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Novel Techniques to Estimate and Extend Transformer Life

Use of Paper Degradation Products for Diagnostics and Condition Assessment

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Technical Update, December 2010

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PRODUCT DESCRIPTION

This work is a continuation of Electric Power Research Institute (EPRI) report 1017736, *Use of Paper Degradation Products for Diagnostics and Condition Assessment: Phase 2—Identification of Marker Compounds of Insulating Paper.* In this phase, laboratory experiments were performed to identify non-furanic marker compounds as diagnostic indicators and for monitoring the degradation of mixed paper systems (kraft and thermally upgraded paper [TUP]). Such knowledge is necessary to estimate the condition of the mixed-paper insulation systems more accurately and to detect hot spots. The research identified marker compounds specific to the decomposition of the additive dicyandiamide (DICY) in TUP and to the rupture of the cellulosic bonds and their rate of production. To accurately monitor the level of the marker compound(s) in both oil and headspace, an analytical method for on-line monitoring (OLM) was developed.

This technical update describes the work to date on the continuous OLM method to identify trends of the marker compounds concentrations for early detection of transformer faults. A hollow fiber unit is used for the removal of gases and marker compounds. Laboratory equipment was designed and built to represent fault conditions as encountered in transformers. For this purpose, model transformer test chambers with selected sensors were designed and purchased. The goal is to develop an efficient on-line continuous monitoring system with suitable sensors to detect and monitor the target marker compounds of paper decomposition.

Results and Findings

In Phase 2, benchtop laboratory experiments were performed to identify marker compounds specific to the degradation of the DICY additive on TUP, thermally upgraded kraft paper, and insulating oil that decomposes in the presence of moisture, heat, and oxygen. The decomposition of DICY produced specific nitrogen-containing compounds such as ammonia, pyrrole, and pyrazines. Although the DICY decomposes completely in the presence of moisture, heat, and oxygen, the level of nitrogen compounds on the paper does not go to zero. Approximately 30% of the initial nitrogen is retained on the paper as other nitrogen by-products. These by-products provided thermal stability to the insulating paper compared to regular kraft paper. The level of ammonia in oil was related to the amount of DICY remaining on the paper. A logarithmic relationship between the concentration of ammonia in oil and DICY remaining on the paper was established and used to estimate the remaining percent of DICY and the degree of polymerization (DP_v) of the paper.

Controlled thermal aging tests on paper and oil systems carried out in the laboratory revealed a relationship between the rupture of the (1,4-β-glycosidic) bonds in cellulose and the presence of specific marker compounds in oil, regardless of the amount of additive (DICY) in the paper. Based on the results of the benchtop experiment, a transformer model was designed and built. The model consisted of a distribution-class tank and a disk-type coil built with TUP and resembling that of a power transformer. The unit was fitted with hollow fiber extractor units, an oil pump, a vacuum/circulation pump, valves, gauges, sampling ports, and safety devices. The unit was internally heated and designed to run at different temperatures and different conditions.

This update summarizes the development of the transformer model designed and built to represent fault conditions as encountered in transformers with the sensing and monitoring techniques that were assessed for an on-line application. These techniques were evaluated with

the target compounds and typical operating conditions for selectivity, sensitivity, and detections limits. Using the transformer models and the OLM techniques, the equation relating the level of methanol and degree of polymerization will be evaluated and validated.

Challenges and Objectives

The best technique for evaluating the aging of insulating paper is still the determination of the DP_v of the constituting cellulose chains. However, the technique is often impractical because of the difficulty in retrieving paper samples in the field. The aim of this phase was to identify and validate an on-line continuous monitoring system with identified sensors and analyzing techniques that can measure the level of gases and marker compounds from the decomposition of insulating paper. The next step is to validate the relationship between the marker compounds and the condition of the paper from the DP_v at different fault conditions in an on-line setup.

Applications, Value, and Use

This report will improve industry knowledge of the remaining life of transformers and therefore lead to improved fleet management.

EPRI Perspective

Detailed knowledge of the specific marker compounds due to decomposition of a paper system independent of the type of paper, their amount, and their rate of production is essential for transformer diagnostics and condition assessment. There are several potential benefits to the electrical utility. With a relationship identified between the level of marker compounds and the degree of polymerization, an estimation of the loss of life and the remaining life of a transformer is possible. This might reduce the need for capital investment for new transformer units. Second, with OLM of the marker compound(s), a more accurate determination of the condition of transformers with mixed-papers systems will be possible, resulting in a potential decrease in unscheduled outages or failures. Finally, this work will allow more accurate thermal models, which will provide improved overload management capability during emergency situations.

Approach

This report is a continuation of Phases 1 and 2 and addresses Phase 3 of a multiphase project. Task 1 of this phase consisted of the preliminary development of an OLM system. A state-of-art review was conducted to assess knowledge and development in the field and to identify available and emerging sensors and monitoring techniques suitable for this application. The sensor/monitoring technique was evaluated with the target compounds identified for selectivity, sensitivity, and detection limits. Task 2 involved the designing and building of laboratory equipment to represent fault conditions as encountered in transformers to determine the sensors' suitability to detect and monitor the target fault products in an on-line continuous mode.

Keywords

Degree of polymerization
Cellulose
Thermally upgraded paper
End of life of transformer
On-line monitoring
Marker compounds
Cellulose degradation

ABSTRACT

This work is a continuation of efforts toward the identification of marker compounds of transformer insulating paper. In this phase, laboratory experiments were performed to identify non-furanic marker compounds better suited as diagnostic indicators and for monitoring the degradation of mixed paper systems (kraft and thermally upgraded paper [TUP]). Such knowledge is necessary to more accurately estimate the condition of mixed-paper insulation systems and to detect hot spots. The research identified marker compounds specific to the decomposition of the additive dicyandiamide (DICY) in TUP and to the rupture of the cellulosic bonds and their rate of production. To accurately monitor the level of the marker compound(s) in both oil and headspace, an analytical method for on-line monitoring was developed.

This technical update describes the work to date on the continuous on-line monitoring method to identify trends of the marker compounds concentrations for early detection of transformer faults. A hollow fiber unit is used for the removal of gases and marker compounds. Laboratory equipment was designed and built to represent fault conditions as encountered in transformers. For this purpose, model transformer test chambers with selected sensors were designed and purchased. The goal is to develop an efficient on-line continuous monitoring system with suitable sensors to detect and monitor the target marker compounds of paper decomposition.

