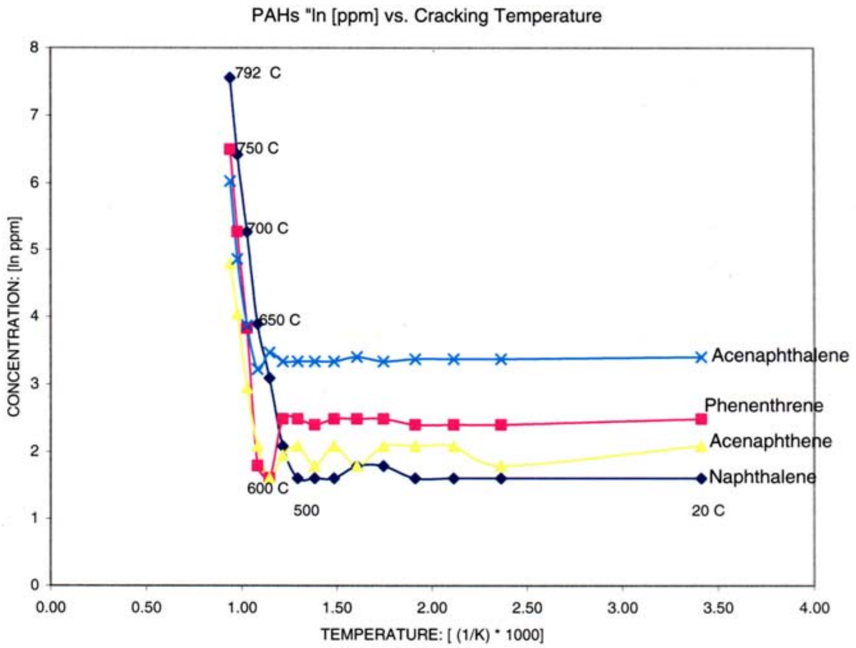

Figure 4-6
Thermal Formation of Polyaromatics from Transformer Oil

Should such surface deposits be exposed to higher temperatures (typically around 800°C), one may observe the typical formation of coke as reported by Marek in his doctoral thesis [24]. We have observed the growth of filamentous coke and the other forms of coke, as described by Marek.

Figure 4-7 shows globular as well as filamentous coke (coils), which was formed in the micro furnace at around 800˚C.

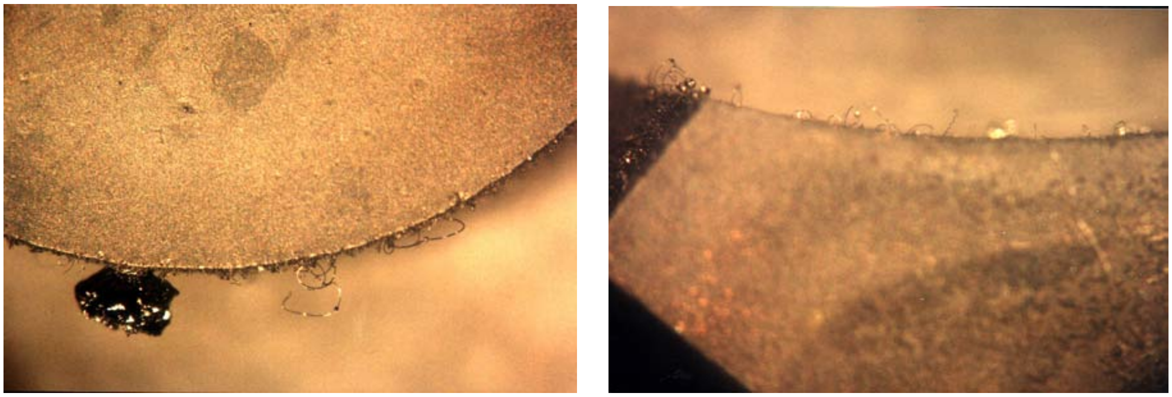

Figure 4-7
Micro-furnace: Growth of Globular and Filamentous Coke (coils) at ≤800˚C

We propose that depending on the type of stress: thermal, arcing, corona and other specific conditions, some of the listed precursors (Hebei; Figure 3-2), which are found in thermally stressed, mineral-based transformer oil, can reach significant concentrations and begin to adhere and form surface deposits.

These surface deposits, in a secondary process, suffer dehydrogenation and the molar ratio of hydrogen versus carbon[*] declines until this ratio reaches a value of perhaps <0.3 and eventually turn into graphite like substances, which contain inorganic matter (Figure 4-24 and Table 4-3).

The <u>laboratory work</u> provided a temperature profile for the thermal formation of fault gases (Figure 4-1). The details and the thermal profiles for these and other chemical compounds are graphically displayed on the following pages, and proved useful for LTC fault diagnostics.

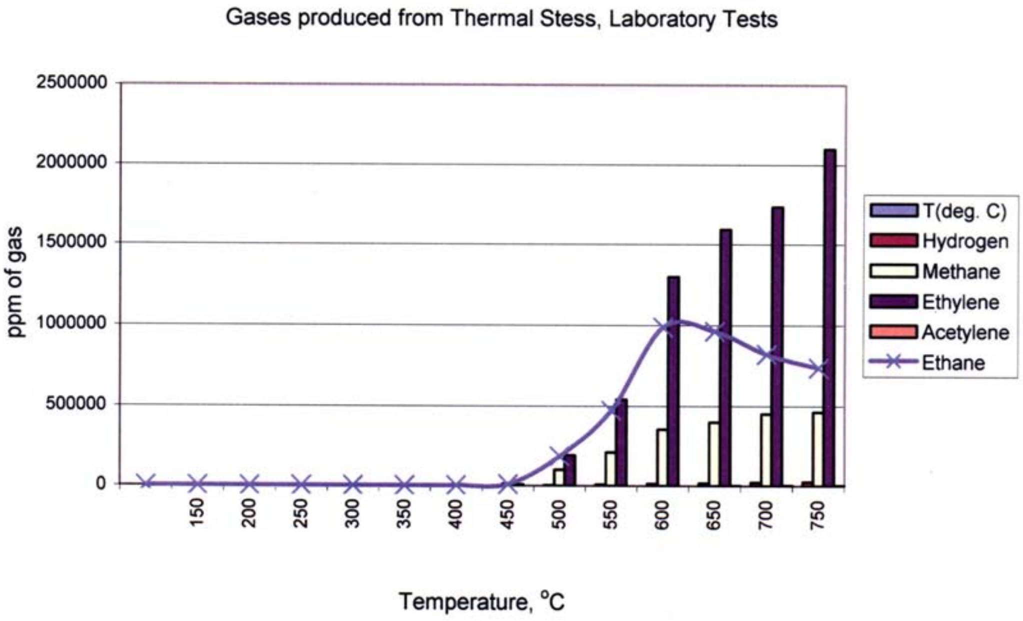

Figure 4-8
Gases Produced from Thermal Stress, Laboratory Tests

Powertech Labs Inc. found that, in the <u>case of arcing</u>, experimental set-ups appear to have a very minor influence on the outcome of "arc-chemistry". The proportions of hydrogen, methane, ethane, ethylene, and acetylene are almost identical over a very wide range of arc energies. Table 1 shows a comparison of total gas[*] (Vol.%).

The data being taken from similar tests, *two decades apart and at different laboratories* are compared, including the data from the 1998 "case-study" (Kent).

---

[*] headspace, gas-in-oil

Table 4-1
Comparison of "Total Gas"

C_2H_2	C_2H_4	C_2H_6	CH_4	H_2	(headspace+gas-in-oil)
26.8	4.9	0.16	4.0	64.1	IREQ, 1978 [21]
24.4	3.7	0.21	3.5	68.2	Kent, 1998
24.7	2.7	0.14	4.4	67.9	PLI, 1997, lab data

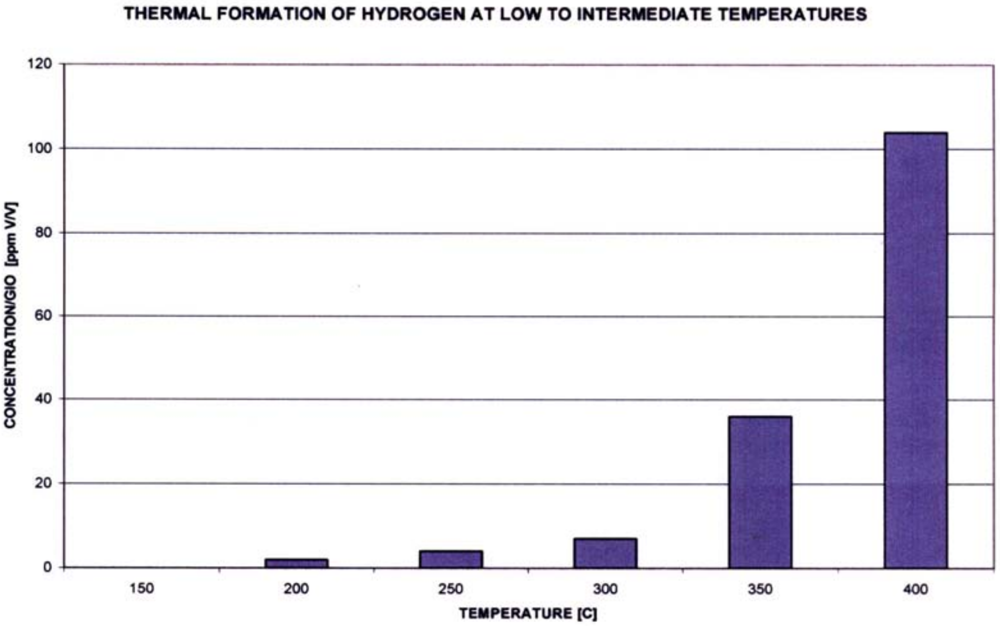

Figure 4-9
Thermal Formation of Hydrogen at Low to Intermediate Temperatures

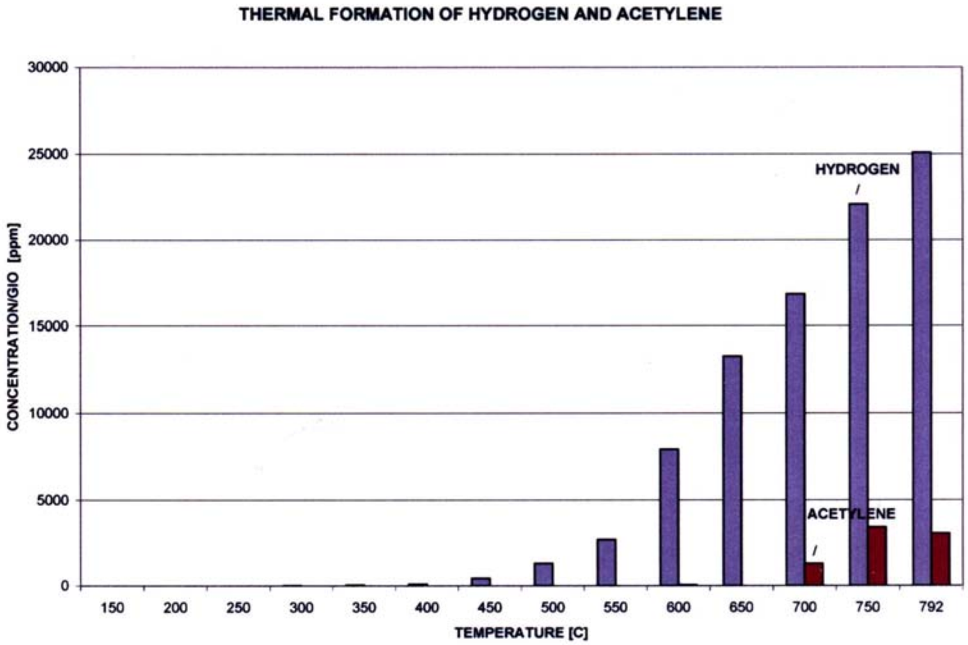

Figure 4-10
Thermal Formation of Hydrogen and Acetylene

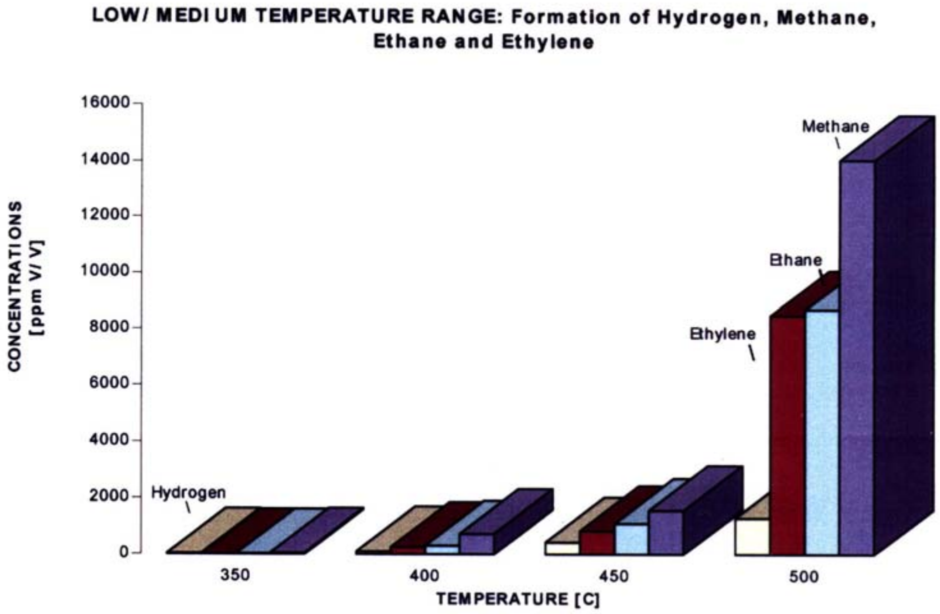

Figure 4-11
Low/Medium Temperature Range: Formation of Hydrogen, Methane; Ethane and Ethylene

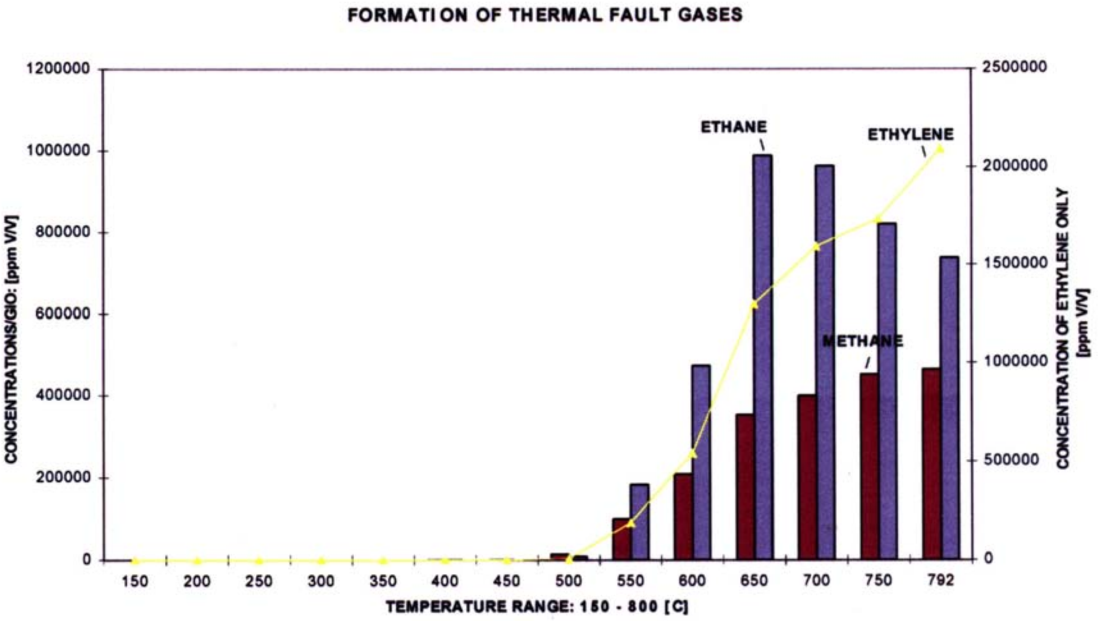

Figure 4-12
Formation of Thermal Fault Gases

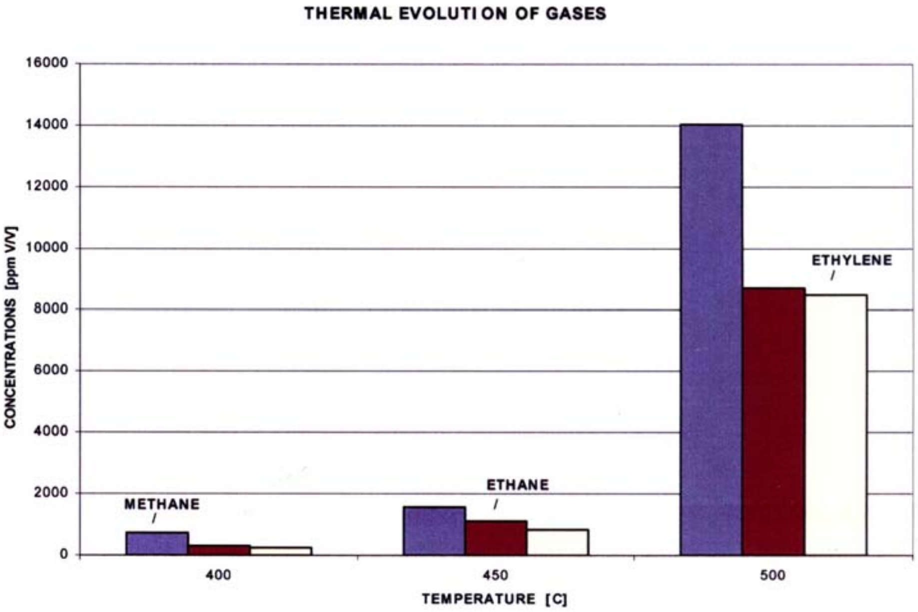

Figure 4-13
Thermal Evolution of Gases

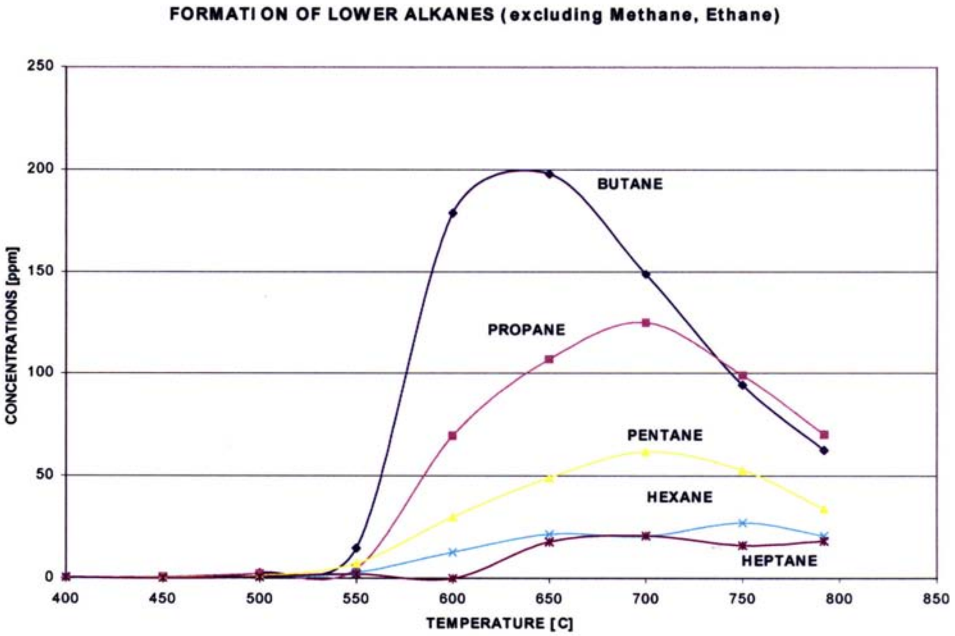

Figure 4-14
Formation of Lower Alkanes (excluding Methane, Ethane)