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1
INTRODUCTION AND BACKGROUND

Introduction

The life of a transformer is strongly dependent on the ageing of the conductor insulation. For transformers without major faults, the ageing markers of the inaccessible paper insulation are of prime importance for purposes of asset management. The best technique for evaluating the ageing of insulating paper is still the determination of the degree of polymerization (DP_v) of the constituting cellulose chains. However, this technique often turns out to be impractical due to the difficulty in retrieving the paper samples in the field. The importance of a relationship between the cellulose DP_v and a molecule in the oil that comes exclusively from paper ageing have been recognized early on. Indirect methods investigated up top now were based on CO and CO_2 and a family of furanic compounds, especially 2-furaldehyde (2-FAL). However, the applicability of the former approach was found to be limited considering that the carbon oxides would rise not only from the degradation of paper but also from the long-term oxidation of the oil components that occurs in open-breathing units during normal operations or in nitrogen-conservator units facing air ingress. With the latter approach, the thermally upgraded paper (TUP) is known to produce much less 2-FAL than standard papers for an equivalent degree of polymerization. The presence in a given unit of mixed insulation (standard Kraft and Thermally Upgraded paper) as shown in Phase 1 of this study showed that the relationship between the amount of such molecules in the oil and DP_v would change.

Background

In Phase 2 of this project, bench top thermal-ageing tests on paper/oil systems carried out in our laboratory revealed the formation of specific molecules in the oil, regardless of the amount of stabilizers in the paper. Marker compounds that are specific to the rupture of cellulosic bonds were identified and a relationship between the concentration of the marker compound and the degree of polymerization of the insulating paper was produced. The marker compounds identified were narrowed down to methanol and acetone. It was observed that insulating paper was not the sole source for the production of acetone. Thermal decomposition of oil produces acetone as well but at a lower concentration than insulating paper. It was also observed that the concentration of acetone produced was dependent on the presence of DICY and moisture present. Hence, acetone can be used as a screening compound for hot spot but not as a marker compound for paper decomposition. It can be identified in the laboratory using GC-MS and online using GC-QUAD. There are some commercially available sensors for acetone however they are not selective of acetone in the present condition and fault results may occur in the presence of other alcohols and ketones.

Methanol was the other marker compound identified. It is obtained by sole decomposition of cellulose and a linear relationship was observed between the concentration of methanol and the degree of polymerization independent of temperature and the presence of dicyandiamide while performing bench top experiments. However, the rate of production of methanol increases with temperature. It was observed that for every 1 scission two molecules of methanol was produced

and a linear relationship between the degree of polymerization and the concentration of methanol was observed even after the complete depletion of dicyandiamide from insulating paper. Methanol can be identified online using the GC-QUAD. Commercial sensors for methanol are available, however they are not selective and false results can be obtained in the presence of other decomposition compounds of insulating oil and paper.

2
OBJECTIVES AND SCOPE

Scope

Although considerable amount of work have been carried out to relate the decomposition insulating paper with furanic compounds, many issues still remain unresolved, namely:

- Identification of furanic compounds in oil is performed through an off-line analysis resulting in a loss of informative dynamic behavior.
- There has historically been a lack of guidance or interpretation algorithms that more accurately relates furanic compounds in oil to the DP_v of a mixed paper system. Phase 1 of this project was aimed at developing an algorithm to use as a guide by transformer maintenance engineers and was successfully completed.
- There is a need for the identification of marker compounds better suited for the determination of the condition of the DP_v of Thermally Upgraded paper and mixed paper system. This was completed in Phase 2 of this project where a specific compound due to the decomposition of cellulosic insulating paper was identified.
- There is a lack of sensors or detection systems of key marker compounds suitable for on-line monitoring. This phase of the project will address this issue.

The method of monitoring the state of transformers by measuring relative amounts of dissolved hydrocarbon gases (performed online and offline) and chemical indicators (off-line) in their insulating oil is well established. However, not much work has been performed to identify novel compounds specific to paper degradation, especially those that can be detected on-line. Continuous on-line monitoring allows trends on the chemical indicators concentrations to be followed by early detection of transformer faults.

The project work was carried out in phases as described below and this technical update covers tasks 1 and 2 of Phase 3.

Phase 1: Interpretation Guide for Furanic Compounds in Oil.
This phase was aimed at establishing different correlation of furanic compounds especially 2-FAL to the DP_v dependent of the type of paper at the copper coil. Two relationships were identified, one for regular Kraft paper at the coil and one with Thermally Upgraded paper at the coil. These equations can be used as a guide by transformer maintenance engineers and was successfully completed.

Phase 2: Identification of Marker Compounds.
This phase was a continuation of Phase 1 and included the identification of marker compounds that are better suited as indictors for monitoring mixed paper system degradation. With the dependency of the amount of 2-FAL produced on the type of insulating paper, there is a need to

identify novel products that are better suited as diagnostic indicators for monitoring the degradation of mixed paper systems. Such knowledge is necessary for more accurate estimation of the condition of the mixed paper insulation systems (mostly found in North America) and for the detection of potential hot spots. In Phase 2, marker compounds specific to the degradation of dicyandiamide additive in TUP were identified and correlated with the % DICY present on the paper as well as the DP_v of the paper. Marker compounds specific to the rupture of the cellulosic bonds independent of the type of insulating paper was also identified along with the correlation with the DP_v of the paper in order to estimate the end of life the transformer in a non-intrusive manner.

Phase 3: Development of On-line Monitoring Method.
There are currently no monitoring systems suitable for on-line detection of known paper degradation products. This task will build the required knowledge and will include the development of an on-line monitoring method for identified marker compounds from paper degradation. The rate of production of the identified marker compounds and their relationship to DP_v of insulating paper will also be correlated. This could be used to estimate the end of life of a transformer in a non-intrusive manner.

Objectives

The scope of this present phase (Phase 3) is comprised of three main sections:

1. Sensor Acquisition and Evaluation
   A state of the art review was conducted to assess the current knowledge and developments on the field and to identify available emerging sensors and monitoring techniques suitable for our application. Sensors suitable for the measurement of the identified marker compounds were acquired and adapted for application as needed. The sensors were evaluated with the target compounds identified in Phase 2 of the project and typical operating conditions for selectivity, sensitivity and detection limits were identified.

2. Equipment design and Simulation of Faults
   Laboratory equipment was designed and built to represent the fault conditions as encountered in transformer. For this purpose, new equipment and model transformer chambers were built with selected detection techniques and specific sensors. The goal was to determine the suitability of the sensors to detect and monitor the target fault products identified in Phase 2.