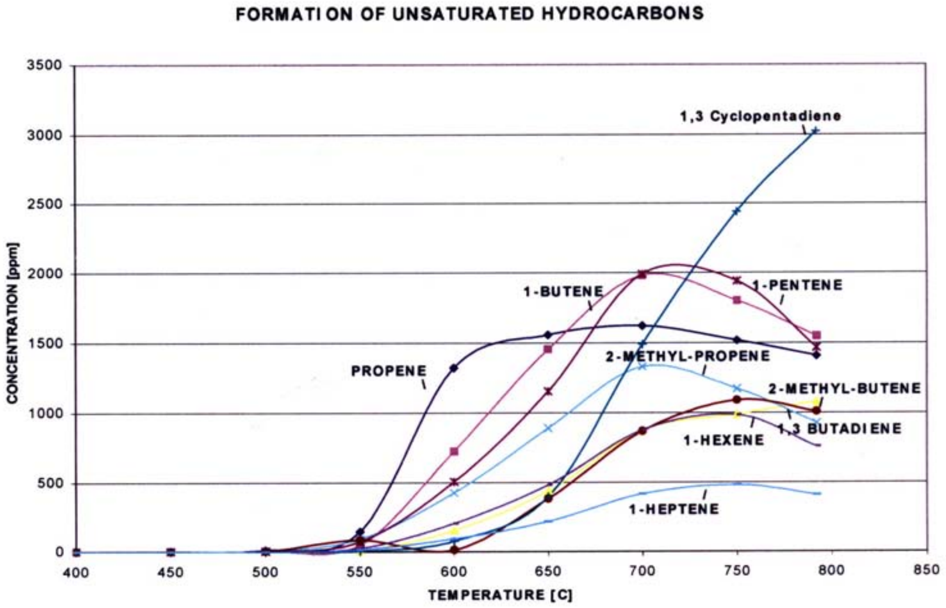

Figure 4-15
Formation of Unsaturated Hydrocarbons

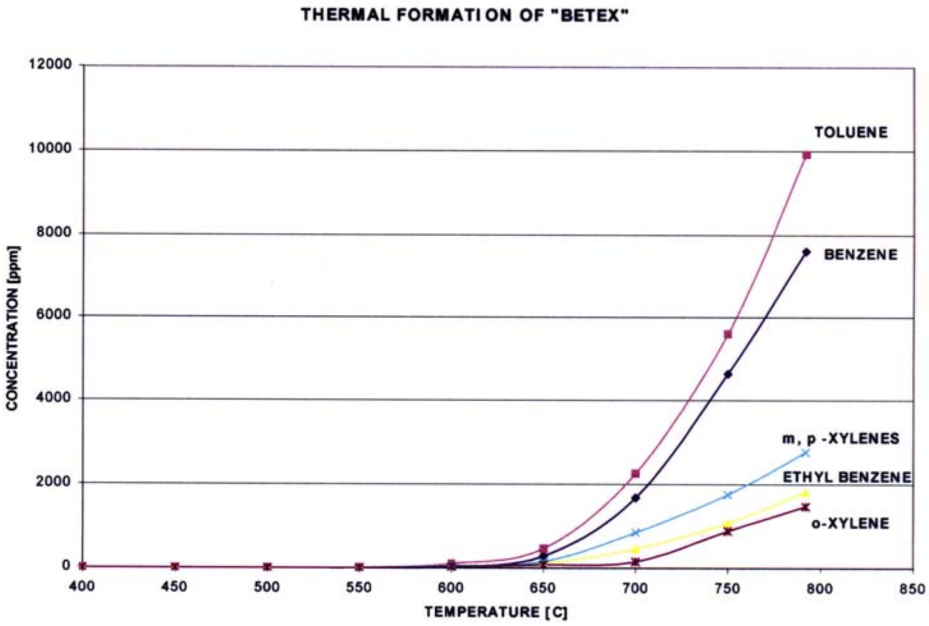

Figure 4-16
Thermal Formation of "Betex" Compounds

Effects of Recirculation

Re-Circulation of Insulating Oil (Voltesso-35) Over Heated Elkonite Surfaces

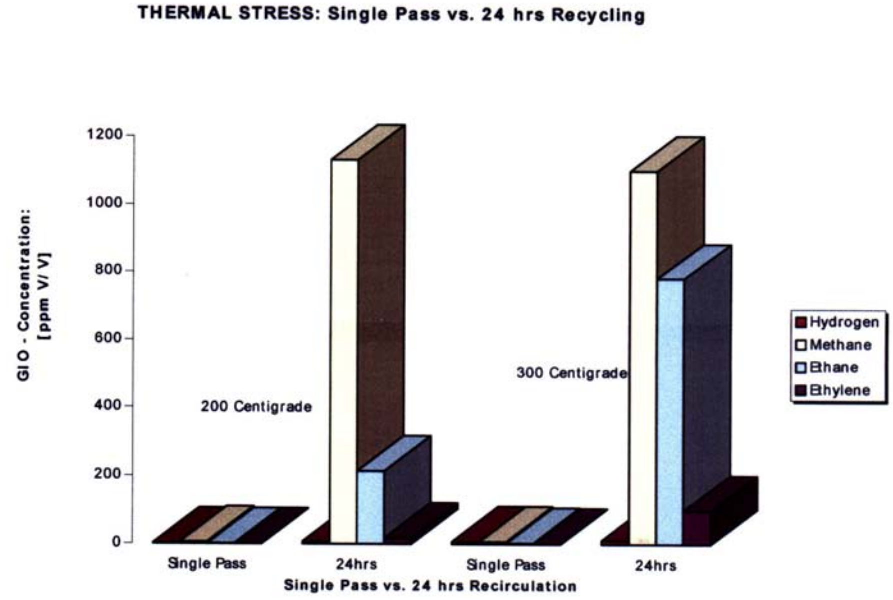

Figure 4-17
Thermal Stress: Single Pass vs Recirculation with Elkonite Furnace

The next Figure 4-18 shows how some of the important unsaturated compounds will accumulate in an oil over time. The ideal conditions for the formation of surface films on metallic contacts are created in the medium temperature range.

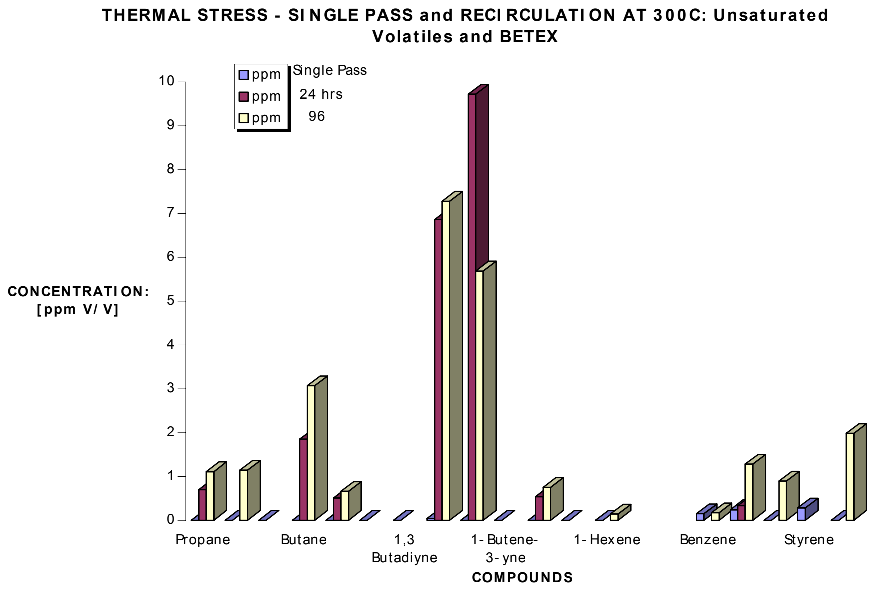

Figure 4-18
Thermal Stress – Single Pass and RECI Recirculation at 300C: Unsaturated Volatilies and BETEX

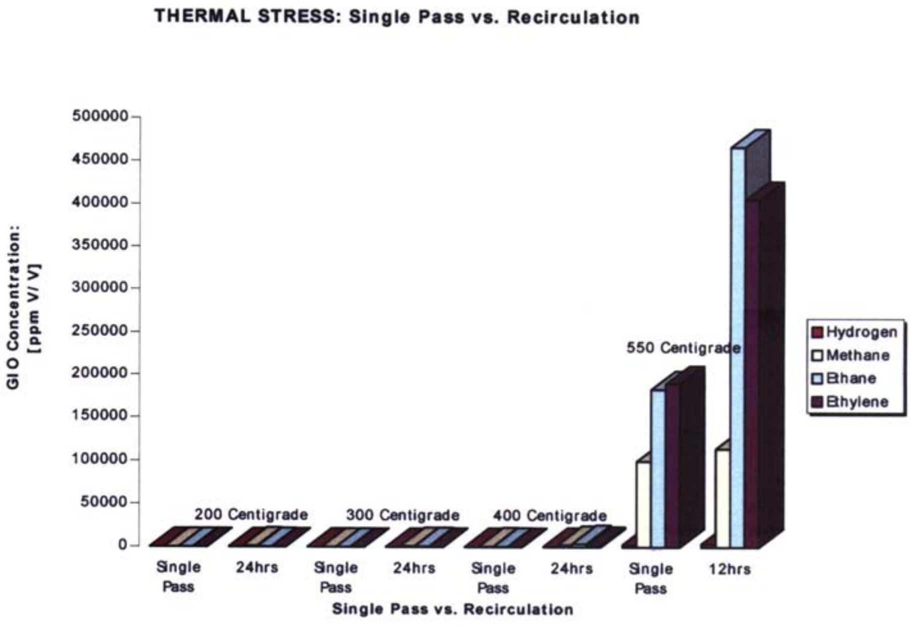

Figure 4-19
Thermal Stress: Single Pass vs Recirculation

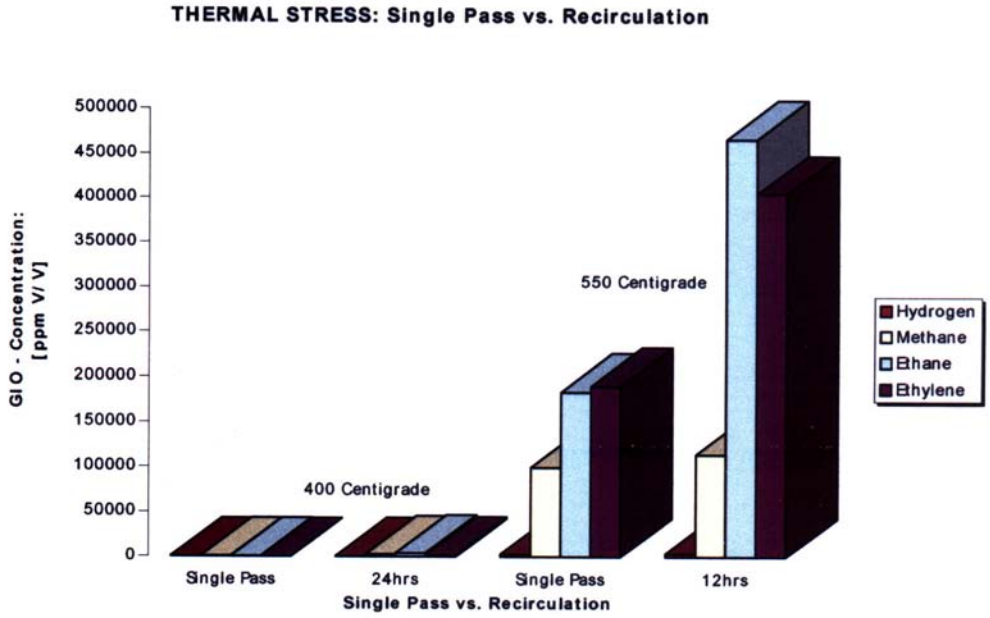

Figure 4-20
Thermal Stress: Single Pass vs 12 hrs / 24 hrs Recycling

Discussion

Table 4-2
Temperatures and Observations

Temperature Range	Observations Concerning Gas Evolution
For the temperature range of 150-350˚C:	Slow evolution of methane and hydrogen, which is followed at 300˚C by a slow evolution of ethane and ethylene.
In the temperature range of 350-500˚C:	Methane is the major gas formed, which is followed by the evolution of ethane and ethylene (which outpace hydrogen. At a temperature above >500˚C, experimental conditions favor the evolution of ethylene followed by ethane; the rate of methane and hydrogen generation occupy now the third and fourth place according to the observed rate of evolution.
For the temperature range of 500-800˚C:	Ethylene evolution continues at a high average rate, while the rates for the other gases fall substantially behind. The temperature of 550˚C is of special interest. At 550˚C there is a dramatic change in the "DPPH" response (an agent for the detection of free radicals) of thermally treated Voltesso-35. In the thermal window of 550˚C to 800˚C, DPPH activity of the thermally generated products increases exponentially (Arrhenius behavior) and could be

Temperature Range	Observations Concerning Gas Evolution
	interpreted as an increase in thermally generated free radicals. At a temperature of 700˚C, the incipient thermal evolution of acetylene is observed, and the rates become more significant from thereon onwards. Compared to the other reaction products, acetylene is still a minor component (about 0.15% of the ethylene production at 800˚C).

The work with the micro-furnace provided a hotspot profile for the pyrolysis of common transformer oil between the temperatures of 150˚C and 800˚C. This profile is summarized in Table 4-2 and in more detail in the figures. The kinetically significant breakdown for the formation of coke precursors takes place around 500˚C. Recirculation of transformer oil over hotspots will accelerate this process, but is less likely in large LTC – oil volumes.

The sudden appearance of fault gases and un-saturated volatiles together with a change in the temperature profile should set fault alarms for LTCs and other oil-filled equipment.

Micro Coker (Schematic View)

Figure 4-21 shows the micro-coker, which can be used in single pass or re-circulation mode.

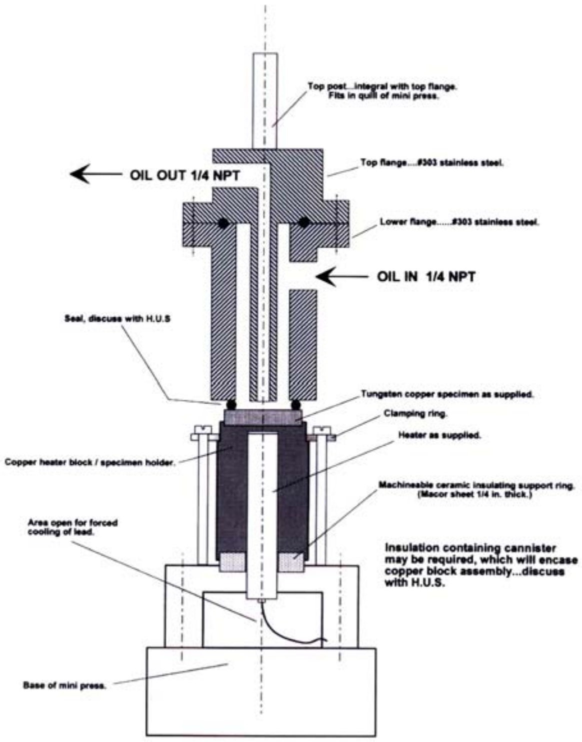

Figure 4-21
Cross-section of Micro-Coker

Figure 4-22
Micro-Coker with Four Point Resistivity Connections

Experiments

This system was designed to test the formation of deposits on metallic surfaces between temperatures of 50°C to 400°C (±0.2°C). Accurate temperature control was achieved with the help of subsurface thermocouples embedded in the test coupons. Oil re-circulation is the usual mode of operation.

The circulating apparatus was used to pass oil of ambient temperature over the hot surface of a metal coupon, which was temperature-controlled up to 400±0.2°C. The initial intent was to observe the formation of surface-deposits and measure their four-point resistivity (Figure 4-22).

The effects for the re-circulation of oil over heated surfaces, as discussed here, are quite different from a single circulation of oil over a heated surface. New compounds, not previously present in virgin transformer oil, are formed during a single pass of the oil over a hot surface. New reactions and products will result when the oil re-enters consecutively the thermal and catalytic regime of heated surfaces. With each pass the chemistry and interactions become more complicated.

The first impression might be, since the sample stream reenters the same thermal regime at temperature $T_{x,}$ that more of the same chemistry will occur. This is not necessarily the case. If we analyze for the products formed after the first pass of the oil, we will see those that are above the detection limit of our instrument. This then is the reason why we included ‘re-circulation’ experiments in this project, to imitate more realistically long-term processes in transformers or some other electrical piece of equipment, which may contain oil in contact with hotspots. Even at ambient conditions, transformer oil is far from inert and static, continuous chemical changes take place, especially if the oil is in contact with air and/or light. These chemical dynamics can be seen using different techniques: the monitoring of absorbance (changes around 450 nm) or with the help of free radical reagents.

We studied, among others, "changes in state" like the formation of surface deposits (Figure 4-25), since there is an interest in processes that increase contact resistivity (Figure 4-23) and which might explain certain fault/failure modes. The previous figures compare changes in fault gas formation of single runs with re-circulation (Figures 4-17 to 4-20).

Results

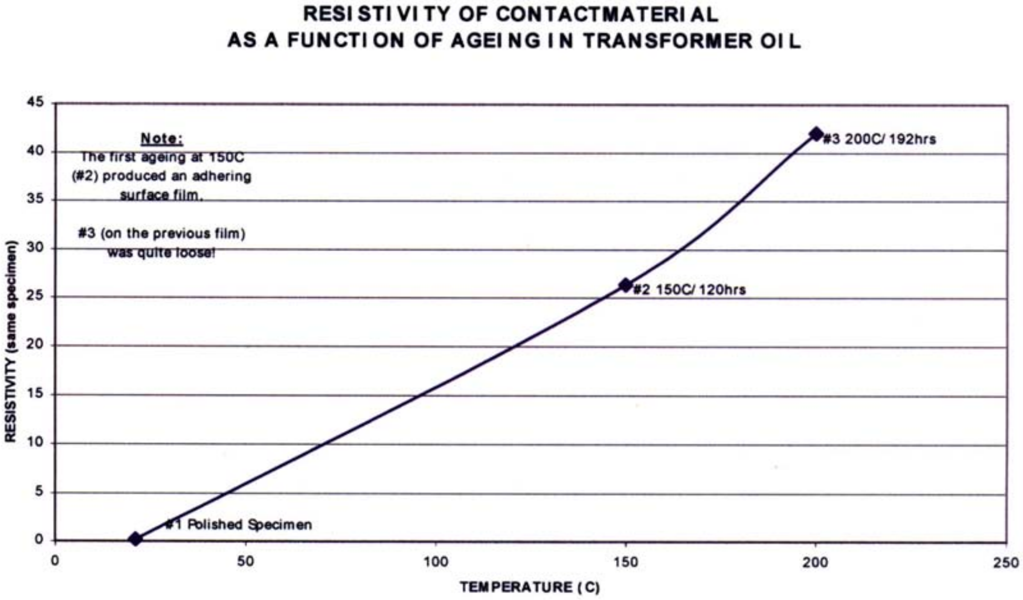

Figure 4-23
Resistivity of Contact Material as a Function of Ageing in Transformer Oil

The qualitative effects of different contact metals on deposit formation are presented in Figure 4-26. Presently, complementary studies on contact resistance (four point measurements) and thickness are underway at Powertech Labs Inc. The results will become available in spring of 2002.

Middle distillates (fuels for example) contain low levels of organically bound oxygen, while sediments and deposits contain 7 to 25% oxygen. Similarly, both laboratory and jet engine system surface deposits show similar high levels of oxygen [26]. A number of measurements have shown that sediments of middle distillates typically contain compounds of about 400 to 600 molecular weight units, which would indicate that instead of polymeric compounds, these deposits consist of something like dimers and trimers [26,27]. Once their "agglomerated forms" are large enough, "configurational entropy effects" [29] might take over and sediments (a solid phase, more efficient packing) form. Direct supercritical fluid extraction – mass spectrometry (SFE-MS), which allows for high molecular weight materials (up to 400,000 molecular weight has been demonstrated) extractions with direct introduction to the mass spectrometer, for on-line analysis, was used for the analysis of fuel sediments [27]. We speculate a similar picture will emerge for the formation of sediments in LTC – transformer oils.

Concerning organic compounds, Powertech Labs Inc. identified the following. We investigated the composition of the diverter contacts from Kent, two sets of contacts from LTCs that had failed or were about to fail. In all three cases the carbon deposits were collected, extracted with solvent and then analyzed for poly-aromatic hydrocarbons (PAHs) by GC/MS. The scope of the analysis was broadened to include a wider range of compounds than in our previous work.

Analysis identified the following compounds or classes of compounds:

- Phenanthrene and substituted phenanthrenes
- Methyl dibenzothiophene and other substituted benzothiophenes
- Substituted benzophenanthrenes
- Biphenyls and substituted biphenyls
- Substituted napthalenes
- Fluorenes

Of these compounds the thiophenes are of great interest, as we had observed the presence of sulfides and/or sulfur on contacts by energy-dispersive x-ray spectroscopy in previous investigations (Figure 4-24), while Table 4-3 gives some typical elemental compositions by inductively-coupled plasma emission spectrometry (ICPES).