3. Accelerated Thermal Aging Studies
   In this task, the model transformer will be heated internally to winding temperatures of up to 150 ^{o}C. The temperature will be cycled from a low of 50- 60^{o}C to a high of 150 ^{o}C. This model transformer is more representative of the field transformers and the level of gases and marker compounds will be tested using the identified online monitoring techniques. The DPv of the paper at different positions at the windings will also be measured at different times and a relationship between the level of the marker compounds and the DP_v (life of the transformer) will be validated. This will give an indication of the applicability of the identified online monitoring techniques of gases and specific marker compounds obtained due to the thermal decomposition of insulating paper.

3
APPROACH

Phase 2: Bench Top Experiments:

In Phase 2 of this project, specific degradation products from insulating paper and insulating oil were identified. A summary of what was achieved in Phase 2 is described below:

- ***The life expectancy of Dicyandiamide, the additive on Thermally Upgraded Pape***r
  The results showed that the rate of decomposition of Dicyandiamide is dependent
  1. the amount of water present and
  2. temperature

  DICY decomposes to nitrogen compounds such as ammonia, urea, guanidines and melams. The nitrogen content of paper never goes to zero even though there is complete depletion of DICY. Around 1 % of the nitrogen is retained by the paper indicating that DICY nitrogen containing decomposition products remain on the paper providing extra stability.

  Out of all these nitrogen compounds, ammonia is the one that is more soluble in oil and that can be easily detected from the oil or headspace by gas chromatography. A linear increase in the concentration of ammonia with respect to time is observed until the complete depletion of DICY. Other nitrogen containing compounds such as pyrrole and methyl pyrazines were identified; however, they are not produced by the sole decomposition of dicyandiamide but by the reaction of ammonia and other decomposition products of paper. Pyrrole was found to have high volatility and is not ideal as a marker compound for Thermally Upgraded Paper.

  The ammonia can be detected using a GC-QUAD with four different columns that can detect polar and non-polar compounds simultaneously. However, the GC has limitations on low concentration of ammonia. Commercially available sensors can be used to detect ammonia in the headspace in the range of 0-100 ppm.

- ***Marker Compounds Specific to the Rupture of Cellulosic Bonds***
  Marker compounds specific to the decomposition of the cellulosic bonds independent on the amount of DICY present were identified in Phase 2. The marker compounds were narrowed down to acetone and methanol. Acetone was found to be produced by both decomposition of oil and paper, however at a higher concentration from paper. Hence, acetone can be used as a screening compound rather than a marker compound.

  Methanol was obtained by the sole decomposition of cellulose and a linear relationship was observed between the concentration of methanol and the degree of polymerization independent of temperature and the presence of dicyandiamide on a bench scale experiment. The bench scale experiment is not fully representative of a transformer since external heating of the windings and the oil was performed for the bench top experiments. Hence, the next step was to validate the relationship between the marker compounds and the DP_v and the life of the transformer which will be verified in Task 3 of Phase 3 on a model transformer.

Acetone and methanol can be identified online using GC-QUAD. Other commercial sensors for acetone and methanol are available, however they are not selective and false results can be obtained in the presence of other alcohols and ketones.

Phase 3: Transformer Simulation Experiments

Typically, in-service transformers operate under non-equilibrium conditions. Operational parameters such as temperature, component concentration, rate of productions, etc are dedicated by operational demands and cannot be changed at will. These complexities preclude the use of operational transformers for studies designed to determine the effect of specific variables. This can only be done under controlled laboratory conditions allowing each variable to be changed independently. For this purpose, transformer models designed to simulate transformer parameters and conditions were designed and built.

Transformer Models

Two transformers models with the same oil preservation systems-conservator type (free breathing and membrane) and with an expansion cylinder mounted directly on the top of the chamber and connected via a tube were built to simulate transformers. The transformers were constructed with a Tank Volume of 84 L with Thermally Upgraded Paper at the disk winding, with oil circulation pumps, internal heaters, expansion cylinders, sampling ports, thermocouples, sampling ports instrumented with data acquisition systems and safety devices. Photographs of the assembled chambers are shown in Figure 3-1. More details of the transformer model are provided in the Appendix section. The second transformer model was built to serve as a baseline for this project where an online degassing and dehydration was performed to extend the life of the transformer. Some specifications of the transformer models are given in

Table 3-1.

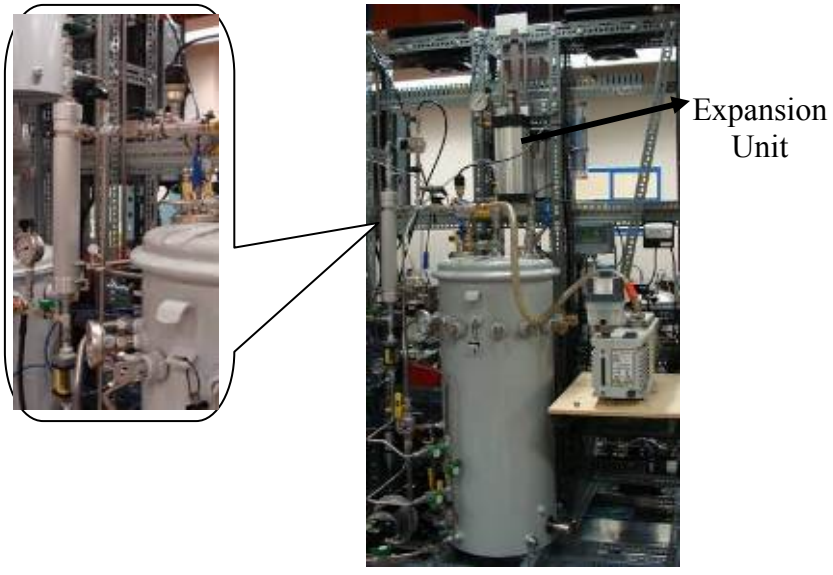


Figure 3-1
Overall View of the Transformer Model with the On-Line Hollow Fiber Extractor

Table 3-1
Transformer Model Specifications

Parameter	Conservator Type Transformer Model
Volume of Oil in Tank (L)	84 L
Conservator Volume (L)	5 L
Oil Flow Rate (L/min)	0-20
Winding Temperature Range (^{o}C)	25-150
Bulk Oil Temperature Range (^{o}C)	25-130
Conductor Heating Mode	Low Voltage Winding
Heating Method	Resistive via Winding
Cooling Model	Air to Oil Heat Exchanger with Fan
Sampling Ports	Oil (2 available), Headspace (from HFE)

Equipment Set up

The oil used for these experiments was a typical naphthenic mineral oil used throughout the industry. Degassing and dehydration was done using heat and vacuum in a stainless steel "conditioning chamber" plumbed directly to the two test chambers. This conditioning chamber was equipped with heaters, pumps (vacuum and circulation), gauges, and controls and connected to a data acquisition system. After the oil had been conditioned, it was transferred to the desired chamber.