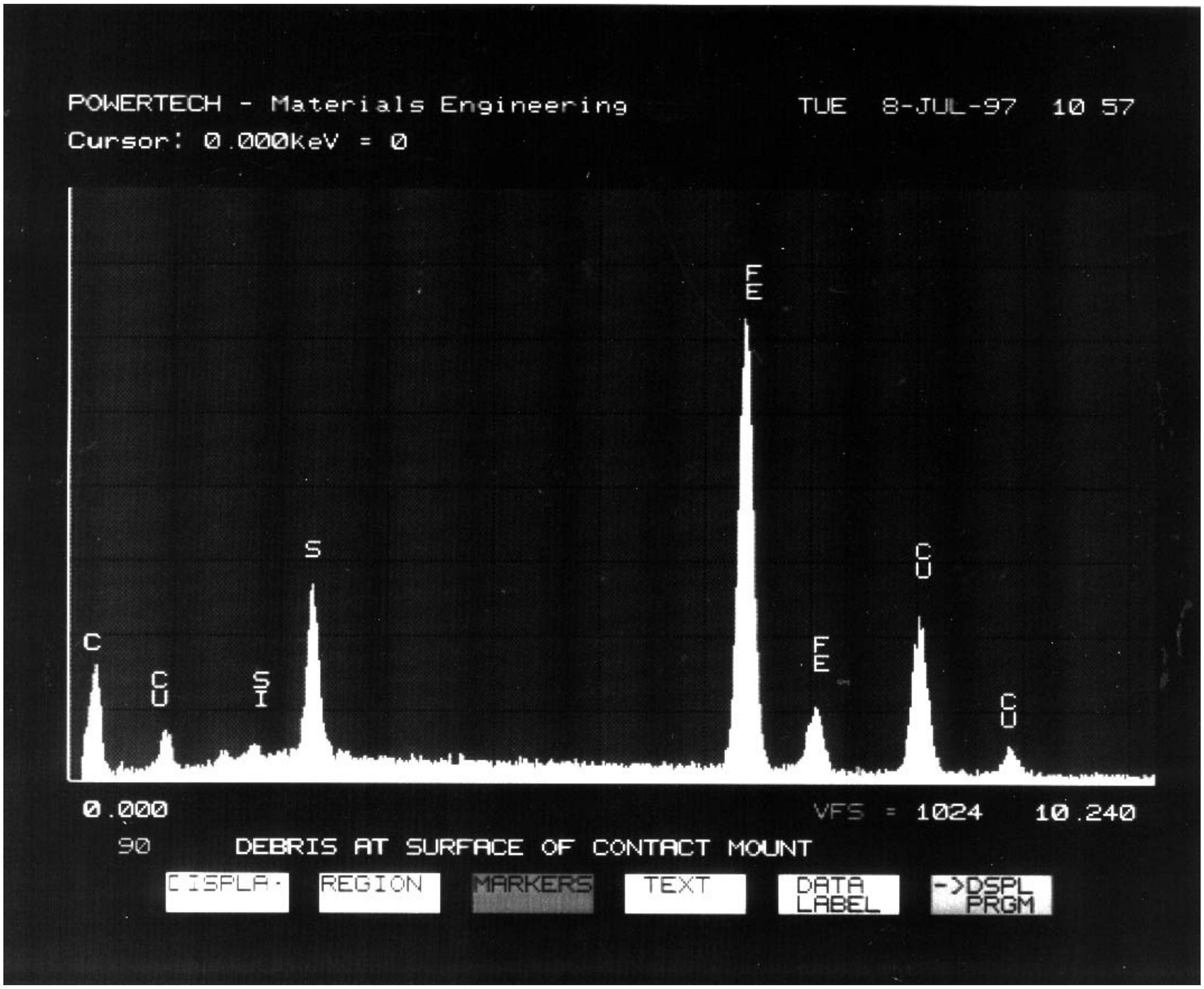

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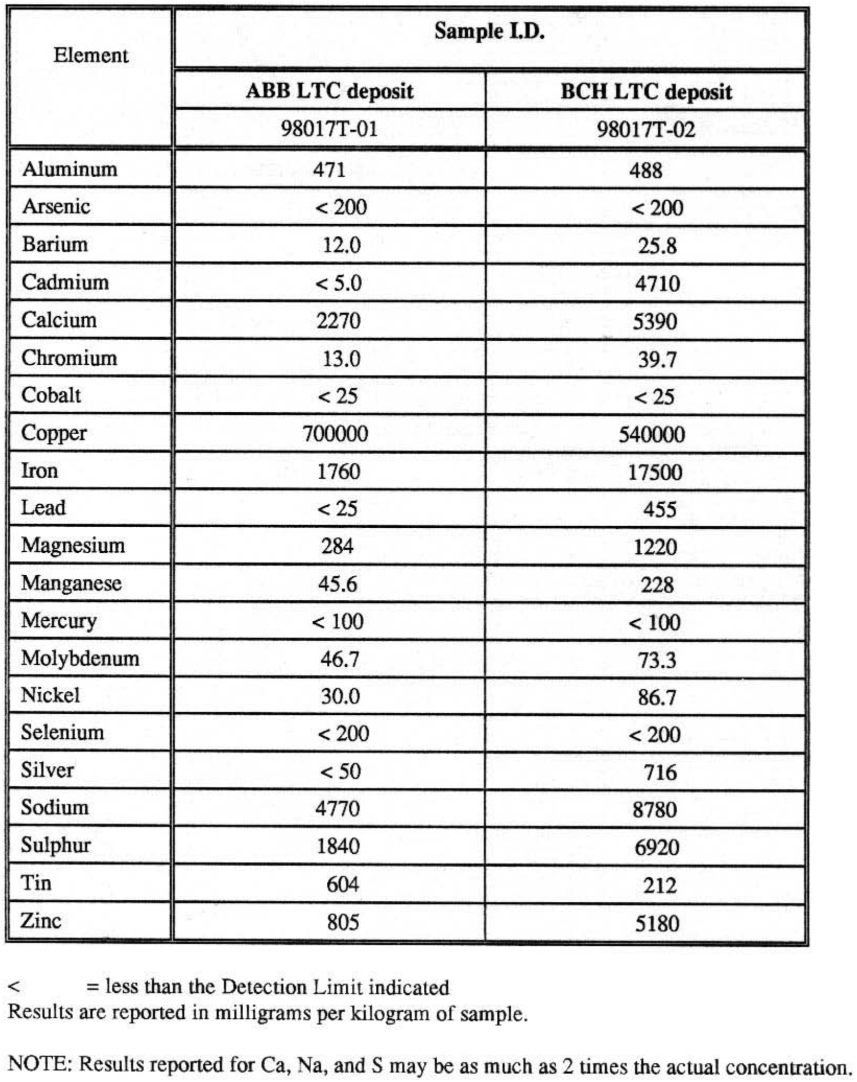
Figure 4-24
LTC-Diverter Switch Contact
Elemental Scan: Not the Sulfur Peak

Table 4-3
Elemental Composition of two deposits from Diverter Switch Contacts (different samples than in previous Figure 4-18)



Element	Sample I.D.	
	ABB LTC deposit	**BCH LTC deposit**
	98017T-01	98017T-02
Aluminum	471	488
Arsenic	< 200	< 200
Barium	12.0	25.8
Cadmium	< 5.0	4710
Calcium	2270	5390
Chromium	13.0	39.7
Cobalt	< 25	< 25
Copper	700000	540000
Iron	1760	17500
Lead	< 25	455
Magnesium	284	1220
Manganese	45.6	228
Mercury	< 100	< 100
Molybdenum	46.7	73.3
Nickel	30.0	86.7
Selenium	< 200	< 200
Silver	< 50	716
Sodium	4770	8780
Sulphur	1840	6920
Tin	604	212
Zinc	805	5180

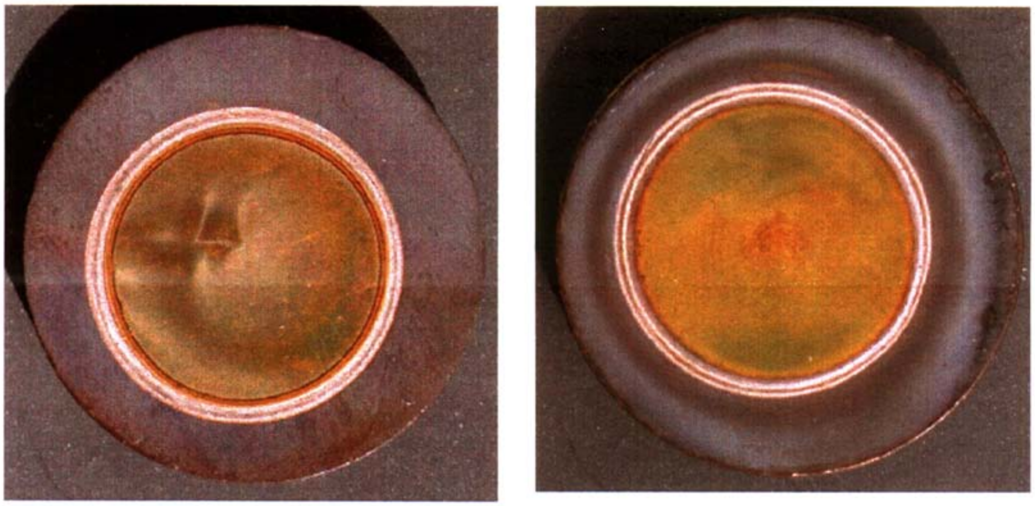
< = less than the Detection Limit indicated
Results are reported in milligrams per kilogram of sample.

NOTE: Results reported for Ca, Na, and S may be as much as 2 times the actual concentration.

Results of Significance (Micro-Coker

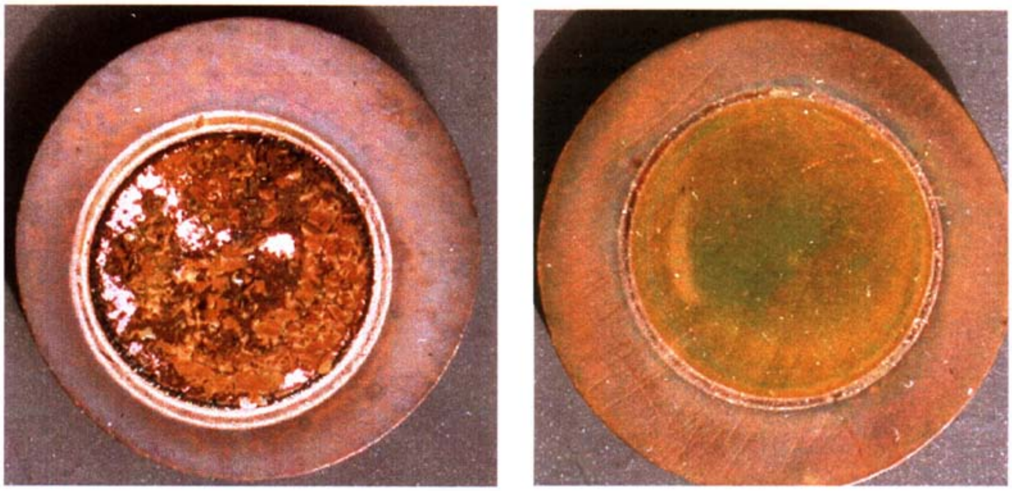
Contact Time: 24 hours, 1 atmosphere, air saturated

Results for Copper Test Specimens



225°C: New Voltesso-35

225°C: New Luminol



225°C: Old Voltesso-35
(The deposit is flaking off)

200°C: Old Voltesso-35
(No black deposit)

Figure 4-25
Contact Coking Test at 225˚C and 200˚C: Surface Deposits

Note: The above transformer oils were filtered through Millipore 0.8 μm pore size. The tests were run in duplicate with identical outcome. At the present time, we investigate in more detail the effects of transformer oil on hot, metallic surfaces: Silver, Copper and Elkonite.

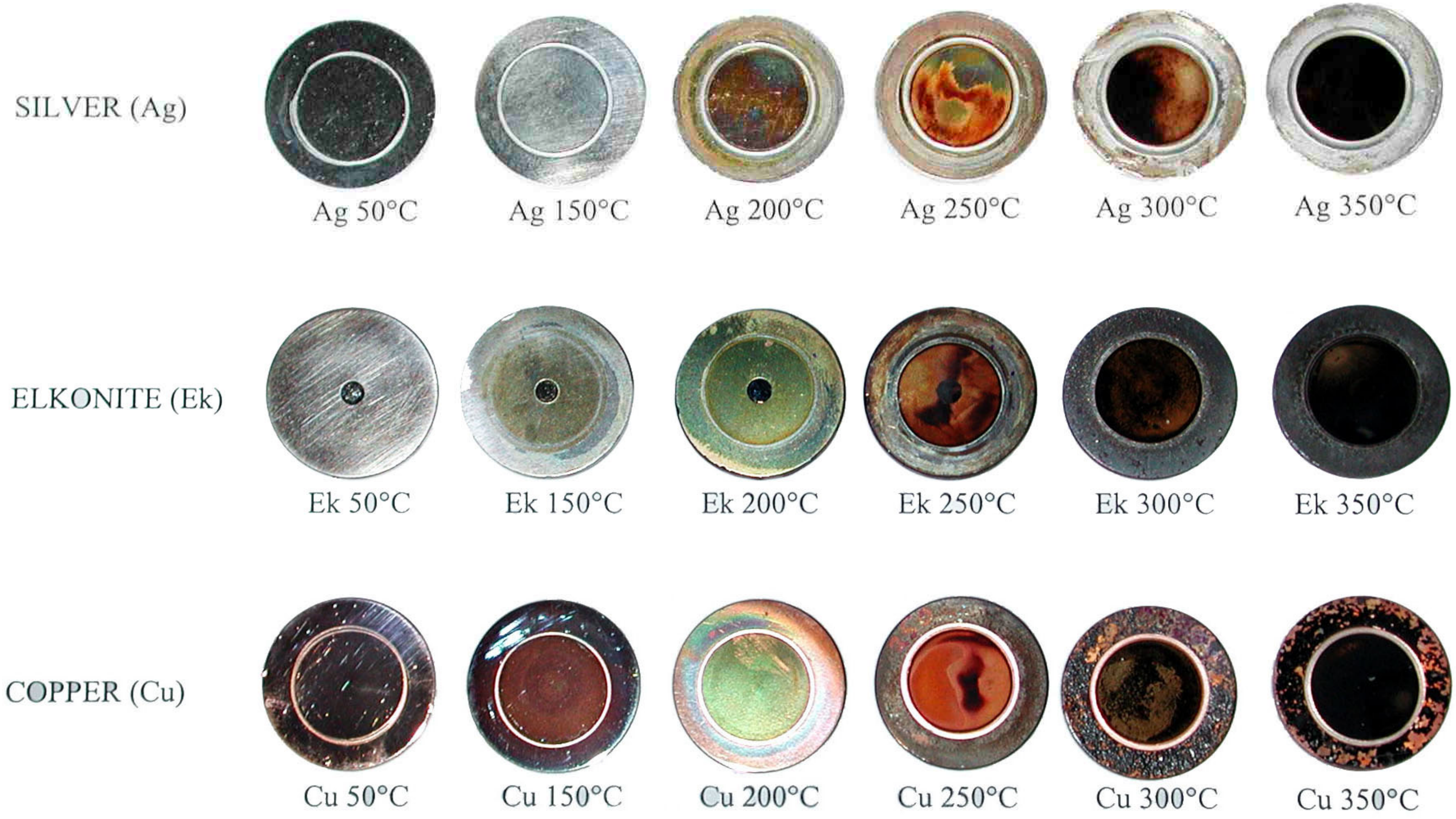


Figure 4-26
The Effects of Contact Materials

Comment: The metal coupons at 50˚C were all shiny and metallic in appearance similar to the Elkonite. The appearances in the picture, (Figure 4-26, is misleading.)

Discussion

The micro-coker is an effective piece of equipment to evaluate the quality of transformer oil for oil filled electrical equipment (including LTC).

The precisely controlled flow and surface temperature control of the easily removable test coupons lends itself to study the formation of surface films and their properties up to about 400˚C. The significance of arcing on the formation of surface coke was demonstrated for the first time. At 225˚C arc stressed oil as compared to 150˚C thermally stressed transformer oil resulted in a rich deposit of surface coke for all oils tested.

No effective, preventative additive has been found so far. The Hebei mechanism for coke formation (Figure 3-3) appears to be valid.

Electrical Stress

Electrical Arcing

The effects of simulated arcing were studied in a custom-built glass vessel (Figure 4-27) and compared with in-field findings. Some of the results are reported in Table 4-4.

The arc temperature is in some LTC-designs sufficiently high, despite existing heat sinks of conductive metal insulating oil and sacrificial copper (Elkonite is a copper-tungsten composite). This apparatus was operated in the enclosure of the Gassing Tendency Equipment; ASTM D2000 (Figure 4-28). This piece of glassware was rinsed prior to experimental runs with inert gas (nitrogen). It has one external moving part: a positive displacement gas syringe. The different ports permitted the withdrawal of syringe samples of gas and oil via septa. Stainless steel posts allowed the application of high voltage (5 to 13 kV, <40 mA) and current to a pair of conical Elkonite electrodes.

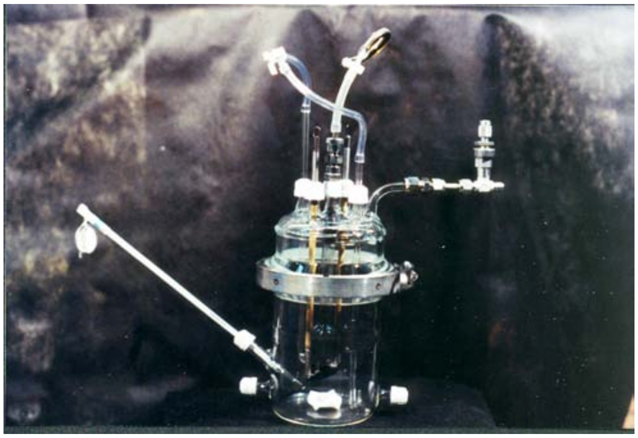


Figure 4-27
Glass Vessel for Arcing Experiments

Figure 4-28
Gassing Tendency Apparatus

Experiments

Although the laboratory arcing conditions were quite different from those encountered in the field, the basic observations for the two scenarios are similar. Under laboratory conditions, it was observed that the main products of arcing are hydrogen, acetylene, ethylene; methane and ethane (Table 4-1) and a fine suspension of solid carbon. Thermodynamically, exposing hydrocarbons (HC) to the high-energy environment of the arc favors the formation of acetylene (and other alkynes). The formation of acetylene from the elements, in contrast to the formation of other HC, is highly endothermic. Some of the energy of the electric arc is stored in the triple "π-bonds" of acetylene (Le Chatelier's Principle). At high temperatures, methane is thermodynamically the most stable alkane. As can be seen from the following Table 4-4, large numbers of coke-precursor compounds are formed (Hebei). Among the list of compounds are the following of interest: 1,2- propadiene (allene), 1,3-butadiene (erythrene), 1,3-butadiyne (diacetylene), and 1,3-cyclopentadiene. These are all known intermediates in organic synthesis. For example, 1,3-butadiene polymerizes spontaneously, if not inhibited.

These arcing products readily adhere to hot surfaces, and at lower temperatures in the presence of oxygen [26]. Once, a sufficient level of these compounds accumulate in the insulating oil, relative sudden sludge formation is a possibility and coking may occur; this may result in failure of the equipment. Powertech Labs Inc. observed at least one such occurrence in the field.

Typical transformer oil sludge has an atomic H/C – ratio around one (~1). Analytical results for a dry sludge are shown in Figure 5-6. A typical middle distillate has an "elemental" composition for gum/sediment of [28]: C - 74.2% (by wt); H - 5.6%; N - 2.6%; S - 6.7%; O - 11.2%.

These middle distillate data are equivalent to an atomic H/C ratio* of 0.9. The data are similar to what one would rationally expect from two similar petroleum fractions (middle distillates). The significance of Powertech Labs Inc.'s findings are explained briefly in Section 3 under the heading "Reverse Refining". We would like to take the opportunity and mention this "ad hoc" terminology. According to our thinking, this and the well established scheme of ageing by oxidation explain the deposit and sludge formations in on-load and off-load tap-changer and other oil-filled switchgear. We venture to remark that some of the processes in transformer might be explained in a more illuminating fashion with a combination of processes "reverse refining" and "normal" ageing of transformer oils. The compounds are present in oil filled, electrical equipment whenever conditions for active thermal, arcing or partial discharge processes exist. The tools of gas chromatography/mass spectrometry should be applied to investigate the presence of olefines and alkynes in addition to the classical fault gases: ethylene, propene and acetylene. These unsaturates are the precursors to deposit and sediment formation causing for example high contact resistances and the associated problems. Arcing can play a much more significant role than associated or run-away thermal environments..

Results

Table 4-4
Arcing Experiments: Concentrations in ppm (wt/wt)

Arc Time (minutes): Compounds	5	10	15	20	30	60	93	153	213	263
Propane	0	0	0	0	0.02	0.03	0.06	0.09	0.14	0.19
Propene	0.2	0.36	0.63	0.78	1.41	2.44	4.27	6.47	9.25	11.65
Propyne	0.1	0.21	0.34	0.48	0.76	1.39	2.37	3.66	5.25	6.94
Butane	0	0	0	0	0	0.03	0.05	0.08	0.1	0.17
1-Butene	0.03	0.06	0.1	0.13	0.23	0.47	0.84	1.41	2.13	2.97
1,2 Propadiene	0.29	0.52	0.9	1.12	2.03	3.55	6.07	9.26	12.43	14.82
1,3 Butadiene	0.08	0.16	0.26	0.36	0.64	1.29	2.16	3.52	5.11	6.96
2-Methyl Propene	0.04	0.08	0.12	0.15	0.23	0.52	0.78	1.24	2.11	2.88
1,3 Butadiyne	8.25	16.21	22.57	26.38	34.27	142	202	251	306	338
1-Buten-3-yne	0.84	1.76	2.76	3.71	6.37	12.07	22	36	49	63
1-Pentene	0	0	0	0	0.09	0.19	0.29	0.5	0.79	1.14
2-Methyl Butene	0	0	0	0	0.05	0.27	0.45	0.77	1.14	1.61
Butyne	0	0.03	0.04	0.06	0.11	0.23	0.39	0.66	0.98	1.36
1,3 Cyclopentadiene	0.23	0.45	0.69	0.94	1.7	3.4	5.2	7.89	11.04	14.21
Pentane	0.17	0.18	0.18	0.18	0.2	0.19	0.21	0.23	0.23	0.28
1-hexene	0	0	0	0	0	0	0	0.15	0.31	0.38
2-Methyl Pentene	0	0	0	0	0	0	0	0.2	0.32	0.48
Methyl Cyclohexane	3.17	2.98	3.32	3.12	3.34	3.12	3.02	3.07	3.04	3.12
Heptane	0.66	0.58	0.53	0.81	0.74	0.71	0.67	0.8	0.79	0.71
Benzene	1.07	2.2	3.33	4.53	7.62	15.36	24.66	52	66	88
Toluene	2.94	3.27	3.64	3.9	4.68	6.24	8.44	12.3	17.74	21.89
Ethyl Benzene	1.16	1.12	1.28	1.24	1.32	1.04	1.65	2.28	2.63	2.79
M, P &O-Xylene	2.83	2.5	0.97	3.06	2.96	3.47	3.6	4.18	4.66	4.76

*(Other examples of such ratios: methane = 4, decane = 2.2, acetylene = 1, benzene = 1, anthracene = 0.7, anthracite coal = 0.3 – 0.4)

We consider these results significant. Work in progress at Powertech Labs Inc. shows that "arcing" of oil has a dramatic effect on sludging and the formation of coke-like surface deposits at temperatures as low as 225˚C. Two of the compounds and their evolution with arc time are shown in Figures 4-29 and 4-30. Overall the arc time[*] will determine the yield, although catalysts and other parameters will have an effect. This explains the good agreement between field and laboratory data for the dissolved gas in oil results (Table 4-1).

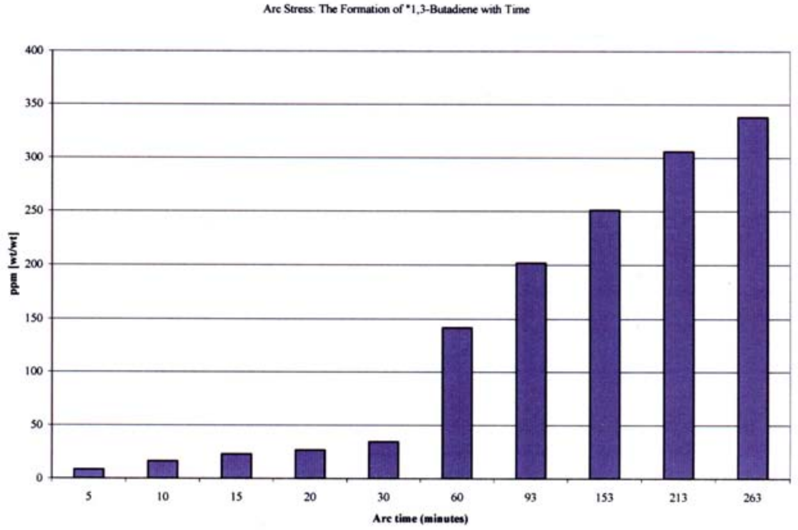


Figure 4-29
Arc Stress: the Formation of 1,3 Butadiene with Time

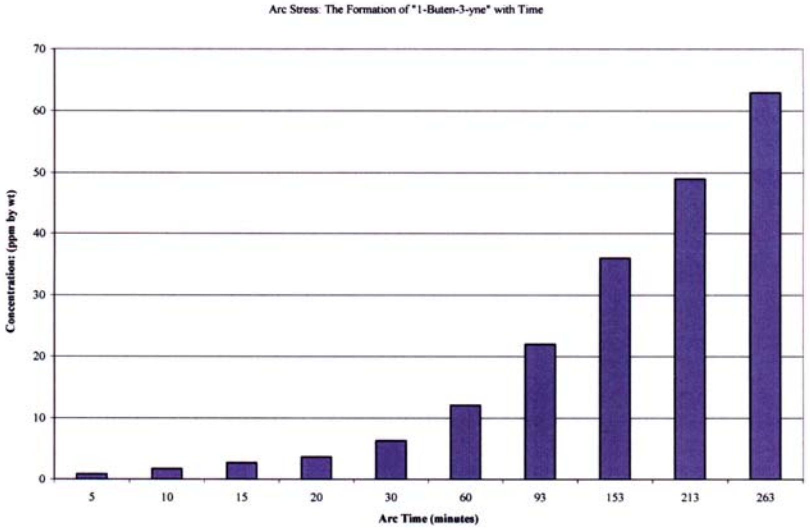


Figure 4-30
Arc Stress: the Formation of 1-Buten-3-yne with Time

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[*] Number of switch operations

Discussion

Coking of Contact Surfaces

The necessary parameters for coke formation are all there: an organic film of coke-precursors, pressure and temperature, the latter due to an enforced current (= watts, = Joule heating). In the initial stages the temperature of the contacts will hardly change, as the heat sink capacity for heat dissipation is enormous compared to heat generated by the interfacial films. Graphitic carbon, as a conductor, has a negative characteristic. It's conductivity increases with temperature for as long as the dehydrogenation of the substrate takes place ending in the formation of graphite-like material (coke). This material, although very thin, will be at higher temperatures than the metals it is in contact with because of its negative characteristic.

Based on present and unpublished work (subject: LTC under different current loadings and contact materials), we suggest that if the inter-contact layer becomes substantial enough, the current flow will induce a surprisingly high local temperature, estimated by some investigators to be around 2100°F [14,15].

Over the same time frame, the process will lead to diffusion of various elements into each other, explaining the gradual and irreversible increase of the resistivity (Powertech Labs Inc, 2001 unpublished) after changes in current loading. This would lend support to the results reported by R. Crutcher this year [15]. That report describes in detail some of the findings, which are the results of investigations of 'solid' LTC-deposits by light microscopy, electron microscopy (SEM) and associated techniques like wavelength dispersive x-ray spectrometry (WDS) and energy dispersive x-ray spectrometry (EDS).

In another scenario, which is perhaps the more frequently encountered, a mechanical failure of some type occurs, which will lead to excessive arcing and/or Joule-heating. As a result of these activities, some surface(s) within the LTC will reach high temperatures (>500°C). This situation, if not detected, will result in the cracking of some of the oil, independent of oil quality and the presence of oil- protecting additives (usually antioxidants and metal deactivators). The experiments with the Elkonite furnace (Figures 4-1 and 4-2) demonstrated this point. The contact time of oil and hot surface of the failing part is relatively short, but it is sufficiently long to result in severe oil degradation. All the precursors for the coking of contacts (see Figure 4-4) are produced at a rapid rate, although the overall oil quality might appear unaffected. Contacts might get coated faster than the interfacial layer "burns off" leading to failure. The fault gases and other chemical compounds produced at this point are sufficiently high in concentrations – and can be detected in the laboratory. The LTC can be flagged ("fault-alarm").

Partial Discharge (Preliminary Data)

The results for corona discharge experiments under nitrogen using a modified Pirelli Cell (ASTM D2300-71) were reported early on. The test set-up liberated 0.5 µl of gas per second for a power input of 1W at 10 kV. The composition of the gas corresponded to "conventional" oil corona, being approximately 86% hydrogen, 13% methane, and 0.5% ethane with traces of ethylene and carbon monoxide [17].

Operated according to ASTM D2300 the gassing tendency unit (Figure 4-28) allowed the investigation of corona/partial discharge on gas phase composition. For example, it permitted the study of compositional changes for a charge of hydrocarbons over time (methane), of the type that might be encountered in a vacuum and related units. ASTM D2300 and modified, related studies benefited the interpretation of gas-in-oil field data.

These findings might explain some of the highly different DGA data collected for certain "advanced" LTCs of low oil volume and high switch rates. Arcing in these types of units appears to be highly suppressed.

5

FIELD WORK AND CASE STUDIES

Kent Voltage Regulator (Accelerated Conditions)

Introduction

To validate the laboratory findings and establish a correlation with operating conditions, a field case study was undertaken.

We like to think that most reversing and selector switches act like some type of immersion heater. Their status has to be monitored via resistivity and condition assessment, if not via regular inspection/maintenance to assure these switches do not turn thermal by entering fault modes (which in the majority of cases are of mechanical nature). Electric arcs in LTCs and the respective insulating oil involve the formation of a high-pressure plasma channel at temperatures well above the melting point of most metals. The diverter switch contacts are subjected to intense local heating and mechanical shock by arcing. Typically, 50 to 1000 J of electrical energy will be dissipated in the oil for each switch operation. This energy is transferred within a few milliseconds; the oil breaks up into its elements carbon particles, hydrogen, and partially recombines to form acetylene, ethylene, and other hydrocarbons. The intense heat also vaporizes the surface of the arcing contact and some larger particles may be removed from time to time.

The energy input from resistive heating at the selector switch contacts will depend on the current (typically 300 Amps) and the contact resistance. The resistance between moving and fixed contacts is normally in the micro-ohm range, and the Joule heating will be only a few milli-watts. If the contacts become uneven, or develop resistive layers, the overall energy dissipation will increase and hotspots will appear. A contact resistance of only a few milli-ohms will increase the energy input to several watts. There is sufficient voltage behind the contacts to ensure that current is maintained, and the heating may be sufficient to cause localized decomposition of the oil. The contact deterioration associated with this type of fault may proceed very slowly, sometimes over a period of years. There are many examples in the literature describing how "burned", "charred", and "coked" conductors produce copious amounts of gas, predominantly ethylene. The process seems to require high temperatures. Oil refiners commonly produce ethylene by “cracking” hydrocarbon feedstocks at 500°C - 600°C, and the current series of laboratory tests confirm that similar conditions are required for transformer oil. There are also some reports of “intermediate temperature” faults, which produce higher proportions of hydrogen, methane, ethane, and very small amounts of ethylene.

Temperatures below about ~200°C are insufficient to decompose the primary constituents of the oil or the amounts are too small to be detected, but there may be minor gassing from catalytic reactions, oxidation, or photolysis. But, a LTC, which contains transformer oil that has chemically broken down due to thermal or arcing stress and in the presence of oxygen, could support sludge deposition and the formation of coke, perhaps, at much lower temperatures possible at temperatures less than 225°C. We are studying this possibility at the present time.

Equipment

Details of the voltage regulator and a photograph of the field set up are shown below in Figure 5-1.

❑ 3-Phase Voltage Regulator

- Manufacturer: Federal Pioneer
- Year Built: 1975
- Voltage Class: 12 kV
- Rating: 12470 V; 300 amps
- kVA: 6500/7280
- No. of Steps: 33
- Temp. Monitor: Barrington Consultants
- Unit Designation: KEN 12VR53M

Figure 5-1
Voltage Regulator at Kent Substation

The arcing contacts used for this case study are shown in Figure 5-2 and a picture of the switch compartment is shown in Figures 5-3 and 5-4 (Diverter Switch).

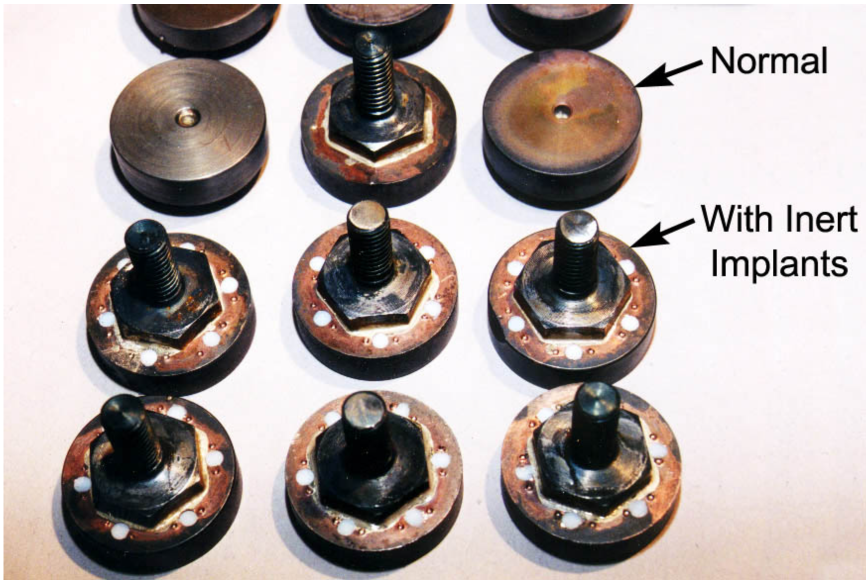


Figure 5-2
Implants for Contacts at Kent Substation

Figure 5-3
Kent Voltage Regulator 121VR53; Switch Compartment/Open

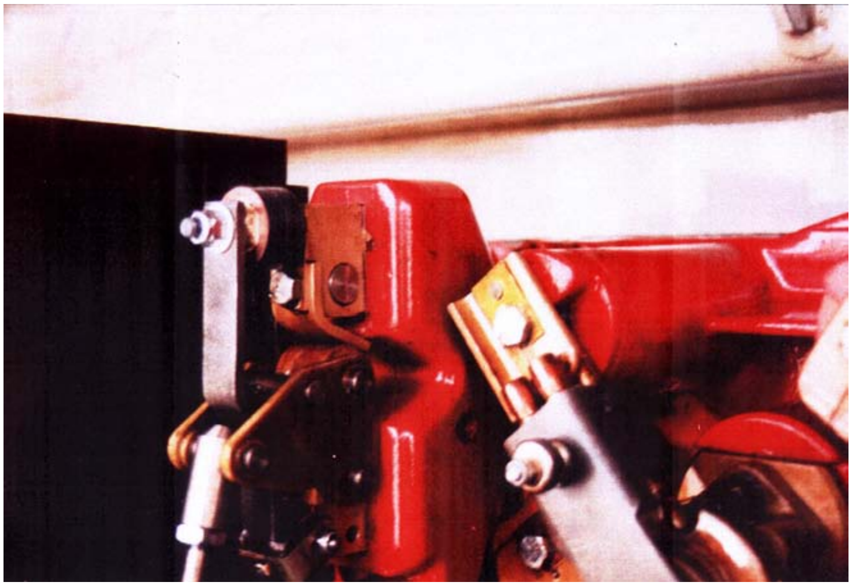


Figure 5-4
Diverter Switch at Kent

Test Program

Baseline data was obtained from a comprehensive series of tests on an LTC fitted to a power transformer at BC Hydro's Kent substation [30]. The unit was a 12 kV Federal Pioneer 33-step voltage regulator, 1975 model, rated at 300 Amps, equipped with a Velcon TP-2 oil filtration unit. The regulator was overhauled, cleaned, fitted with new diverter switch contacts, new filter cartridge, filled with new transformer oil and was set to operate at between taps #7 and #11 (6% to 4%, away from the neutral position) at approximately 800 tap change operations per day. The LTC was energized but operated at zero load for a period of 60 days in order to stabilize the oil and the mechanical components. Phase 1 proceeded with no loading, followed by 96 amps for one week and then by 120 amps for about 42 000 operations. The unit was then opened up and a new set of diverter switch contacts with Teflon implants* (Figure 5-2) were fitted and the oil was changed again. Phase 2 began with a load of 96 amps for one week, which was then increased to 120 Amps for a further 88 500 switch operations. Phase 3 was similar to Phase 2, except that the switch contacts were not replaced. At this stage measurements of contact wear were made (Figures 5-11 and 5-12) and the oil filtration unit was brought on line. Phase 3 was terminated after 82 000 operations because there were signs of erratic performance. The diverter switches had reached the Teflon implants (Figures 5-2 and 5-4).

Results

As far as we could tell, the only significant source of gassing in the Kent voltage regulator was arcing at the diverter switch. The average amount of gas and the proportions of hydrogen, methane, ethane, ethylene, and acetylene produced by the diverter switch were remarkably consistent over thousands of operations. The weight of suspended solids, carbon, iron and copper also increased linearly with the number of switch operations. (Figures 5-5 to 5-10). It is confirmed that arcing produces a very consistent "signature" of combustible gases. The proportions of hydrogen, methane, ethane, ethylene, and acetylene are almost identical over a very wide range of arc energy. The proportions of total gas (%) are shown in Table 4-1, the data being taken from similar tests, two decades apart, at different laboratories, with different types of arcing contacts: (please compare with Figure 5-7).

The volume of gas produced by arcing depends on the energy, but the composition seems to be remarkably constant under conditions ranging from minute sparks in the ASTM D1816 test, small-scale laboratory tests (e.g. needle to sphere breakdowns), limited arcs in switches and circuit-breakers, and major sustained arcing in power transformers. The "Kent" Phase 2 tests produced about 1.5 ml of gas along with 0.6 mg of precipitate (0.4 mg carbon mixed with 0.2 mg metal) per switch operation. The IREQ tests established that about 90 mL of gas is produced per kJ of arc energy.

There were indications that the amount of gas produced per switch operation increased by about 25% over the course of the Phase 2 tests. The gas-in-oil data are influenced by movement of gases into the headspace, subsequent leakages from the headspace to the atmosphere, and variations in pressure and temperature. Hydrogen, methane, and carbon monoxide are far less soluble than the other combustible gases and tend to escape to the headspace. Hydrogen migrates particularly rapid because of its high diffusion coefficient. Figure 5-8 shows the proportions of gases in the oil (570 L) and in the headspace (90 L) for the Kent Tests. The hydrocarbon gases (C_2H_2, CH_4, C_2H_4, and C_2H_6) in both the oil and the headspace increased in step with the number of switch operations. However, the dissolved hydrogen rose to a maximum of about 15 000 ppm (~20% of its saturation level) after 60,000 switches. The amount of nitrogen (N_2) in the oil decreased from 75,000 ppm to about 50,000 ppm over the same test period. The corresponding headspace levels were 36.7% H_2, 53.3% N_2, 5.2% O_2, 3.2% C_2H_2, 1% CH_4, 0.4% C_2H_4, and 0.02% C_2H_6.

In spite of diffusion and leakages, the ratio of acetylene to ethylene in the oil remained constant throughout the Phase 2 tests (Figure 5-10). This result is important for diagnostic purposes because it may provide a general indication of how much ethylene has been produced from arcing as opposed to other sources.

A mass-spectrometer/gas-chromatograph procedure was used to identify and measure a wide range of other gases and aromatic compounds in the oil samples. All of the gaseous hydrocarbons and "unsaturated, volatile compounds", except BTEX, are absent in new oil, and were formed in various amounts during laboratory tests. The oil used to fill the Kent LTC already contained some of the more interesting BTEX and poly-aromatic materials (PAH). BTEX compounds have also been detected in LTC oils by other researchers.

The "unsaturated volatile compounds" provide useful additional information, and were produced in significant quantities during the Kent tests. The laboratory work shows the major differences between the by-products from arcing compared to thermal decomposition (Figures 6-2, 6-3 and 6-4). Some of these compounds are characteristic of thermal stress and can be used as "thermal markers" for diagnostic purposes.

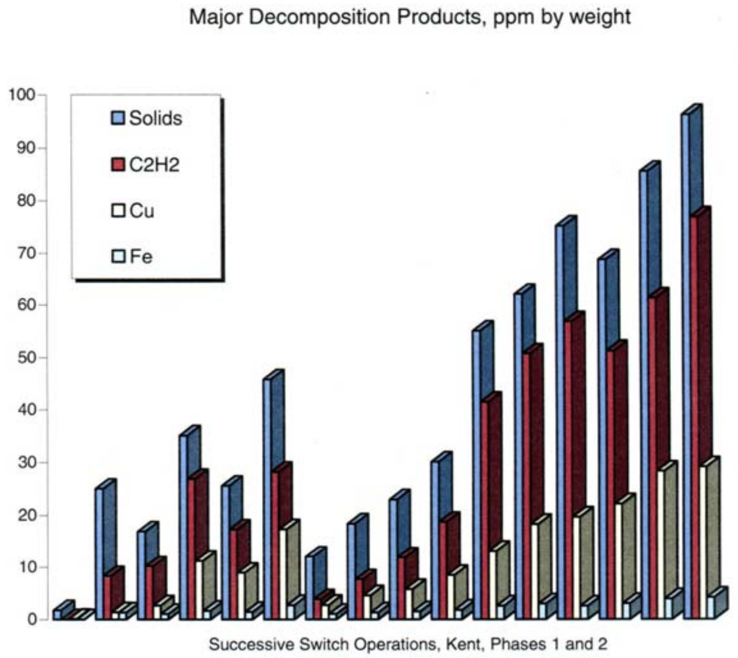


Figure 5-5
Kent Case Study: "Normal" Increase of Decomposition Products with Successive Switch Operations