In addition to accessories, and controls described above, the conservator type transformer model was further fitted with:

- A Hollow Fiber Extraction (HFE) Unit. This unit contains a collection of hollow fibers that was used to efficiently separate dissolved gases, low molecular weight volatiles and moisture from the oil. The separated gases could be sampled and analyzed. The ammonia sensor is attached on the outside core of the hollow fiber. Details are provided in the next chapter.
- A Single Hollow Fiber Unit with the oil flowing on the outside, which was heated at a specific temperature of 70 ±1 ^{o}C and allowed to reach equilibrium for 20 minutes before analyzing the separated dissolved gases and moisture from the oil using GC-QUAD.
- Sampling Ports for oil from the bulk of the transformer model, oil entering the HFE and gas from the HFE.

Analytical and Monitoring Techniques

In order to get a clear picture of the dynamics of gases and chemicals, both gas and oil phases had to be monitored as a function of time following an event. They were monitored online as well as off-line for comparison. Needless today there were some analytical challenges that had to be overcome. In particular, conventional oil sampling and laboratory analysis are too slow and would deplete the oil in the chamber. The ideal method to measure the level of marker compounds and dissolved gases in a transformer is by using sensors that are not affected by transformer oil and can be directly be dipped in the oil. However, there are no commercially available sensors to measure the level of dissolved gases and volatiles in oil. Hence, this was overcome by the use of the HFE (Hollow Fiber Extraction), where the gases and volatiles are extracted from the oil. Details of the HFE will be provided in the next chapter. The various gases and chemicals that were monitored, along with their analytical techniques, were:

- Headspace
  - Gases (H_2, O_2, N_2, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6) by the online GC-QUAD
  - Volatiles (Acetone, Ammonia and Methanol) by GC-QUAD
- Oil Phase
  - Gases (as above)- laboratory GC from oil samples for comparison
  - Volatiles- Laboratory GC-MS from oil samples
  - Furanic compounds (furaldehydes and phenols) by high performance liquid
  - chromatography (HPLC) from oil samples.

4
ONLINE ANALYTICAL AND MONITORING METHOD

Previous Work

A literature review was performed to update technical knowledge in the use of the hollow fibers for allowing gases and volatiles to separate from oil. Previous work in this area had identified several products as potential candidates. Preliminary tests were carried out with porous, non-porous and composite type membranes. Among the several commercial products developed for other applications, our studies showed that:

- Porous polysulfone membranes allowed passage of gases and volatiles but they tend to swell and leak after a short application.
- A composite of porous polysulfone/Teflon AF worked well, however, some seepage developed after continuous use was observed
- Porous carbon membranes were promising but was no longer available commercially
- Polyimide membranes showed good performance with no swelling or oil seepage
- Teflon AF worked well, and a single strand is used for separating the gases and volatiles from the oil for analysis

Hollow Fiber Selection

As shown above, some of the commercial units that were evaluated for potential applications to insulating oil had some drawbacks and were not considered. The factors taken into consideration while selecting the hollow fiber included:

- Commercial availability of the hollow fiber
- Cost of hollow fiber
- Performance of hollow fiber in insulating oil
- Suitability to current needs
- Applicability to the field

Based on the above criteria, two sets of hollow fiber were considered, one in a bundle and one as a single strand. These units were evaluated in the lab for key performances including:

- Selectivity of gases, volatiles and marker compounds
- Compatibility with mineral oil
- Ruggedness and durability in the presence of different compounds and temperature

Hollow Fiber Extractor Unit

The unit consisted of a bundle of porous hollow fibers that had been cemented together at both ends then sealed into a housing which contained two access ports. The inside of the hollow

fibers had been coated with a thin film of highly permeable polymer. A diagram and picture of the unit are shown in Figure 4-1 .

In principle, as oil flows through the inside of the hollow fibers, dissolved gases permeate through the wall and into the housing (shell side). This continues until equilibrium is achieved at the operating conditions. If the gases and other products are continuously removed from the shell side by applying a vacuum or a stripping gas, equilibrium will never be achieved and the oil can be completely degassed. In order to determine its merits, the hollow fiber extractor (HFE) was evaluated in the laboratory in various modes including monitoring the equilibrium of the dissolved gases and volatiles as detailed below.