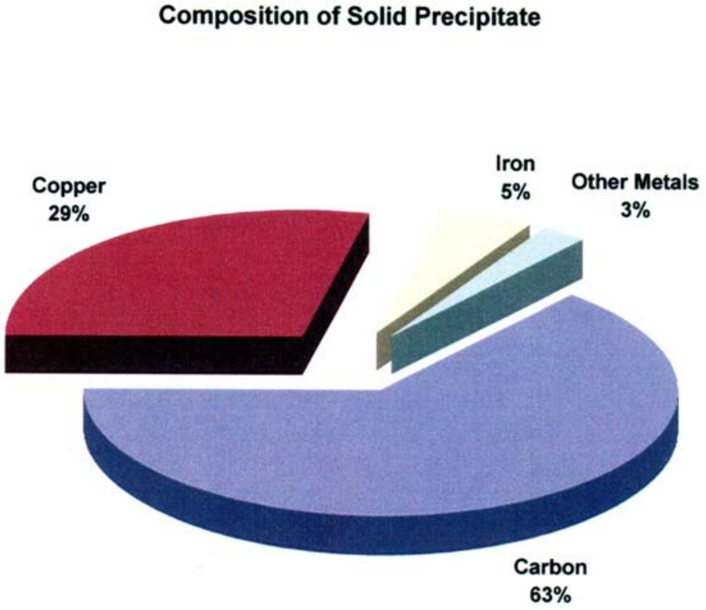
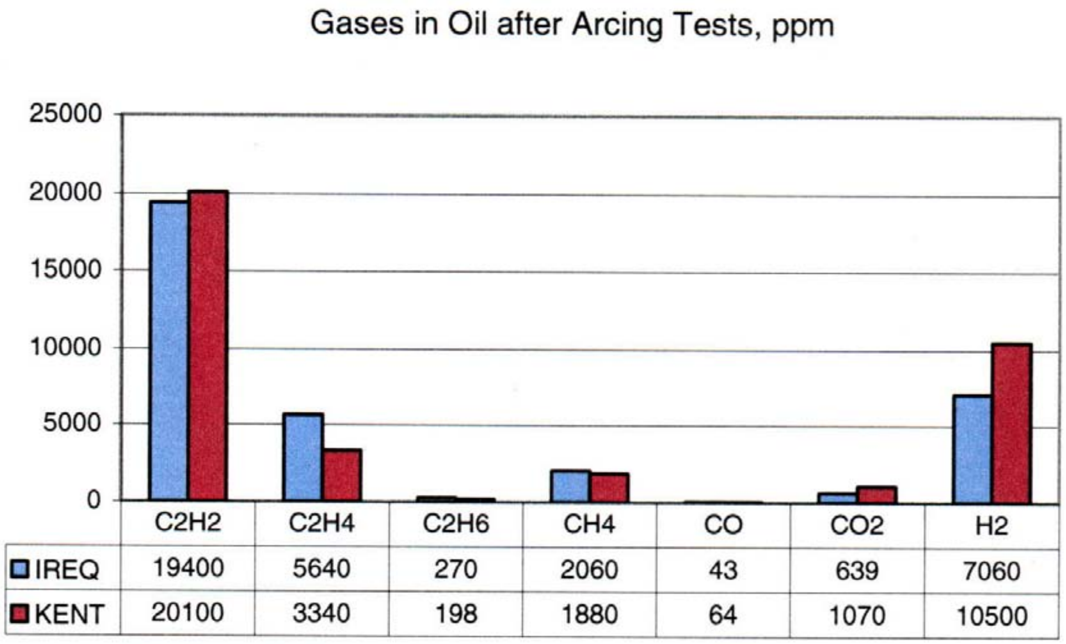
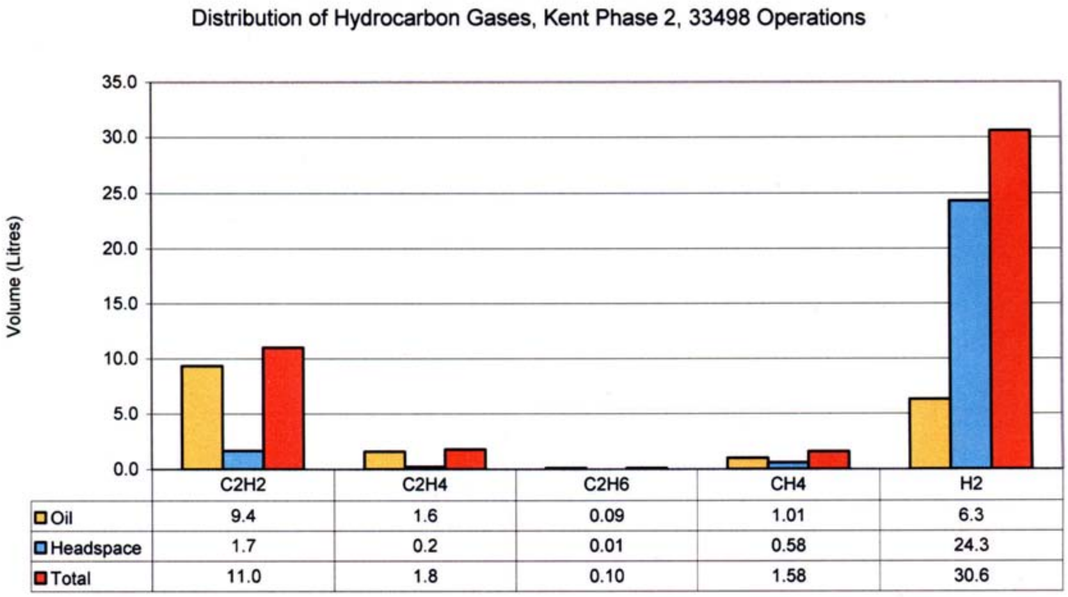


Figure 5-6
Kent Case Study: Averaged Composition of Insoluble



	C2H2	C2H4	C2H6	CH4	CO	CO2	H2
🟦 IREQ	19400	5640	270	2060	43	639	7060
🟥 KENT	20100	3340	198	1880	64	1070	10500

Figure 5-7
<u>Two Studies</u>: Comparison of Arc Data (please compare with Table 1, page 7)



	C2H2	C2H4	C2H6	CH4	H2
🟨 Oil	9.4	1.6	0.09	1.01	6.3
🟦 Headspace	1.7	0.2	0.01	0.58	24.3
🟥 Total	11.0	1.8	0.10	1.58	30.6

Figure 5-8
<u>Kent Case Study</u> : "Normal" LTC Operation

Discussion

The field "case-study" (B.C. Hydro's Kent Substation) provides the background for, what we like to call, the "normal performance" of LTCs. Although, alternate designs of other makes and models of LTC result in different "signatures", the Kent Model constitutes the point of reference for the "normal-mode" of LTC operation (for reasons reflected in Table 4-1). This study and "work in progress" at the present time will use Kent data as reference material for the interpretation of findings. Referring to Figure 5-9, the first two third of the bar graphs, period #1 to #18, show the typical performance of the LTC at Kent. The normalized ("percent") data of "%SumArc", "%SumTherm" and "%SumAlk" are essentially constant*. The quality of the data is reflected in Figure 5-10, which shows the ratio of acetylene versus ethylene.

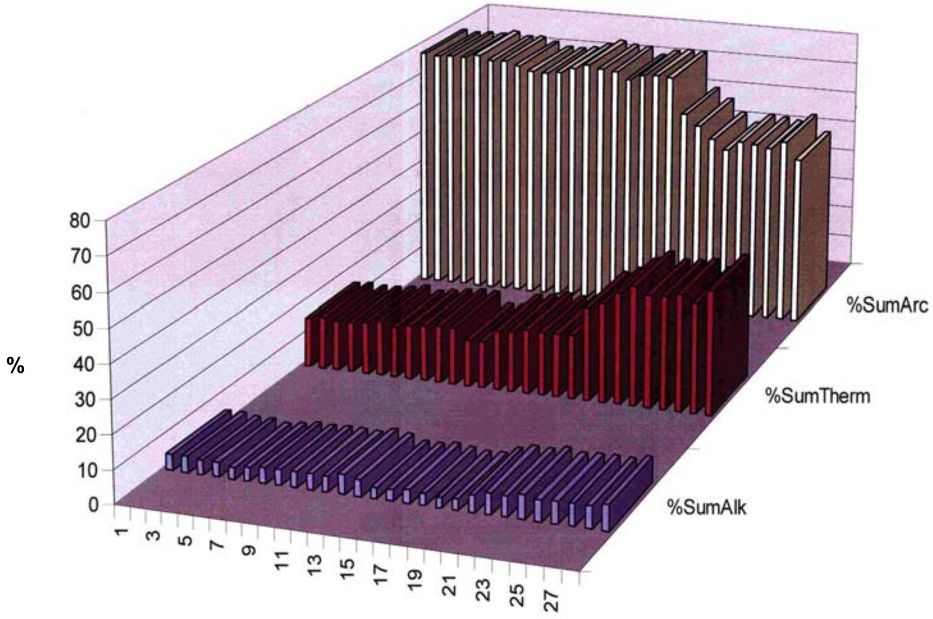


Figure 5-9
Percent (by weight) of Gas-in-Oil vs Sampling Period at Kent Substation

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* SumArc = typically Alkynes; SumTherm = typically alkenes; SumAlk = typically alkanes

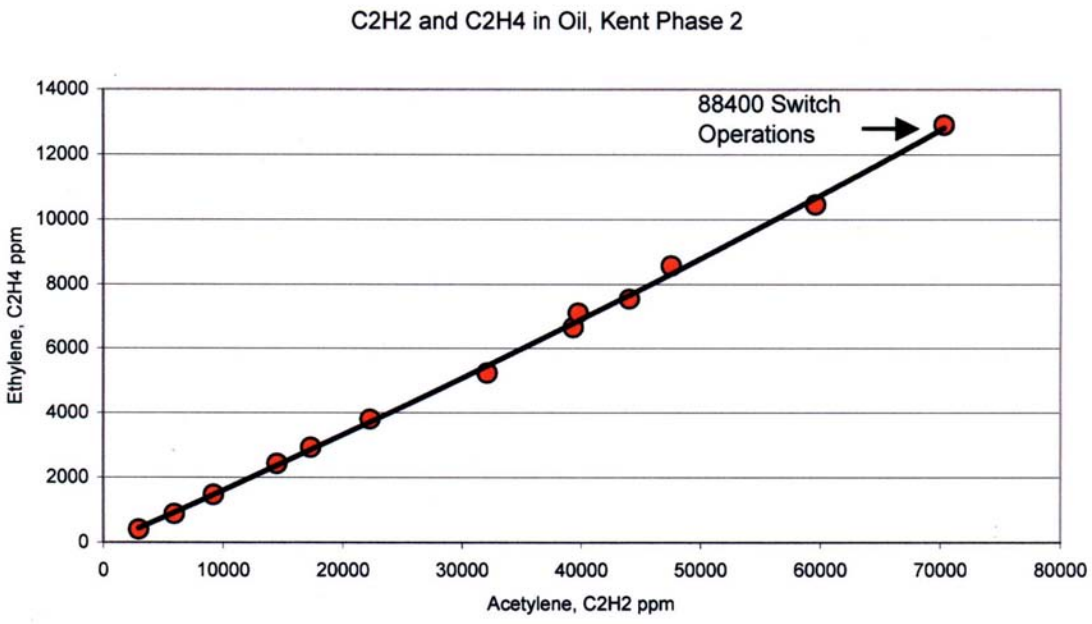

Figure 5-10
Fault Gas Ratios (Normal Operation)

In the case of different makes and models, the ratio as displayed in Figure 5-10 will be constant, although under normal operating conditions the slope might be different. Any deviation from that characteristic slope (make/model) will indicate an operational, usually a thermal disturbance.

Such a transition to thermal mode was evidenced in our *case - study* at Kent Substation. The last third of the data, period #19 to #27 (Figure 5-9) show a significant shift to a greater thermal component. This was achieved with the help of six implants in each of the moving half of the six diverter-switch contact pairs (Figure 5-2). The result is an artificial increase in Joule's heating, which increases the numerical value of term "%SumTherm", especially once the contacts wore down to the implants; or in-brief it resulted in an increase of thermal fault gas production, especially ethylene.

Investigation of Contacts

Powertech Labs Inc. investigated the quality of the diverter-switch contacts used at Kent Substation with a follow-up metallurgical study .

The "grain size" of the Elkonite material appeared to differ qualitatively between different batches of contacts. This was indeed the case and affected the arc damage inflicted on contacts in the field. In conclusion Powertech Labs Inc. recommends that the microstructure and hardness of new contacts should be assessed prior of purchasing large quantities. (Please see the report: "Load Tap Changers - Metallurgical Evaluation of Contact Materials" by Dr. A.S. Rao.)

Figure 5-11
New Diverter Switch Contacts for Kent

Figure 5-12
Kent Diverter Switch Contacts

LTC- Failures

The review of relevant literature and our own experience with LTCs indicate that failure conditions vary greatly. LTC make and model, oil quality, temperature profiles (oil/hot-spots) and the electric load to name a few, all have their share in how the fault mode develops.

The formation of surface deposits can be aided by differential thermal conditions (cold versus hot), thermal convection, electrical field gradients, and a lack of contact movement as in switches, which are dormant for most of the time, examples reversing switch assemblies.

Therefore, we propose, it is more important to develop an understanding and recognize the critical conditions, which are indicative of a beginning fault-mode, rather than to catalogue and provide detailed description for the different types of coke. Coke, the graphite like material, forms often in the last stages before failure when temperatures are truly excessive.

There is one condition when excessive temperatures might not be as trivial and obvious, and that is in the interface between two contact surfaces. Due to the nature of metallic surfaces, which are immersed in oil as in LTC compartments, there will exist a surface film on both metallic surfaces composed of oil or petroleum varnish. This "interface" will be subjected to current flow and resistive heating. The result might be micro-environmental temperatures we do not know much about.

Powertech Labs Inc. is conducting experiments of this nature at the present time. The test equipment is a fully functional, decommissioned LTC, specifically dedicated to carbonization studies of stationary contacts (three phases, three reversing switch assemblies, in series) and simulated field conditions of 13 kV, 200 to 1,000 A).

As to the metallurgy of LTC contacts, the investigation of Elkonite revealed the following findings.

Metallurgical Evaluation of Contact Materials

LTCs – Metallurgical Evaluation Of Contact Materials

The contacts of LTCs for transformers are commonly made of arc resistant materials containing tungsten and copper (Elkonite). These materials have a combination of good electrical conductivity, excellent resistance to arc erosion and high strength.

During a recent inspection of LTCs, extensive arc erosion was found on some of the contacts but not on others. Since all of these contacts had been exposed to identical conditions, it was suspected that the material characteristics might have been responsible for the variation in arc erosion damage. A metallurgical examination was carried out to evaluate the materials characteristics of contacts involved.

Metallurgical Examination

The microstructure and hardness values of contacts containing various degrees of damage were compared. The damaged surfaces were ground and polished using metallographic sample preparation techniques, and then the prepared samples were examined under an optical microscope to reveal their microstructure. The hardness values of the contacts were determined using a Rockwell hardness tester.

The results of the metallurgical examination are as follows:

Terrace Substation Old Contact (Stock No - 364-4053)

Sample #1: This sample had minimal arc damage on its surface. The microstructure shows a compact mass of sintered tungsten particles with a few small pockets of copper segregation. (Figure 5-13)

Kent Substation Old Contact (Stock No - 364-4053)

Sample #2: This sample showed heavy arc damage. The microstructure shows some large cavities in the sintered skeleton of the tungsten particles. Copper is segregated in these cavities. (Figure 5-14)

New Contact (Stock No - 364-4053)

Sample #3: This sample is a new contact. The microstructure shows a dense skeleton of sintered tungsten particles. Apart from a few isolated porosities, the overall microstructure does not show any segregation of copper. (Figure 5-15).

Abbotsford Area New Contact and New Design [Stock No of 4(a) & 4(b) - 364-30011

Sample #4(a): This sample is a new contact [similar to sample #4 (b)] obtained from a local source. The microstructure shows a dense sintered skeleton of tungsten particles with some pockets of segregated copper. (Figure 5-16) Abbotsford Area New Contact & Old Design (Stock No - 364-3001) Sample #4(c): This sample is also a new contact produced using the old design. The microstructure shows a compact mass of sintered tungsten particles. This microstructure is clean and free from porosity or segregated copper. (Figure 5-17)

Abbotsford Area Old Contact and Old Design Set #1 of 6 Pairs (Stock No - 364-3001)

Sample #5 (a): This sample showed heavy damage on its surface. The microstructure shows some large pockets of copper segregation. (Figure 5-18)

Abbotsford Area Old Contact and Old Design Set #2 of 6 Pairs (Stock No - 364-3001)

Sample #6(a): This sample showed heavy damage similar to that of sample #5(a). The microstructure shows some large pockets of copper segregation. (Figure 5-19)

Using EDX analysis in the scanning electron microscope, it was found that the alloy used to braze the contact of sample #4(b) to the copper substrate was BAG1 (Easy flow) alloy.

Discussion and Conclusions

Contacts containing tungsten and copper are made using powder metallurgy techniques. Tungsten powders are pressed and sintered to form a skeleton of the required shape. The molten copper is then infiltrated to the pores of this sintered skeleton to form an approximately 97%

density composite. A properly manufactured contact contains an insignificant amount of porosity or segregation of copper in the sintered mass of the tungsten particle. Its microstructure would show a compacted mass of tungsten particles surrounded by a thin layer of copper.

This kind of microstructure was only observed in samples #4(c) and #3. The microstructure of samples #1 and #4(a) showed a compact mass of sintered tungsten particle with a few pockets of porosity, while the microstructure of samples #2, #5 (a) and #6 (a) showed large areas of copper segregation. The hardness values of the contacts also varied as their microstructures varied. Those with sound microstructure averaged between 95 HRB (Rockwell B) to 98 HRB, while those with copper segregation averaged between 84 HRB to 89 HRB. The contacts which showed sound microstructure and high hardness had better arc resistance than the contacts containing copper segregation. The sound contacts also resistant to a failure mode known as "bridge formation". When a pair of contacts closes, the surface asperities on the mating surfaces make the contact forming current carrying paths. Heat is generated in these areas and if the temperature becomes high enough, then melting takes place on these regions. When the contact is opened the molten metal is pulled apart forming a current carrying bridge. In a properly manufactured contact current carrying paths are formed on the surface asperities of the sintered tungsten skeleton. Since tungsten has the highest melting point, the surface asperities would not melt in the normal operation. If the contact contains copper segregation, current carrying paths are formed on the asperities of both tungsten and copper. The asperities of copper would melt at high current densities and these paths would be broken when the contact points pull apart. This generally results in pitting of one contact surface and buildup of material on the mating surface. This kind of damage was seen on samples #2 [Stock # 363-4053], #5(a) [Stock #364-3001] and #6 (a) [Stock # 364-3001] contacts.

Table 5-1
Hardness

Sample Number	Make and stock Number	Origin of contact	Condition of Tip	Hardness (Rockwell B)	Average Hardness Rockwell B
1	Federal Pioneer Stock # 364-4053	Terrace Sub. Old Contact	Minimal damage	97.4, 97.3, 97.4, 97.5, 96.7	97.2
2		Kent Sub. Old Contact	Heavy damage	87.8, 86.0, 93.5, 89.9, 88.1	89.0
3		New	New	94.9, 95.3, 94.8, 95.2, 94.8	95.0
4(a)	Ferranti Packard Stock # 364-3001	Abbotsford New Design New Contact	New	97.2, 97.4, 99.4, 98.7, 99.4	98.4
4(b)		11	New	95.2, 96.2, 96.5, 95.0, 96.3	95.8
4(c)		Abbotsford Old Design New Contact	New	98.6, 99.7, 98.3, 98.9, 98.5	98.8
5(a)		Abbotsford Old Design Old contact	Heavy damage	86.6, 86.6, 86.4, 87.0, 87.3	86.7
5 b)			Heavy damage	87.8, 88.3, 89.7, 88.6, 87.6	88.4
5(c)			Heavy damage	88.5, 87.9, 89.7, 90.0, 88.8	88.9
6(a)			Heavy damage	84.6, 87.5, 87.2, 85.4, 87.4	86.3
6 b)			Heavy damage	83.2, 85.5, 86.4, 82.1, 85.7	84.5
6(c)			Heavy damage	85.8, 86.4, 85.6, 87.8, 85.8	86.2

These results clearly indicate that the arc resistance of the contacts used in LTCs depends on their microstructure and hardness. A contact with a hardness value around 95 HRB and a compact mass of sintered tungsten particles uniformly surrounded by a thin layer of copper has the greatest resistance to arc and bridge formation. Hence the microstructure and hardness value of the new contacts can be used to evaluate their quality.

Recommendations

The microstructure and hardness value of the new contacts to be used in LTCs should be assessed to evaluate their quality. Since these contacts are normally machined from a bar of tungsten-copper composite (Elkonite), one sample per bar should be inspected for sound microstructure and adequate hardness.