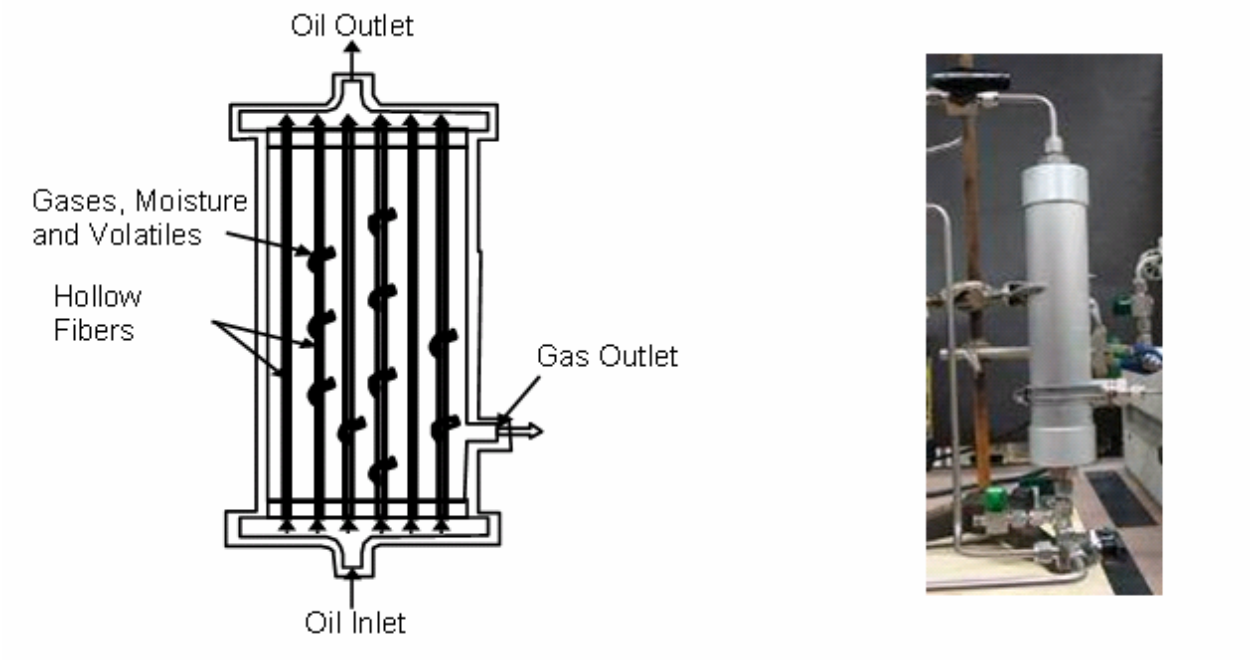


Figure 4-1
Schematic of Hollow Fiber Unit

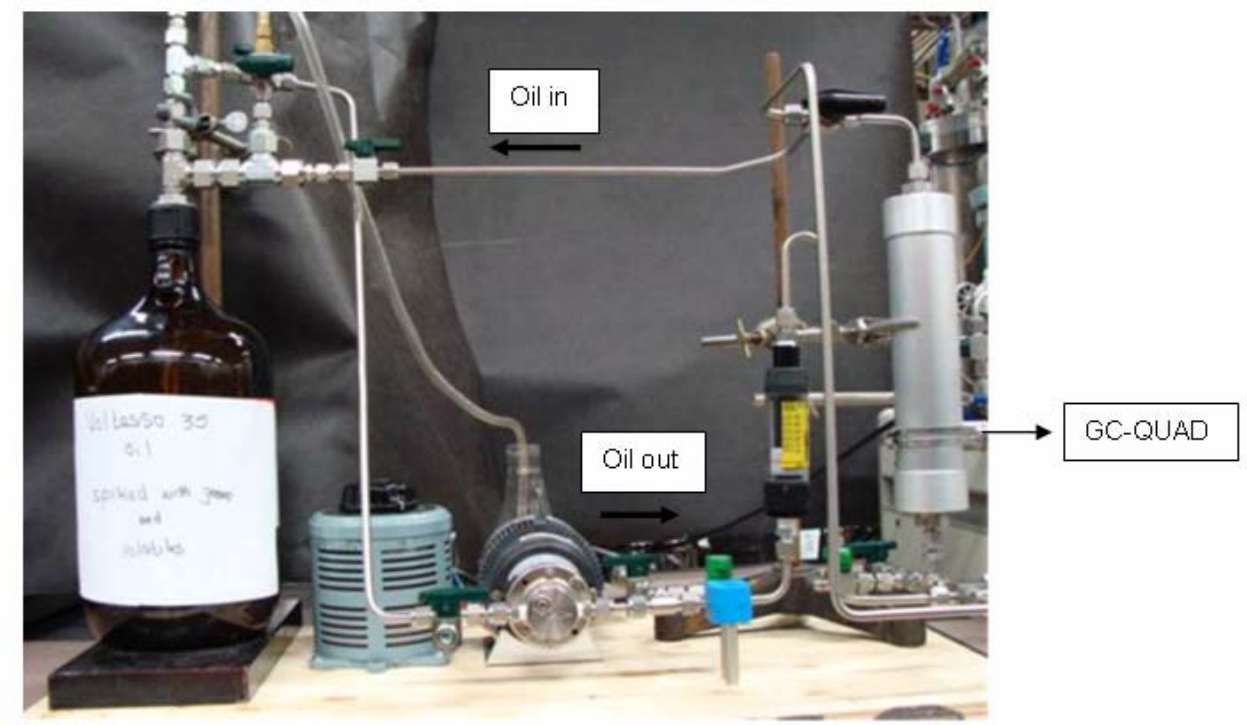


Figure 4-2
Bench Scale Set-up for Gas Transfer Study

Evaluation of Hollow Fiber Bundle

Initial tests were performed at room temperature and fixed oil flow rate. Know volumes of gases were injected into the oil and the oil was circulated to establish homogeneity. The gas transfer rates and equilibrium times were then measured using the GC-QUAD. The diffusion of all the gases (H_2, O_2, N_2, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6) and volatiles (Acetone, Ammonia and Methanol) was observed through the hollow fiber.

Optimization

Performance studies were performed on a transformer model used previously for accelerated aging studies. This consisted of a distribution-size transformer tank fitted with ports, sampling valve, coil and electrical connections for low voltage heating. This unit was connected to a piston type expansion tank in order to avoid contact to a gas phase. The inlet and outlet of the hollow fiber bundle was connected in line to an oil circulation pump to pump the air out of the outside core of the hollow fiber bundles before the flow of oil. Then, the gas phase side was fitted with sampling valves and the GC-QUAD. A picture of the set up is shown Figure 4-3.

Equilibrium studies of the HFE were carried out using oil that had been doped with known levels of gases and volatiles (marker compounds). Different studies to validate the online removal of gases and volatiles were performed as detailed below.

Figure 4-3
Set up Used to Determine the Recovery Time of Volatiles and Gases at Different Temperature and Rate of Flow of Oil.

Pressure Recovery

The pressure recovery time of the hollow fiber was representative on the gas flow rate. This was achieved by putting the outer shell of the hollow fiber under vacuum and measuring the pressure equilibrium with respect to time with the oil flowing at different rate and temperatures. Figure 4-4 shows the pressure equilibrium time at different flow rates of oil at a fixed temperature of 25^{o}C. It was observed that the rate of flow of oil above 0.1 USGPM does not affect the pressure recovery time (gas transfer rate) at 25^{o}C. It takes over 1 h for the pressure recovery as shown in Figure 4-4.