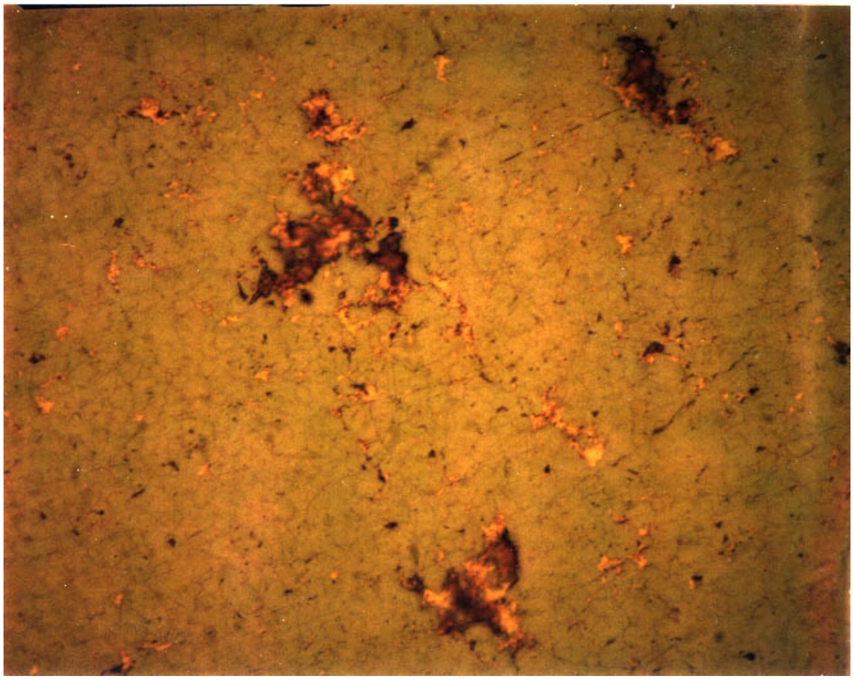

Figure 5-13
Microstructure of Sample #1 in the As-Polished (not etched) Condition
Magnification: 500X)

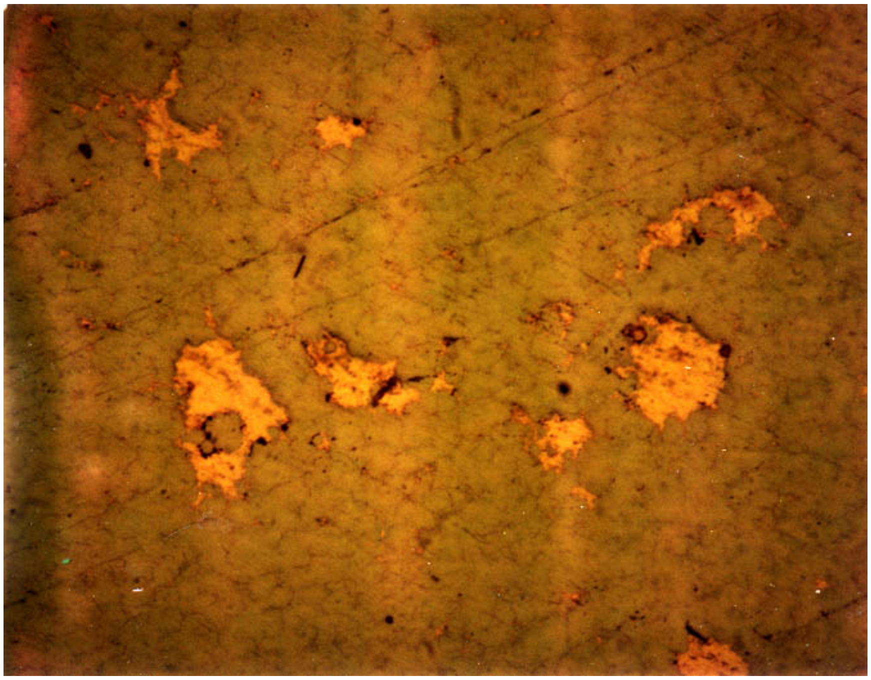

Figure 5-14
Microstructure of Sample #2 in the As-Polished (not etched) Condition (Magnification: 500X)

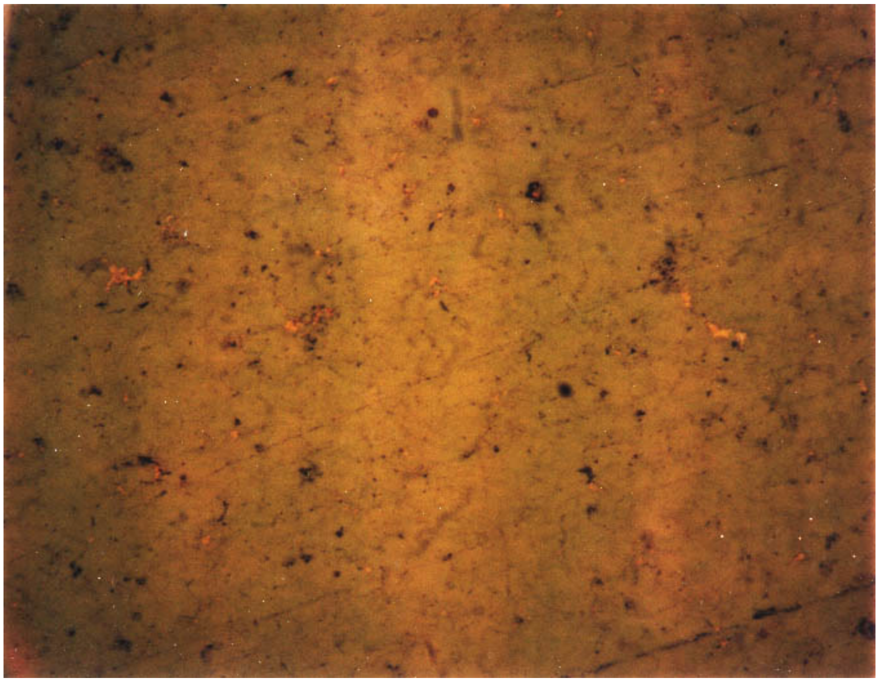

Figure 5-15
Microstructure of Sample #3 in the As-Polished (not etched) Condition (Magnification: 500X)

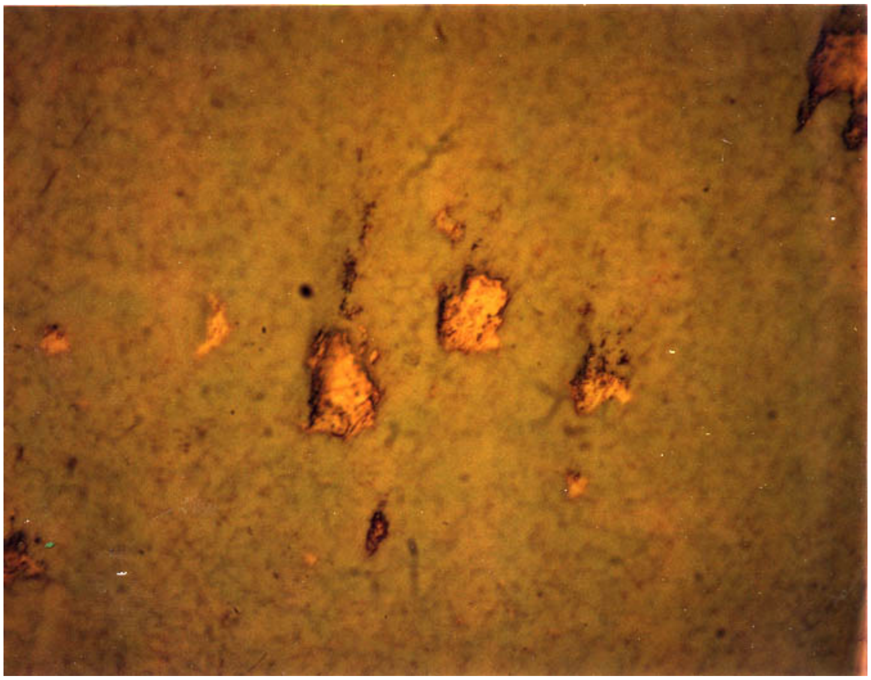

Figure 5-16
Microstructure of Sample #4 in the As-Polished (not etched) Condition (Magnification: 500X)

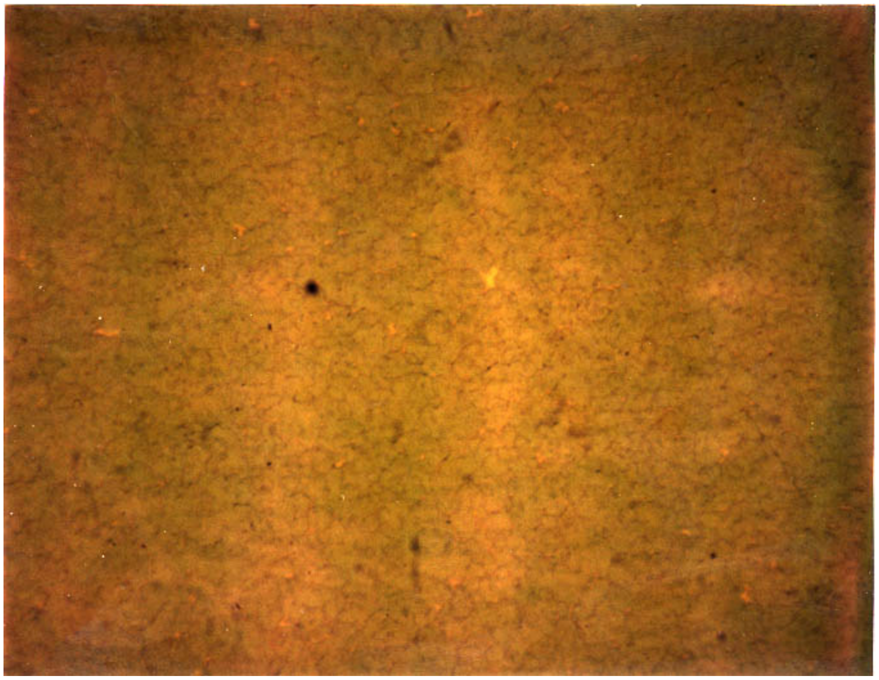

Figure 5-17
Microstructure of Sample #4 in the As-Polished (not etched) Condition (Magnification: 500X)

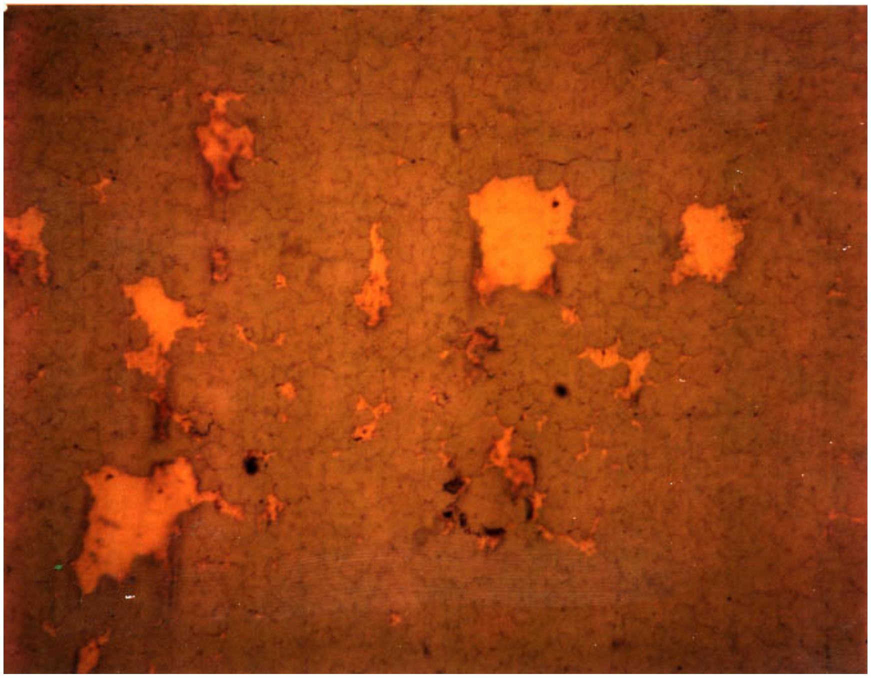

Figure 5-18
Microstructure of Sample #5 in the As-Polished (not etched) Condition (Magnification: 500X)

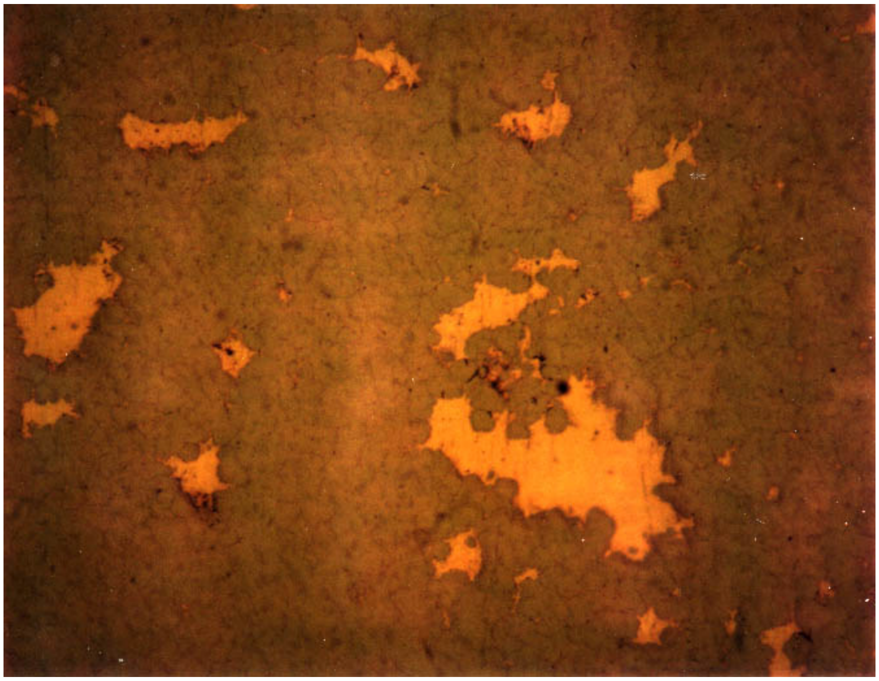

Figure 5-19
Microstructure of Sample #6 in the As-Polished (not etched) Condition (Magnification: 500X)

On-Line Oil Filtration

Introduction

The following work was completed prior to the evaluation of "On-Line Filtration":

i) The set-up of a database encompassing details of the different LTC makes and models at B.C. Hydro (MS-Access/relational), (Section 6). This was necessary to accommodate (ii), (iii) and (iv).

ii) The completion of a thorough, in depth case-study of a single LTC (Kent Substation). This provided a standard model of performance.

iii) A limited survey of LTCs within a utility (B.C. Hydro). This permitted a comparison of the standard model (ii) with a medium sized set of LTCs.

iv) Comparison of identical LTCs: "with" and "without" on-line oil filtration, to show the effects of on-line filtration.

Many utilities, including B.C. Hydro, increased the intervals for time-based maintenance for most transformers from four to six years. This move necessitates the introduction of other preventative measures to maintain the same level of confidence in power delivery.

There are several routes to offset the decrease in field maintenance. One such tool is the addition of on-line oil filtration, especially for reactive LTCs. The other tool is gas-in-oil analysis for LTCs. Some utilities chose to include dissolved gas-in-oil analysis in the routine testing schedule for transformers and sub-equipment, regardless whether these are LTCs of the reactive, resistive or vacuum type.

On-line oil filtration removes particulate carbon, a natural by-product of arcing, from the insulating oil. Aside from maintaining a clean environment in LTCs, the removal of carbon supposedly reduces an early loss in breakdown strength of the oil and carbon build-up on contacts and other sensitive parts of LTCs. The presence of carbon particles reduces the breakdown voltage of small oil gaps above 50°C. An increase in the carbonization of oil will shift the maximum of the breakdown voltage curves from 80°C to lower temperatures.

Powertech Labs Inc. has doubts that filtration alone will eliminate the chemical breakdown products of transformer oil. Work at Powertech Labs Inc. shows that old, filtered oil may carbonize or sludge-up within a day even at surface temperatures below 250°C (Figure 4-25, third frame). Some of this work is currently under study and should become available with the next Final Report, which covers the present work. We also raise the question whether filtration and possible electrostatic charge build-up might not promote the formation of free radicals [35,36]

Case Study – Merits of On-Line Oil Filtrations

Introduction

This case study was initiated by B.C. Hydro and has lasted for several years now. Two identical LTC units with identical service histories were monitored and compared - one equipped with on-line filtration and the other not. Nothing can be said about the advantage or disadvantage of filtration as none of the units progressed into a failure/fault mode of operation.

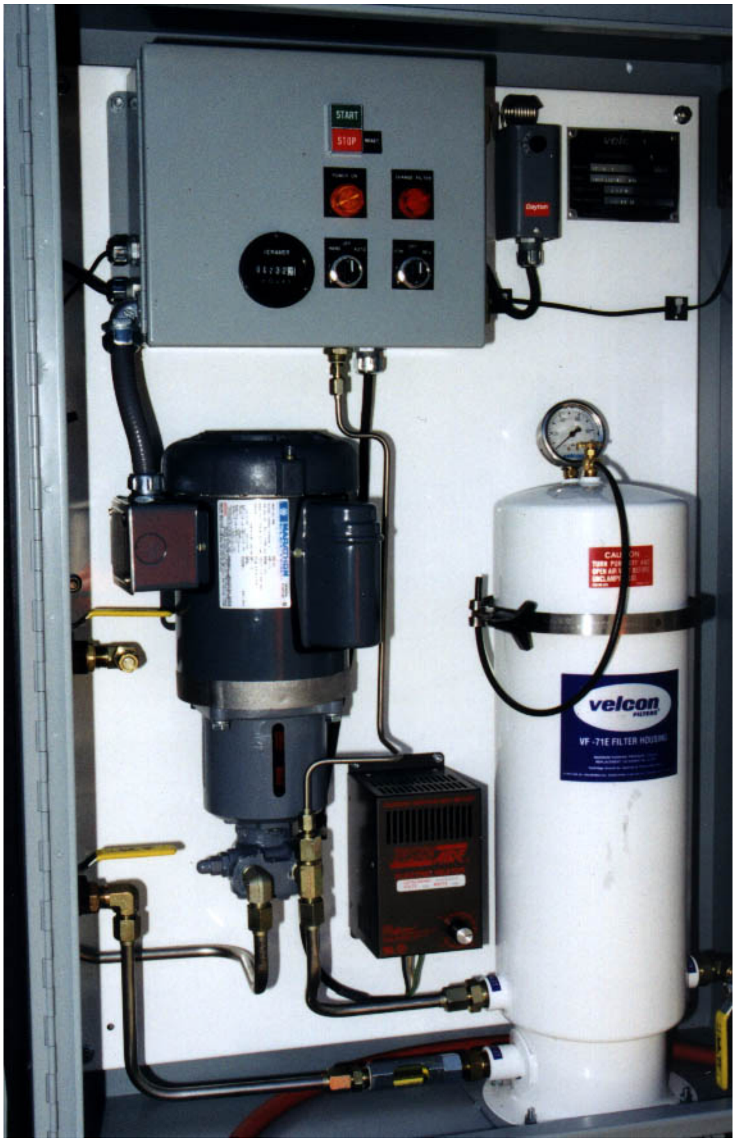

Figure 5-20
Typical On-line Filtration Unit at a BC Hydro Substation (Kent)

The evidence is presented in this report.

In 1996 B.C. Hydro equipped one of two identical LTCs T1 and T2 with an on-line filtration unit, while its sister-unit remained unchanged. Both units were cleaned, overhauled to the same specifications and filled with Voltesso-35 insulating oil. PLI found the following:

The units were monitored over the next few years and the performance compared. The ethylene/acetylene ratio was constant, irrespective of the presence or absence of filtration.

Results and Discussions

Calculating ethylene/acetylene and some other ratios for each analysis (about twelve sets of data over three years) and graphed for both units, the following can be observed. The three-year Figures 5-21 and 5-22 for the units T1 and T2 are almost the same and show the same constant slope (similar to the case-study at Kent Substation).

<u>Unit T1:</u>

Mission Substation: 02-06872 LTC T1-Uzert 380/500 Volts: **MFR Model: ONAN**
Volt/Amp: 75,000,000
Ampere: 447 **MFR Date: 03-June-83**
Filtration Unit: Yes **Type: Velcon TP2**

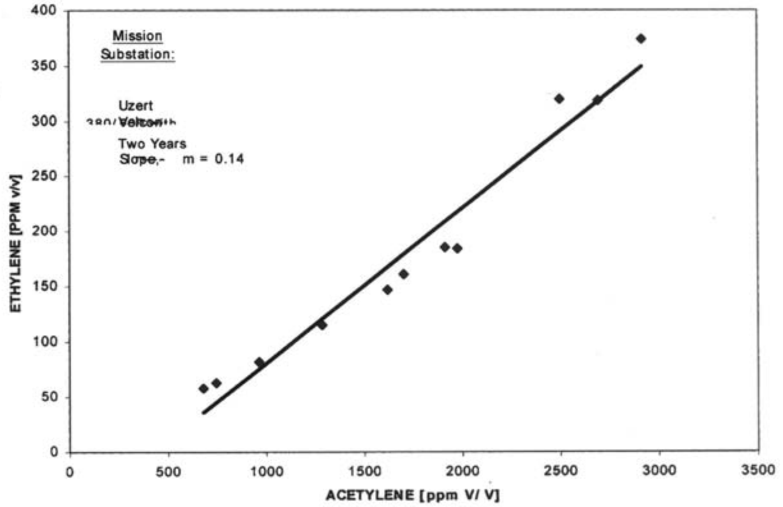

Figure 5-21
LTC-T1: Ethylene Versus Acetylene – with Filtration

The oil qualities were the same and the units were put into service at the same time under equal loadings.

The averaged ratios for acetylene/hydrogen, methane/hydrogen and other hydrocarbon/hydrogen are quite different for the two units. They are higher in the case of on-line filtration and this is not due to the loss of hydrogen as one might have assumed.

However, the ratio for (acetylene + hydrogen)/TDCG, expressed in percent, remains constant for both units over the three years. This is typical for the normal operating mode of most LTCs. The ratio is usually in the 80% to 90% range (Section 6: Figures 6-1 and 6-10).

Unit T2:

Mission Substation:	**02-06873 LTC T/Uzert 380/600**	**MFR Model: ONAN**
Volts:	**3 Phases**	**Volt/Amp: 75,000,000**
Ampere:	**447**	**MFR Date: 03-June-83**
Filtration Unit: No		

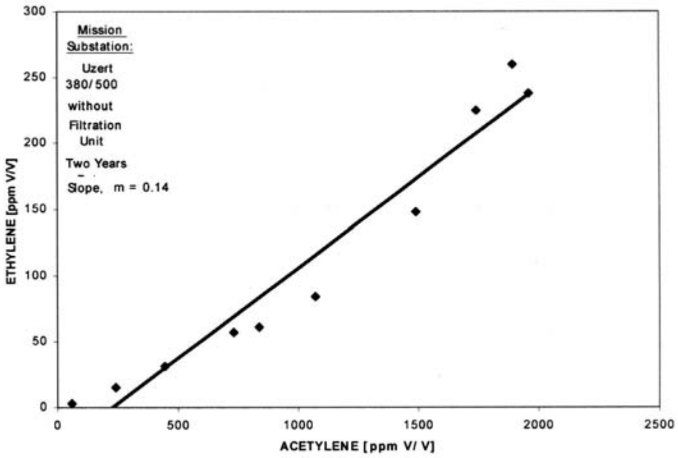

Figure 5-22
LTC-T2: Ethylene versus Acetylene – No Filtration

A downward drift of this ratio with time would indicate an increase in the thermal components (ethylene), which is undesirable. We conclude that on-line oil filtration will not interfere with dissolved gas-in-oil analysis (DGA). How and whether the absence of particulate carbon will affect the development of equipment faults is not known. To evaluate this, PLI is conducting special laboratory runs at the present time. The two LTC at Mission Substation are about as close as one can get to a controlled field trial of two units and their comparison.