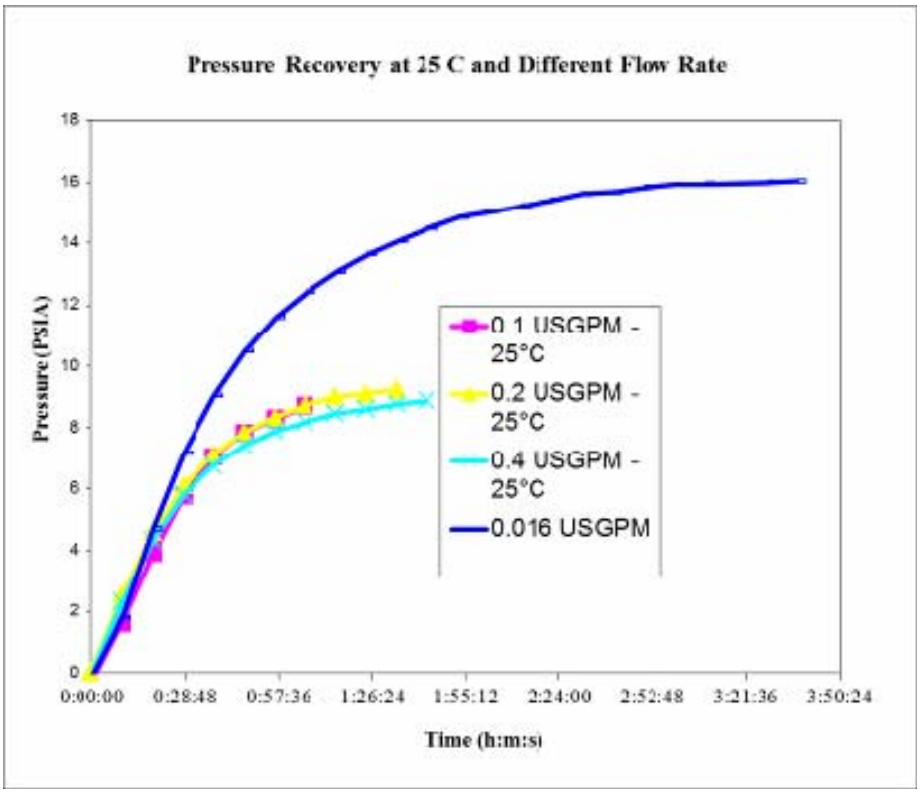


Figure 4-4
Pressure Recovery Time of the Hollow Fiber at Different Flow Rates at 25°C

Effect of Temperature

A similar recovery study was conducted as a function of oil temperature in the range of 25 -60°C and at a constant flow rate of 0.1 USGPM (United State Gallon Per Minute) and it was observed that with an increase in temperature, the equilibrium time decreases with a faster transfer rate. Hence, the pressure recovery time decreases with increase in temperature. Full pressure recovery occurred within 40 minutes at a temperature of 60 °C as shown in Figure 4-5.

Equilibrium Time for Different Gases and Volatiles

As shown above, the gas transfer rate is dependent on temperature and pressure and it is anticipated that discrimination between various gases will occur at different temperatures and flow rates and in order to identify the right time for sampling the headspace, the equilibrium time of each gases and volatiles to be analyzed was determined. The experiment was performed at two different flow rates (0.05 USGPM and 0.20 USGPM) and it was observed that each gas and volatile takes a different amount of time to reach equilibrium. At lower flow rates (0.05 USGPM) the gases and volatiles reach equilibrium faster than at 0.2 USGPM. As shown in Figure 4-6, at slower flow rate of 0.05 USGPM, CH_4, C_2H_4, O_2, H_2 and CO_2 reach equilibrium within 15 minutes and the other gases N_2, CO, C_2H_6 and C_2H_2 take nearly 30 minutes. The volatiles, acetone, methanol and ammonia, on the other hand take nearly 25 minutes to reach equilibrium as shown in Figure 4-7. The same trend is observed at 0.2 USGPM with longer equilibrium time of up to 1 h as shown in Figure 4-8 and Figure 4-9.