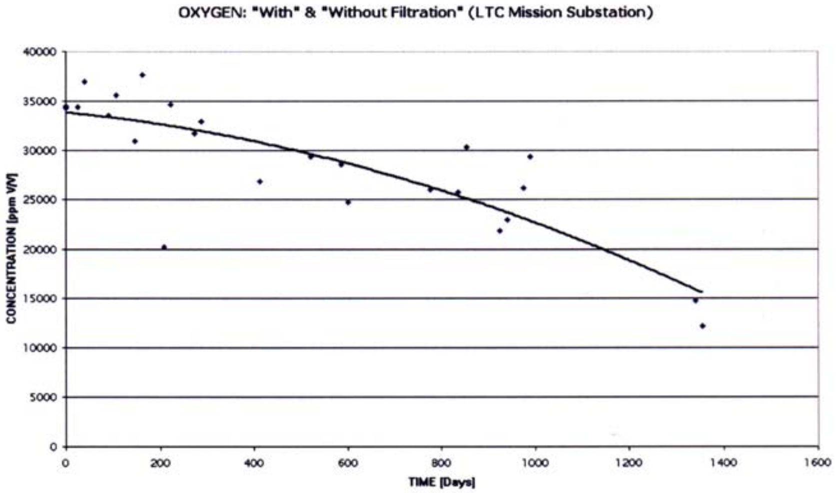

Figure 5-23
Oxygen "with" and "without" Filtration (LTC Mission Substation)

The oxidation of the oil proceeds similar in the filtered and non-filtered unit as shown by the figures for the formation of carbon dioxide and uptake of oxygen. The data for the two units are statistically so similar (data intermingle) that for the purpose of graphing the data sets (filtered and non-filtered) were combined (Figures 5-23 and 5-24). The same can be said about the hydrogen concentrations of each unit, again the data are similar but on the average slightly higher for the on-line filtration LTC.

The hydrogen-to-hydrocarbon ratios are generally higher in the case of on-line filtration; and so are the total dissolved hydrocarbons (TDH) and the total dissolved combustible gases (TDCG) as presented in Figure 5-26. The trends of the ratios are not easily explained. The unit with on-line filtration started with higher DGA-concentrations, possibly due to the variation in the quality of the oil.

On-line filtration removes efficiently particulates of carbon and in-organics (metals). However, there are no improvements observed that might be attributable to filtration. The averages of the breakdown voltages, interfacial tensions, neutralization numbers, and color remain the same. Both units operate normal and the oil quality appears to be effected in a minor way.

We would like to report one significant observation though. The evolutions of CO, for the two LTC units are distinctly different and follow different slopes. We conclude that carbon monoxide and carbon dioxide are, perhaps, created by two distinct and different mechanisms (Figure 5-25).

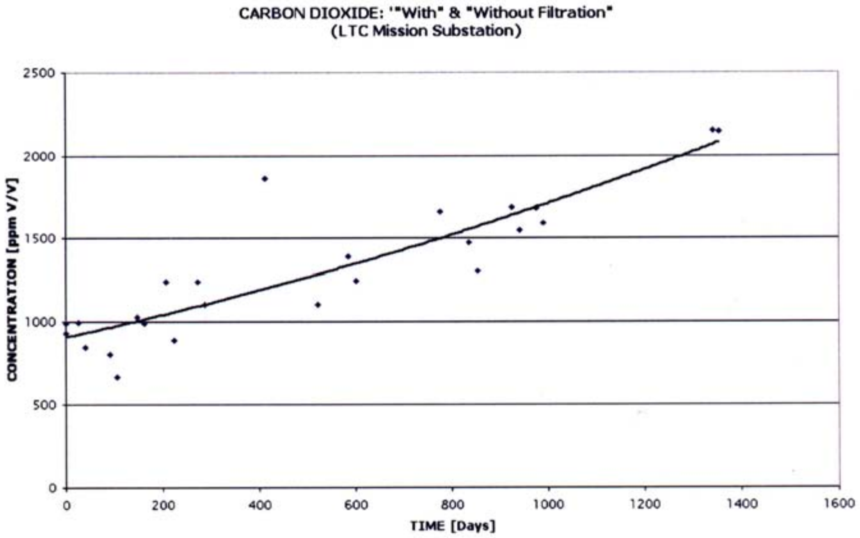

Figure 5-24
Carbon Dioxide "with" and "without" Filtration (LTC Mission Substation)

The Figures 5-21 to 5-26 represent close to four years of gas-in-oil data; and the results demonstrate similar performance of the equipment as well as similar pre-fault status (Figures 5-21 and 5-22) within the documented timeframe.

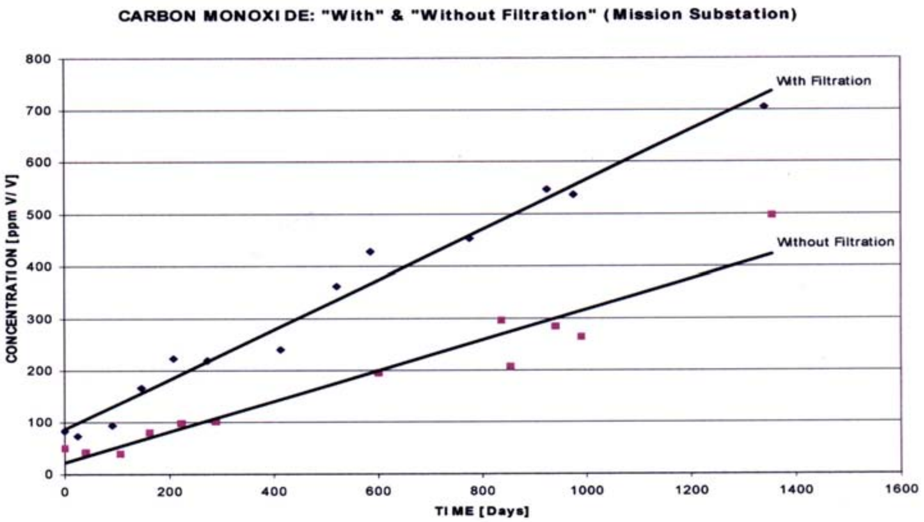

Figure 5-25
Carbon Monoxide "with" and "without" Filtration (Mission Substation)

Discussion/Conclusion

The possible occurrence of a fault mode for one of the two pieces of equipment might provide a chance to judge whether on-line filtration indeed protects the associated LTC unit. The intermingling of data, where reported, is real and not due to sampling faults or laboratory error. The evidence for this can be found in the other data sets like Figures 5-21, 5-22 and those for carbon monoxide (Figure 5-25).

It is often asked, whether on-line filtration protects LTCs from failure. At the present time no definite answer is available. If failure is related to a major build-up of suspended carbon, the answer is "yes", but from our experience that is only a small fraction of all failures.

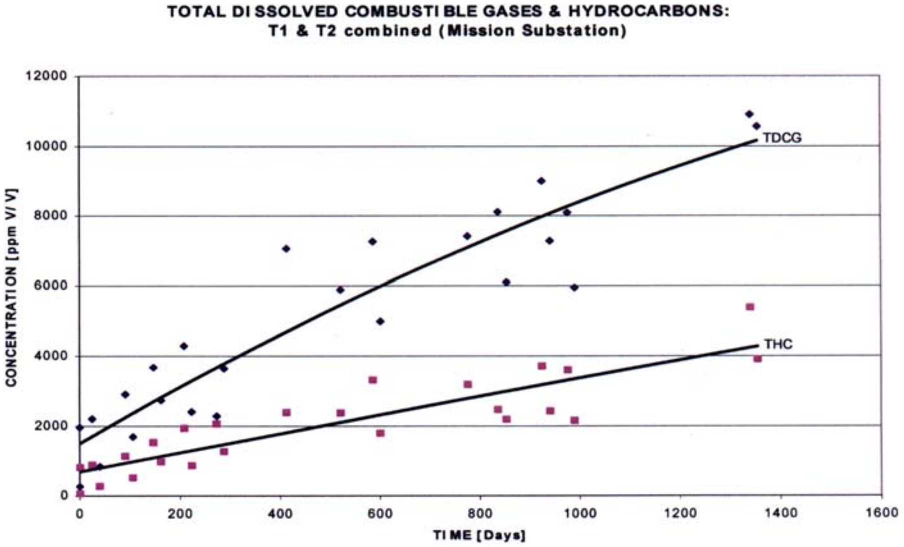

Figure 5-26
Total Dissolved Combustible Gases & Hydrocarbons, T2 & T2 combined (Mission Substation)

The survey of in-field LTCs confirms the formation of unsaturated hydrocarbons in LTCs. These compounds, if high enough in concentration, in the presence of oxygen and suitable catalysts (copper) may result in accelerated ageing of transformer oil. We doubt that the present "state-of-the-art" filtration equipment will remove unsaturated compounds from the oil and failure due to coke formation exists.

6

DATABASE OF LTCS

Introduction

The survey of in-service LTCs revealed data similar to those of the "Case Study" at Kent. Again, the normalized results are shown in Figure 6.1. Powertech Labs Inc's work on "Maintenance-Free LTC" leads to the conclusion that further work, especially the expansion of the data base work, will permit the development of fault algorithms for LTCs. This work is being pursued at Powertech Labs Inc. at the present time. The presentation in Figure 6-1 includes LTCs in the 'fault mode' as well as LTCs with very low levels of "gas in oil" data. In the latter example the normalization amplifies associated errors of analysis. The result is that faults and low levels show up together in the range #50 to #85. These units with low levels of 'gas-in-oil' data do not lend themselves to fault diagnostics, neither is there a need.

Failures are not only associated with particular fault gases but are, in addition, usually accompanied by accelerated rates of gas evolution ("kinetics"). We recognize, however, that the value of the survey is limited to B.C. Hydro's LTCs (Canada) and it ignored the wider field of United States utility component.

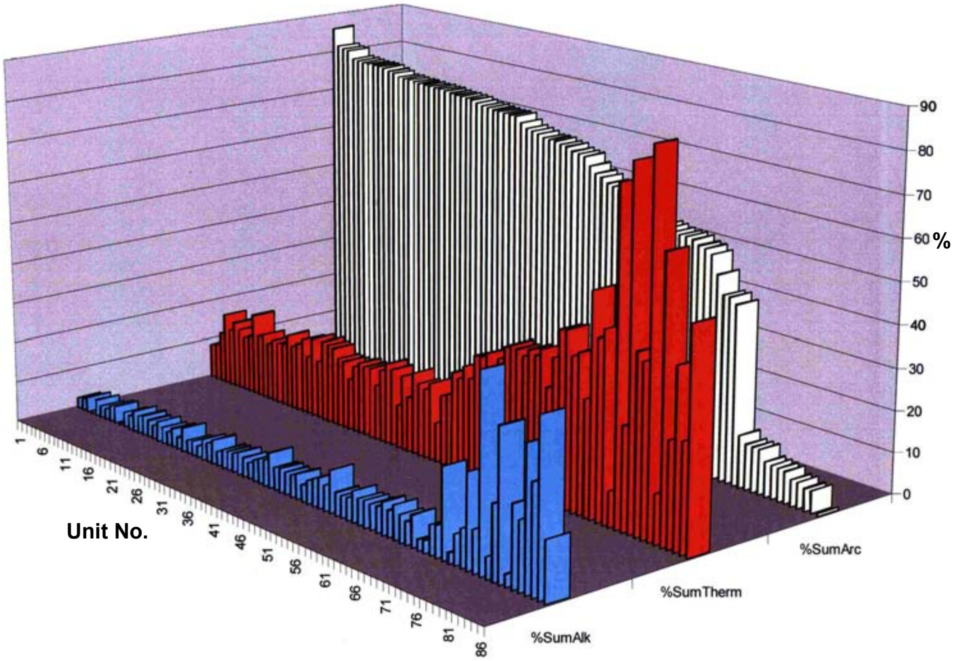

Figure 6-1
Survey of 85 LTCs: Gas-in-Oil Survey in Percent (by weight)

We are working on a second study, which surveys all of B.C. Hydro's LTCs. We are also pursuing another initiative, which is a solicitation of U.S. utilities to share their LTC information with us, especially "gas-in-oil" data. (We are pleased to report that we received already one favorable response.)

LTCs are usually maintained by frequent, external inspections and annual oil testing for dielectric strength, water content, colour, and acidity.

Limited Survey of B.C. Hydro LTCs

An example of data, which permitted the successful prediction of an LTC in fault mode, is provided in Figures 6-2 and 6-4. Historical files provided examples of nine LTC units with "charred contacts or conductors" which failed. The DGA data of these units prior to failure are compared with the "normal data" of the Kent unit in Figures 6-4 and 6-5.

Considerations

The LTCs are used in a wide range of designs and configurations. There are reactor and high speed resistor switching LTCs of different arrangements [33] etc. Data in this database will be reviewed in a short form. The follow-up study, which is more comprehensive, will review the findings in the context of nameplate, service history and parent unit.

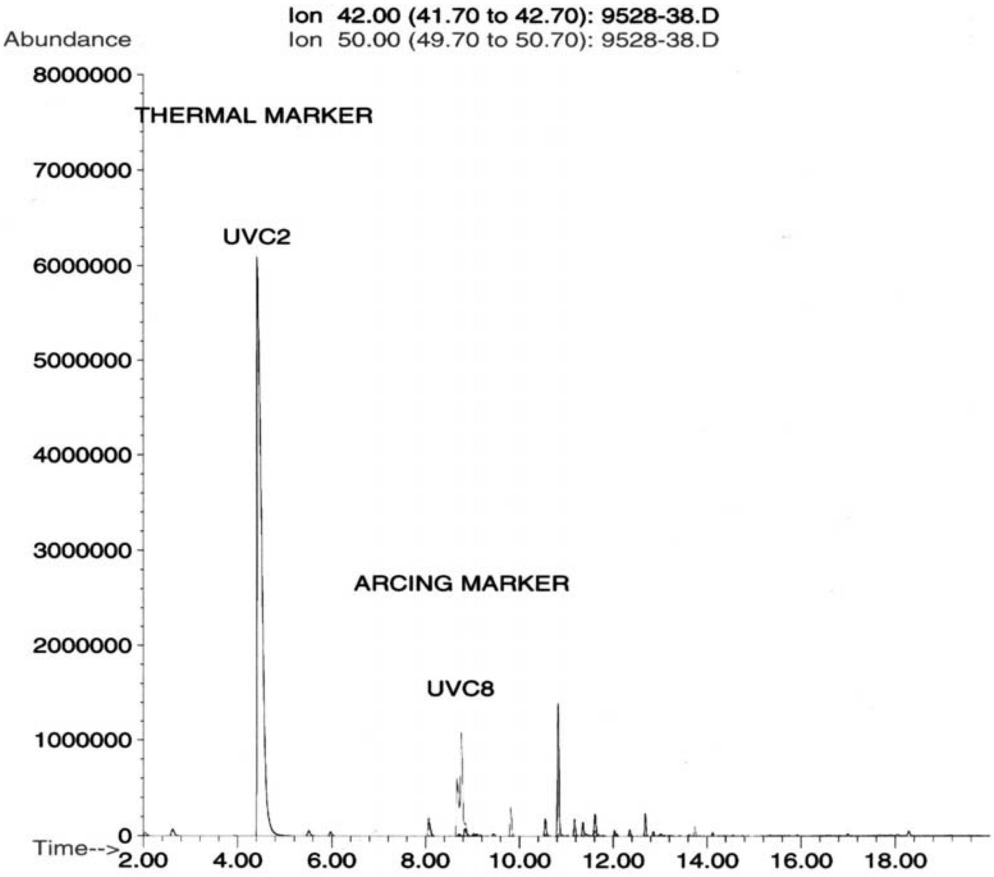

Figure 6-2
Ion Chromatogram for Selected Compounds in Oil, (Sample from LTC in Fault Mode)

Oil Sampling

The oil samples were collected in gas-tight syringes and quart bottles. Sample containers were distributed with special sampling instructions, labels, and a questionnaire on the LTC itself. "Standard Oil Tests" conformed to ASTM standards, and included gas-in-oil analysis, dielectric strength, neutralization number, water content, color, and interfacial tension. All of the samples were tested for "Unsaturated Volatile Compounds" and "Suspended Particles" (including measurement of carbon and metal content. About 90 LTCs in the initial survey were also tested for a range of "Polyaromatic Hydrocarbons", and "BTEX" (benzene, ethyl benzene, toluene, and xylene).

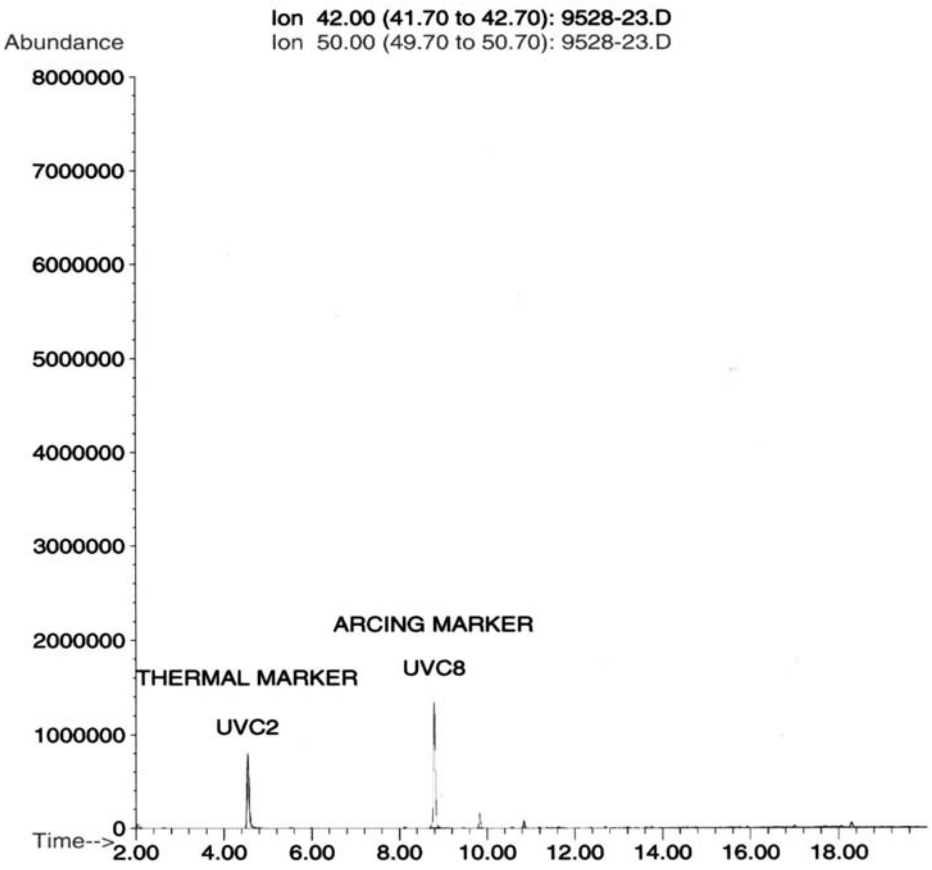

Figure 6-3
Ion Chromatogram for Selected Compounds in Oil Sample from Normal LTC

Discussion

Our experimental and field-test data indicates that some developing faults can be detected in LTCs using modified gas-in-oil analysis. There is also considerable potential for assessing wear or weaknesses in LTC contacts if adequate "fingerprinting" is available.

The top priority was to identify any LTCs exhibiting signs of pending failure (Figures 6-4, 6-5) and to advise BC Hydro maintenance staff as promptly as possible. This was accomplished by sorting the gas-in-oil data into "Normal", "High Hydrogen", and "High Ethylene" categories (Figures 6-6, 6-7, 6-8). There were also a few "Outliers" which exhibited different fault gas patterns (Figures 6-9).

The "Low-Normal" data included LTCs with vacuum diverter switches, and some samples were taken immediately after an oil change. The "Normal" units were selected on the basis of gas-in-oil patterns appropriate to arcing operations and with acceptable total amounts.

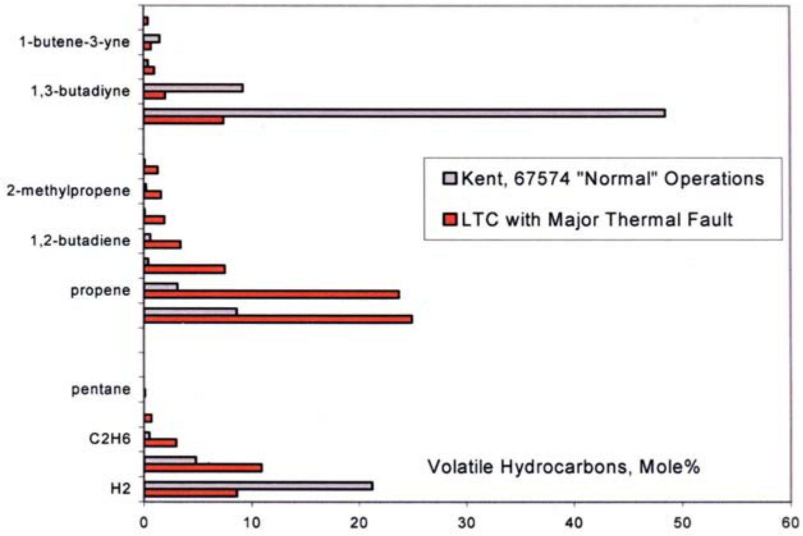

Figure 6-4
Example of an LTC in Severe Fault Mode

The "High Hydrogen" and "High Ethylene" units are being assessed in the light of gas evolution rate, total gas volume, particles, dissolved contaminants, LTC configuration, and further operational data.