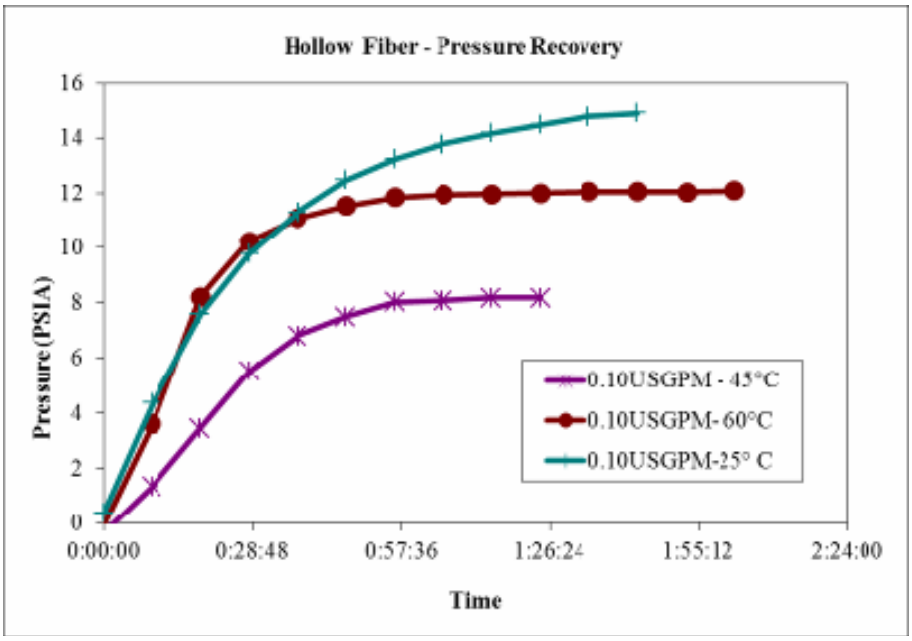


Figure 4-5
Pressure Recovery at Different Temperatures

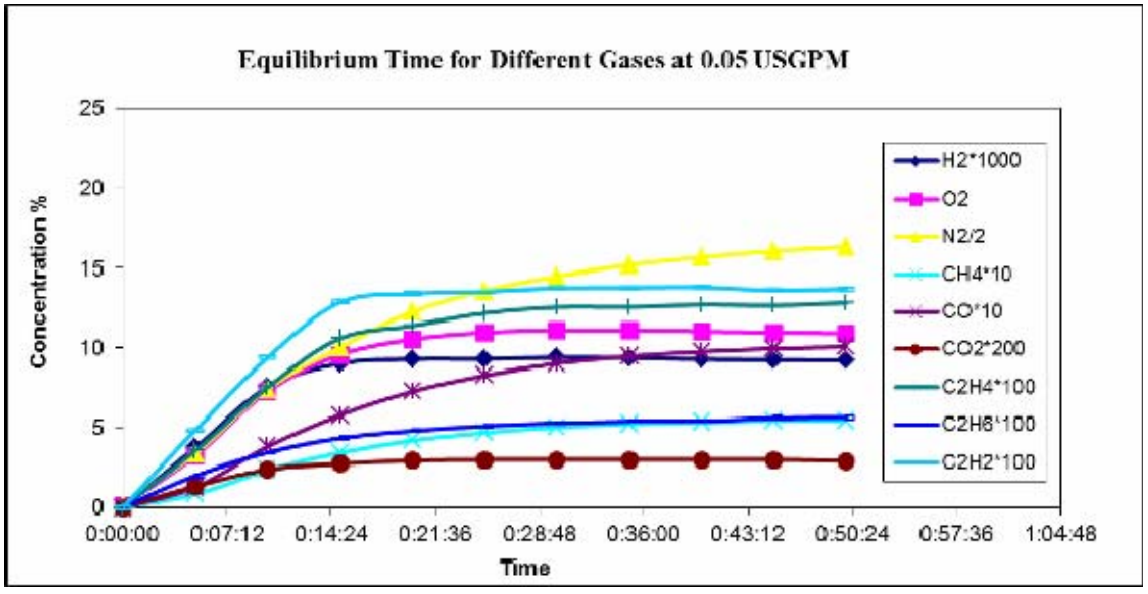


Figure 4-6
Equilibrium of Different Gases at 0.05 USGPM at 25 °C

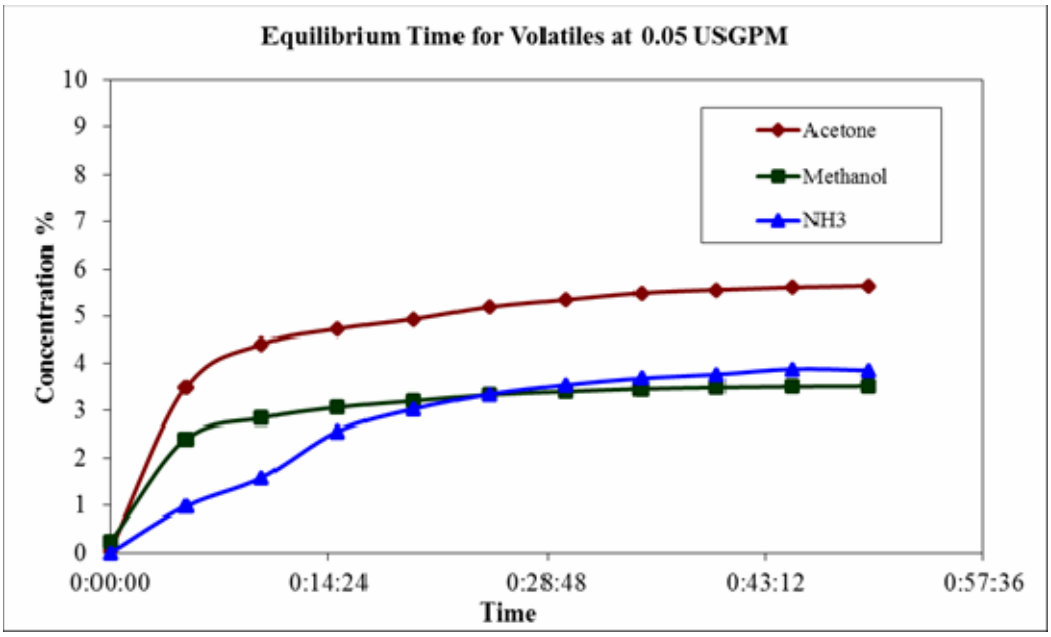


Figure 4-7
Equilibrium of Volatiles at 0.05 USGPM at 25 ºC

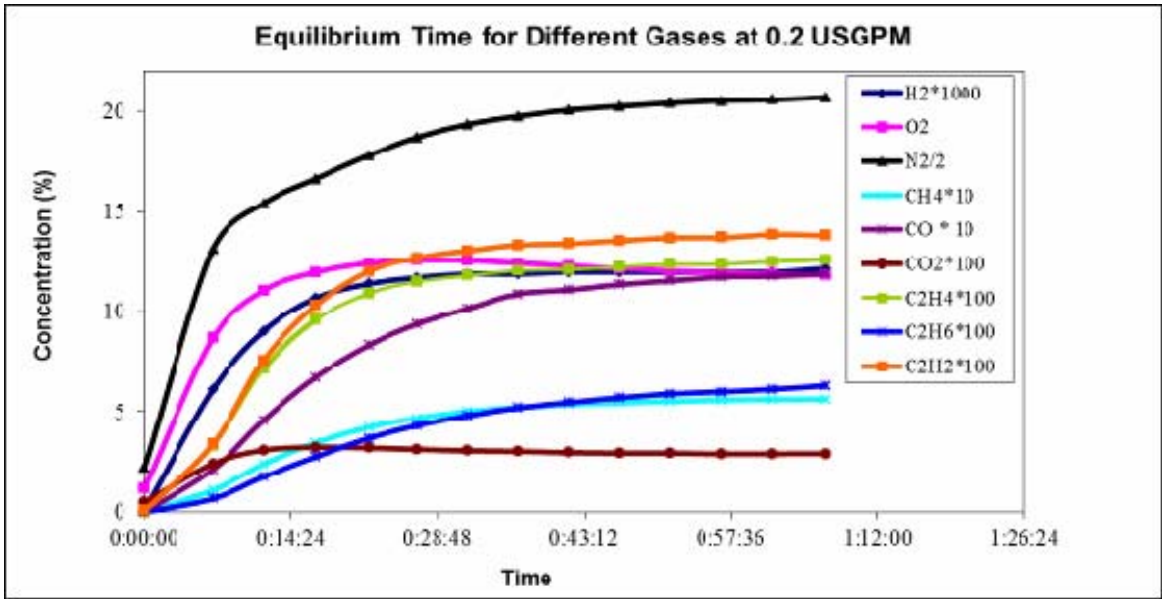


Figure 4-8
Equilibrium of Gases at 0.2 USGPM at 25 ºC

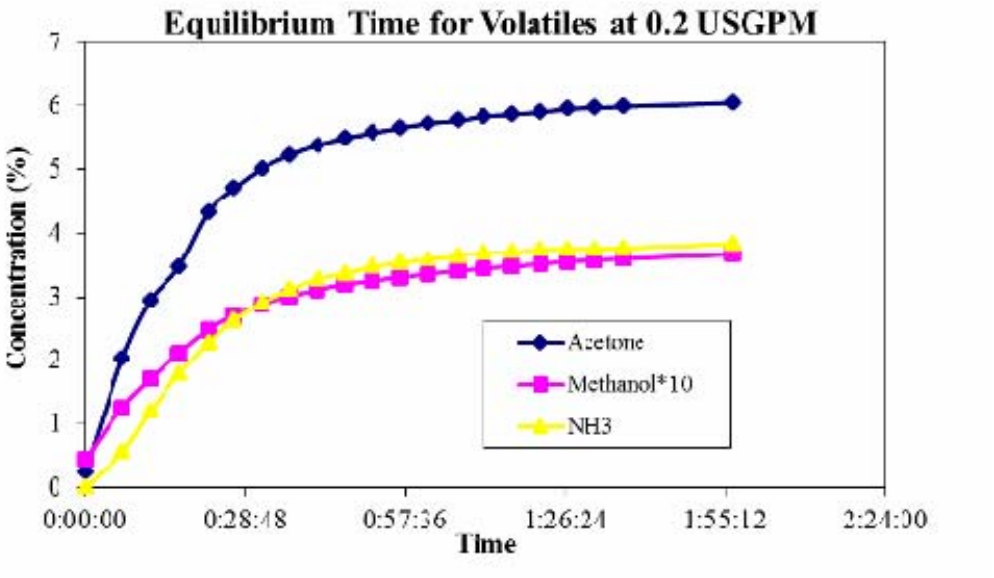


Figure 4-9
Equilibrium of Volatiles at 0.2 USGPM at 25 °C

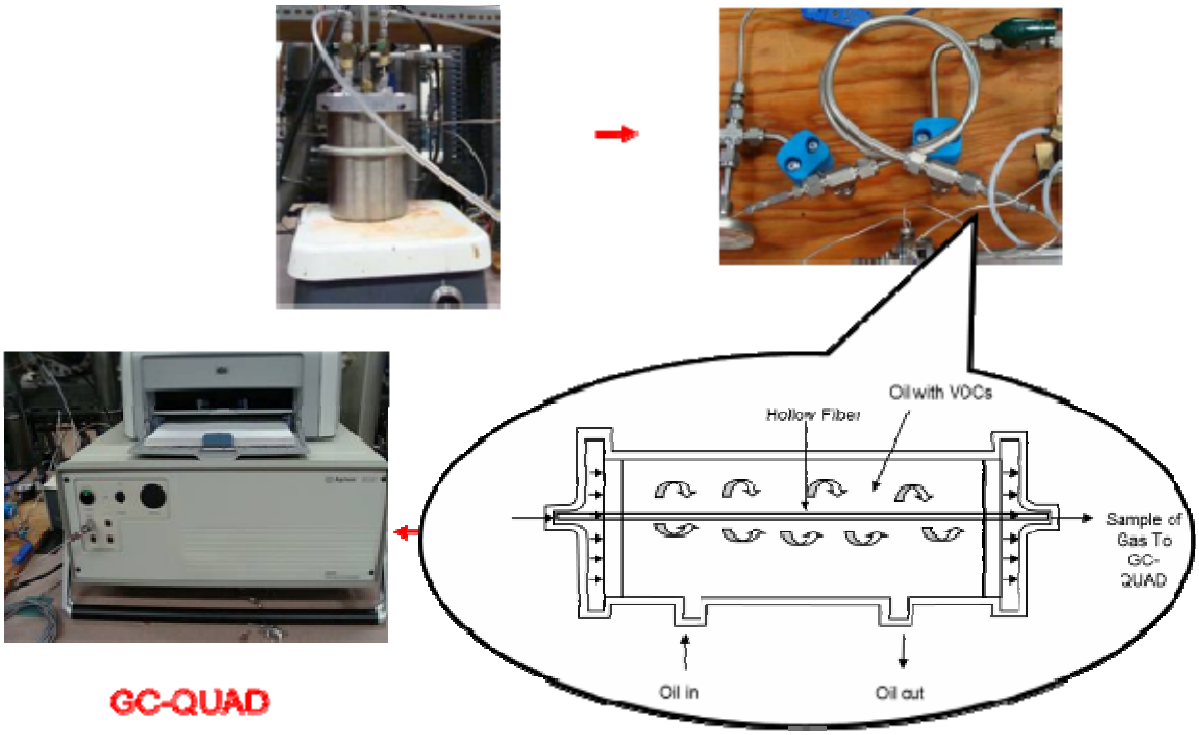
The pressure recovery time and the equilibrium time of the Hollow Fibre Unit were performed in order to evaluate this system for online measurement of the level of gases and volatiles in the headspace using the GC-QUAD. The GC-QUAD does not show a reproducible result unless the pressure of the outside shell has recovered to atmospheric or near atmospheric pressure and equilibrium between the oil and the headspace is achieved. In order to use the Hollow Fibre extractor bundle system online two main factors should be considered:

1. Equilibrium and Pressure recovery.
2. Temperature

The equilibrium and pressure recovery are dependent on the temperature and in order to keep the temperature of the oil constant an external heater will be required. This HFE bundle can hold nearly 80mL of oil and to keep this amount of oil at a constant temperature in the field might be a challenge and additionally with 80mL of oil and a headspace, equilibrium time is longer. Hence, a different alternative of using a single strand hollow fibre with a narrower holding tube was also evaluated as detailed below.

Single Fiber Evaluation