The complete diagnostics ("Algorithms") will have to take into account atmospheric gases: oxygen, nitrogen and carbon monoxide, carbon dioxide, water, other marker compounds and trend data if available.

The future development of LTC monitoring will have to address gas dynamics and temperature monitoring (gas evolution over time and/or per tap change operation). The emphasis will have to shift to chemical kinetics as captured by dynamic on-line-monitoring rather than the determination of static concentrations.

Oil filtration for LTCs, although an excellent supplemental maintenance tool and a first step in preventing critical carbon build-up and the possible deposition of sludge and coke, is neither diagnostic (most LTC failures are of mechanical nature) nor does it provide tools for preventative maintenance [34]. The search for this tool is still on.

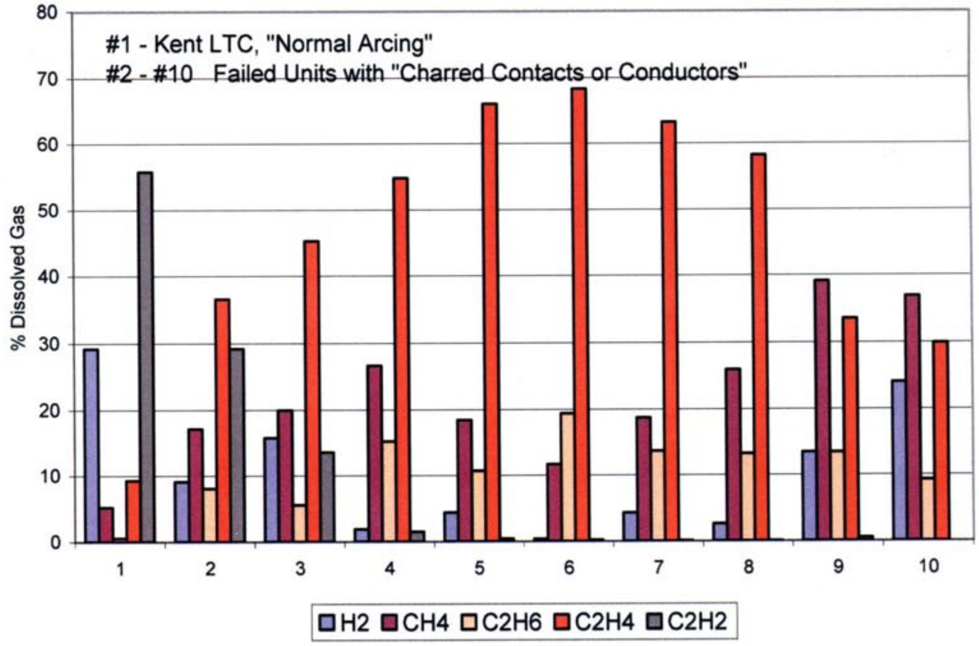

Figure 6-5
Failed Units and CGA Data

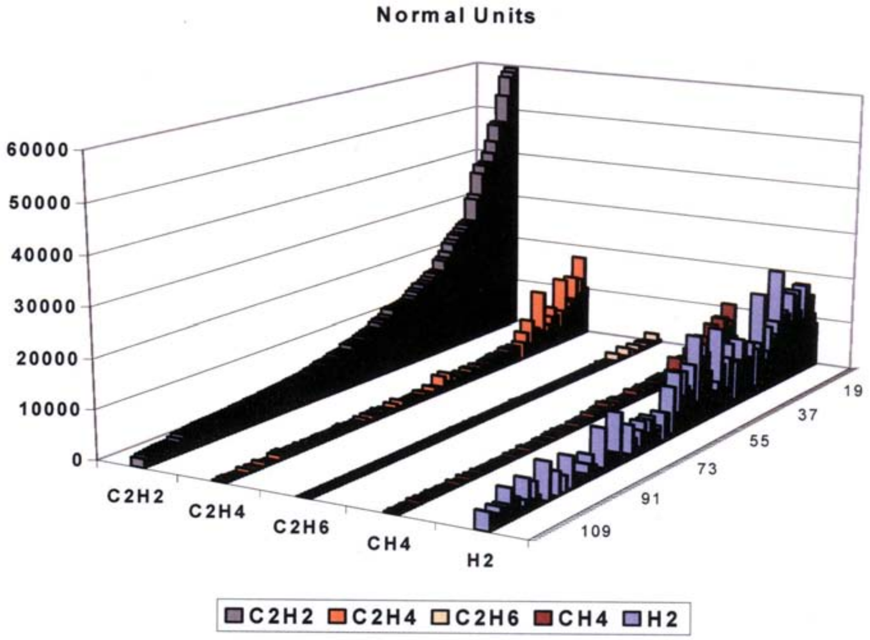

Figure 6-6
LTC Units with "Normal" CGA Results

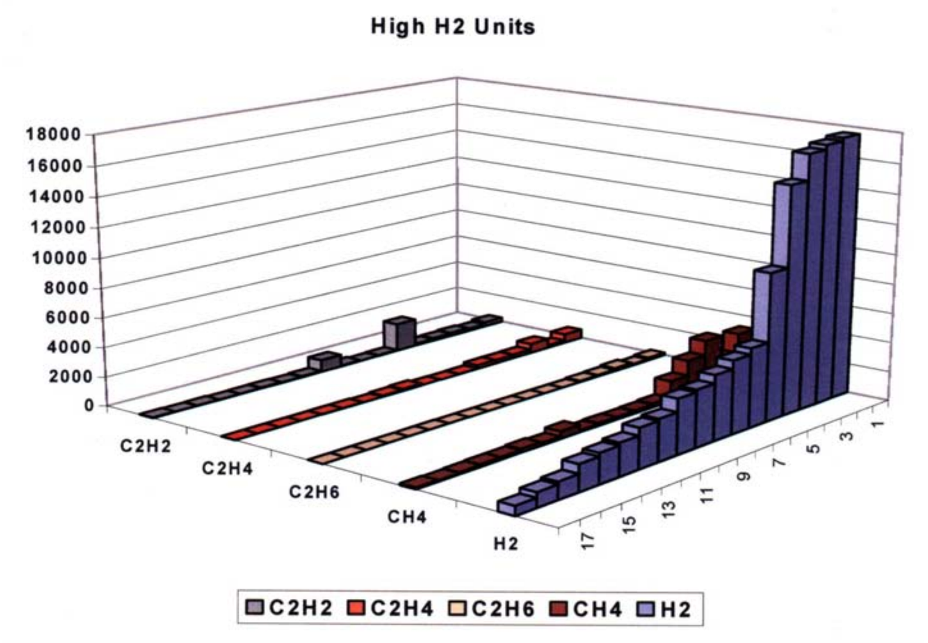

Figure 6-7
<u>LTC Units</u>: CGA Analysis Showing High Hydrogen Concentrations

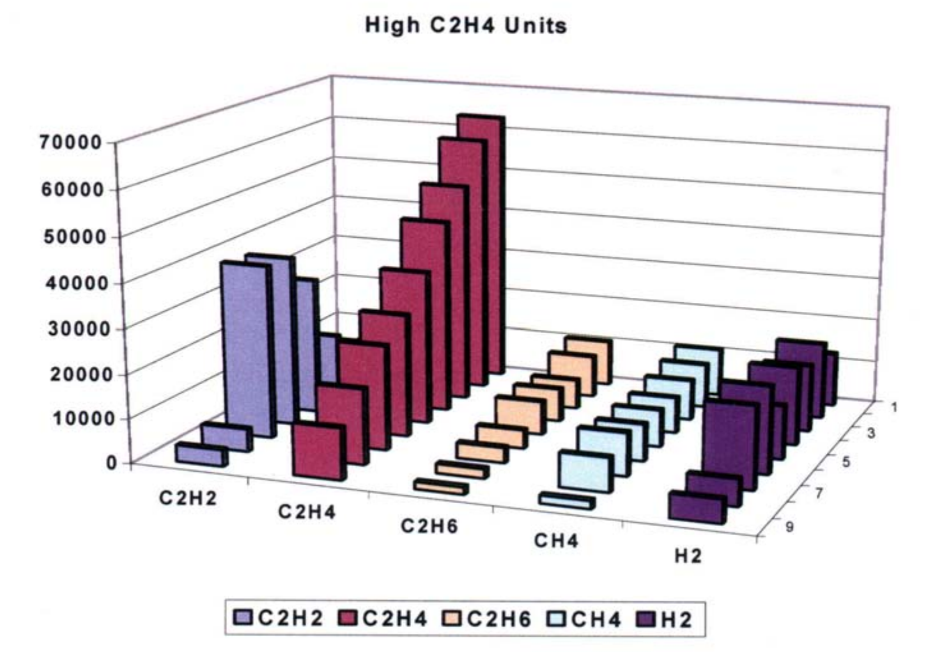

Figure 6-8
<u>LTC Units</u>: CGA Analysis Showing High Ethylene Concentrations

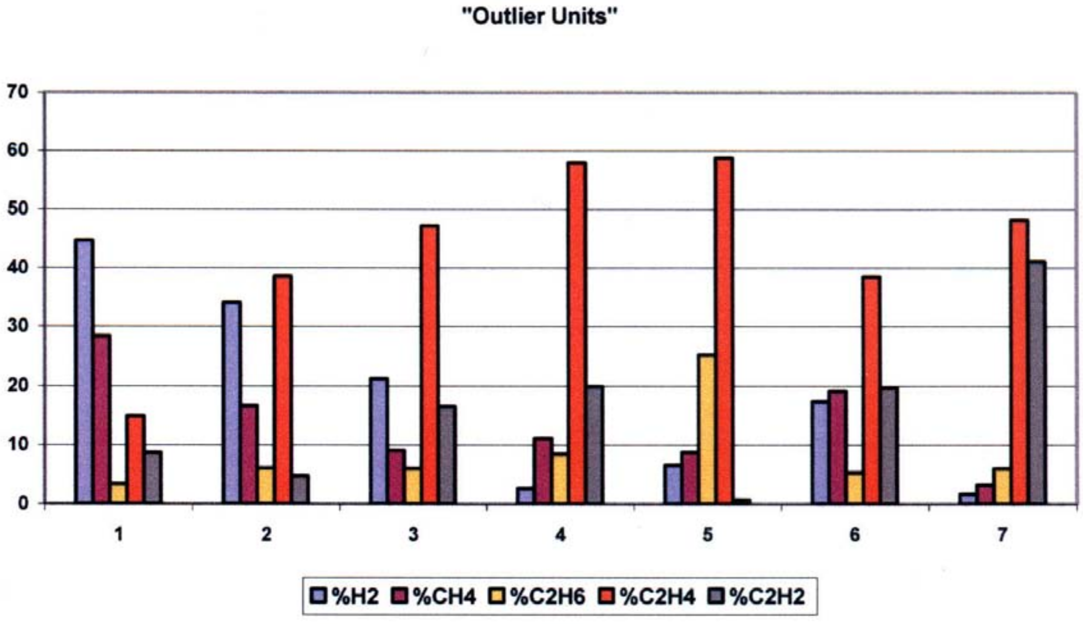

Figure 6-9
Examples of LTC Outlier Units

In Conclusion

It is our experience that every deviation from the ratio, other than expressed in Table 4-1 with a LTC in normally operating mode, is due to major design differences. This will translate into a shift of the balance between the typical arcing gases, typical thermal gases and perhaps other contributions such as resulting from partial discharge/corona. In Figure 6-6 the "classical" gas-in-oil data are shown. High hydrogen data (Figure 6-7) and high ethylene concentrations (Figure 6-8) might be "normal" for certain LTC designs.

The majority though of the different makes/models of LTCs, presently in use at BC Hydro (Table 3-1), seem to follow the trends as displayed in Table 4-1, Figure 5-5 and Figure 6-6.

Powertech Labs Inc. employs additional diagnostic tools, referred to as "unsaturated volatile compounds" (UVC). These compounds were identified and as part of this project. The initial thoughts were, when we conceived the project that the fault gas concentrations would show higher variability and thus be rendered un-interpretable. Thus we searched for additional marker compounds, the UVCs. The UVCs allowed us to point out units in "fault mode", which is on the main due to their greater temperature specificity, lower concentrations and good solubilities.

The major importance of these compounds, based on our findings, is their role as gum and coke pre-cursors. In the presence of oxygen these compounds will polymerize and adhere to surfaces at low and high temperatures. We revised our views about primary LTC fault gases (especially ethylene), but despite this revision still use the information gained from the presence of the unsaturated volatiles.

Powertech Labs Inc. presents the analytical and equipment data for the purpose of this report in Microsoft Access. That database is composed of 15 tables. Initially we combined Access with Visual Basic to provide a menu-driven program for LTC-diagnostics. This approach was given up, when it became evident that EPRI decided to go a more comprehensive route with X-Visor for the utility industry. EPRI is in possession of that Access database.

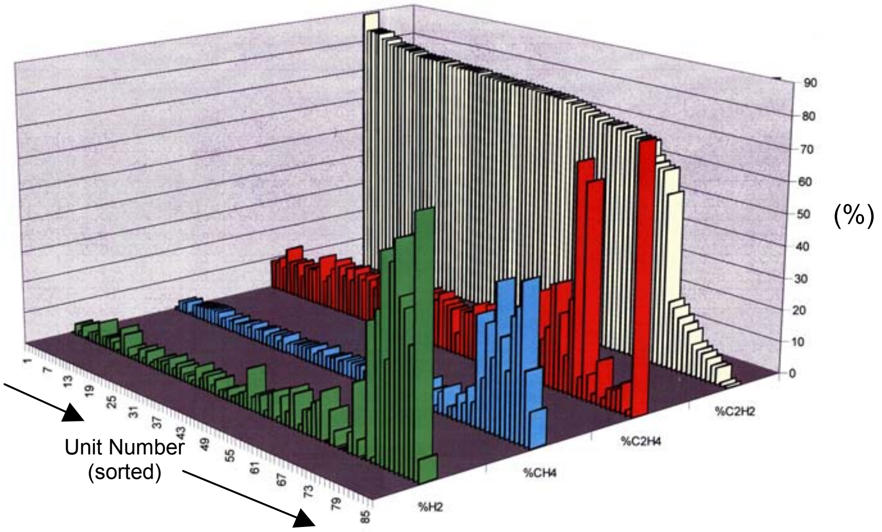

Figure 6-10
Survey of 85 LTCs: Typical Gas-in-Oil Survey in Percent (by weight)

7

DISCUSSION

Thermal laboratory runs of insulating oil show that between 150°C and 500°C the major gases formed are methane and hydrogen, followed at 300°C by ethylene and ethane. Between 500°C and 800°C ethylene evolution is the major decomposition product, as measured by its rate of formation, outpacing significantly all other gases. At a temperature of about 550°C the chemistry of oil decomposition assumes new dimensions, a plethora of new compounds are formed. This change in chemistry appears to be the result of a pronounced increase in thermally generated free radical scavengers, which follow Arrhenius kinetics.

From these observations and those gathered by the arcing experiments, our team moved on to an LTC case-study (Kent Substation of B.C. Hydro) and monitored the following parameters under conditions of accelerated tap change operations:

i) The traditional fault gases of DGA: hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide, carbon dioxide

ii) Other volatile compounds

iii) Mono aromatics (BTEX)

iv) Polyaromatic compounds (PAHs)

v) Dissolved metals

vi) Particulate type, quantity and composition

vii) Moisture content

viii) Dielectric strength and

ix) Additional oil quality data by other non-conventional methods

The results of these investigations informed us that laboratory results mimic quite well "normal" and "fault-mode" behavior of in-field LTCs. For example the gas-in-oil data (DGA) of an LTC in "normal" mode of operation are "cumulative and proportional". We define as cumulative when the concentrations of arcing or thermal compounds are related to the number of tap-change operations (or time). We define as proportional when certain compounds from arcing or thermal processes relate to each other in ratios similar (example: Figure 5-10) to those described by "Rogers Ratios" (for transformers). "Proportional" and "cumulative performance" accompany each other. This rule generally applies to thermal compounds as well as to arcing compounds.

Under normal operating conditions LTCs preserve these relationships. A drift of the data appears to be normal as the equipment and its components approach their operational design limits (for example 100,000 switch operations). The gas composition will shift to a more thermal mode, for example the ethylene concentration increases, as the LTCs age and the contacts develop coatings of poor thermal and electrical conductivity. At this stage the wear and tear of the equipment becomes observable, especially when pushed beyond its design limits.

Our case study at Kent substation is an example. For about nine months we investigated the oil chemistry of an LTC (Federal Pioneer; FPE). The dissolved gas-in-oil results (DGA) show that most of the time *arcing compounds* like alkynes (example: acetylene) and hydrogen make up 75% to 85% of the total combustible gases, *thermal compounds* generally alkenes (example: ethylene) 12% to 20%, and the *remaining* 3 to 5% by volume are alkanes (methane, ethane). The results are tabulated on the accompanying floppy disk.

As the LTCs become worn the characteristic arcing compounds, typically the sum of acetylene and hydrogen, decrease as a percent of the overall ‘gas-in-oil’ composition.

Wear and the possible formation of surface deposits result in an increase of contact resistivities and Joule heating. The amounts of chemical compounds, typical for thermal breakdown of the transformer oil will increase. Powertech Labs Inc. calls this, usually slowly developing change, the *shift* to a pre- fault or thermal mode.

The case study and the field surveys suggest that ‘finger-printing’ the different LTC makes and models is an important step towards the formulation of fault/failure algorithms and condition assessment software and will result in the recognition of "normal", "pre-fault" and "failure" modes of operation. The majority of LTCs shift, as they age, to a mixed mode of arcing and thermal performance. The laboratory will recognize (DGA) this mode of operation.

Exceptions are encountered with some radically different LTC designs. These units may show, as mentioned in the Summary, oil decomposition products (hydrogen, ethylene, ethane) more typical for gas phase discharge, sometimes higher thermal loading. At the present time, we <u>speculate</u> that these LTCs show a small amount of arcing, during the normal making and braking of contacts. This mode is replaced by a different pattern of field excitation akin to corona and / or glow discharge. <u>Hydrogen</u> and other hydrocarbons, with the exception of acetylene, are the principal gases. Gas production may shift later (similar to the bulk of the LTC designs) to ethylene in the “pre- fault or thermal mode” of operation. We are still investigating this mode by investigating further the relative small number of equipment in use at our utility. In some of these instances higher levels of ethylene need not be reasons for raising fault and failure flags.

The use of hotspot indicating compounds serve, under these circumstances, as additional diagnostic tools. These are a number of unsaturated compounds.

Concerning the diagnostics of LTCs, it should be recognized that frequently data from different sources can supplement each other. Oil temperature together with gas composition data can be useful as early indicators of fault modes. It is surprising that a number of utilities do not pay enough attention to LTC oil temperature especially its sudden rise over time [temperature/ time]. The combination of the two (temperature increase and fault gas concentration) was successfully applied at B.C. Hydro with the cooperation of Powertech Labs Inc. to identify existing fault-modes and sudden failure was averted.

It appears that if a change in oil-temperature and a sharp increase in total hydrocarbon gases can reliably monitored (essentially the begin of serious "oil-cracking"), irrespective of composition, the onset of failure can be effectively monitored!

As the in-service LTC increase in age and the insulating oil quality deteriorates, large concentrations of dissolved gases may distort the solubility limits of some compounds due to purge action, and it may become difficult to conduct successfully gas-diagnostics. This is a possibility that is never encountered in transformer diagnostics. It is advisable to replace the insulating fluid in LTCs at the recommended service intervals as determined by the number of switch operations, oil quality and/or time. At the present time, the best preventative maintenance procedure for LTCs would be a weekly "dissolved gas in oil" (DGO) analysis. Currently most utilities, despite an interest in preventive maintenance, can neither effort nor see such an approach as justified. The future development of LTC diagnostics points to affordable, on-line monitoring, specifically the dynamic on-line determination of fault gas concentrations.

On-line oil filtration, although an excellent supplemental maintenance tool for LTCs and helpful in preventing critical build-up of suspended carbon is not the final answer to the maintenance of LTCs. We know that degradation products other than carbon are formed, which will not be removed by filtration of the type available at the present time. These degradation products will participate in the accelerated formation of surface deposits.

Although most LTC failures are mechanical in nature, these surface deposits may lead to premature and sudden failure. The search for suitable diagnostic tools especially on-line diagnostic is still on.

8

CONCLUSIONS

Laboratory experiments have shown that oil decomposition produces “thermal” and “arcing” marker compounds characteristic of overheating and arcing conditions. In normal operating LTCs, the ratio of thermal to arcing marker compounds remained constant regardless of their absolute levels but increased substantially during an incipient thermal fault mode.

If arcing is the result of mechanical fault conditions, thermal effects will give rise to typical fault gases like ethylene, ethane and other hydrocarbons at concentrations competing and exceeding the typical acetylene concentrations. The typical arc gas ratio of [acetylene + hydrogen]/[Total combustible gases][*], which is commonly in the range of about 0.7 to 0.9, will move towards 0.2 and lower. Acetylene, typically the major gas aside from hydrogen, will become a minor component under such thermal fault conditions.

Unsaturated volatile compounds (alkenes and alkynes) are always formed as a result of arcing, partial discharge and high temperatures. These extremely reactive compounds are the precursors to gum and coke (sludge) formation and will adhere to surfaces, in the presence of oxygen, even at low to medium temperatures.

On-line oil filtrations will help to prevent sludge and coke formation. Filtration will not remove soluble coke precursors. Work is still in progress and supplemented by accelerated laboratory studies.

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[*] all expressed in ppm (v/v).

9
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Target:
Substation Operation and Maintenance

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