A single strand of hollow fiber made up of different material compared to the HFE bundle described above was also evaluated in this study for the extraction of gases and low molecular weight volatiles from the oil. The setup used for evaluating the single strand hollow fiber online is shown in Scheme 4-1 below.



Scheme 4-1
Evaluation of a Single Strand of Fiber for Extracting Gases and Low Molecular Weight Compounds

A single strand of hollow fibre has multiple advantages over a bundle of hollow fibres as detailed below:

- Lower possibility of oil leaks into the headspace especially around the area where a multi-fibre bundle is potted
- Lower equilibrium time between the headspace and the oil
- Lower volume of oil required allowing a better control on partitioning of gases and volatiles at specific temperature

To evaluate the suitability of a single strand of hollow fibre, oil with known concentrations of gases and paper degradation marker compounds was circulated in the tube on the outside shell of the hollow fiber. The oil was left stagnant at room temperature for different lengths of time to investigate the degree of equilibrium. During that time the gases and volatiles migrate from the oil into the single strand hollow fiber, which is analyzed online by the portable GC-QUAD. The GC-QUAD is comprised of four different columns that are used to analyze the gases and the volatiles concurrently on a single run. The four channels listed below analyzed the following compounds:

- Channel A: H_2, O_2, N_2, CH_4, CO
- Channel B: CO_2, C_2H_2, C_2H_4, C_2H_2
- Channel C: Low Molecular Weight Paper Decomposition Maker Compounds, Moisture
- Channel D: Low Molecular Weight Paper Decomposition Marker Compounds, Volatiles

Spectra of Channel A, B and D are shown in Figure 4-10,

Figure 4-11and Figure 4-12 below:

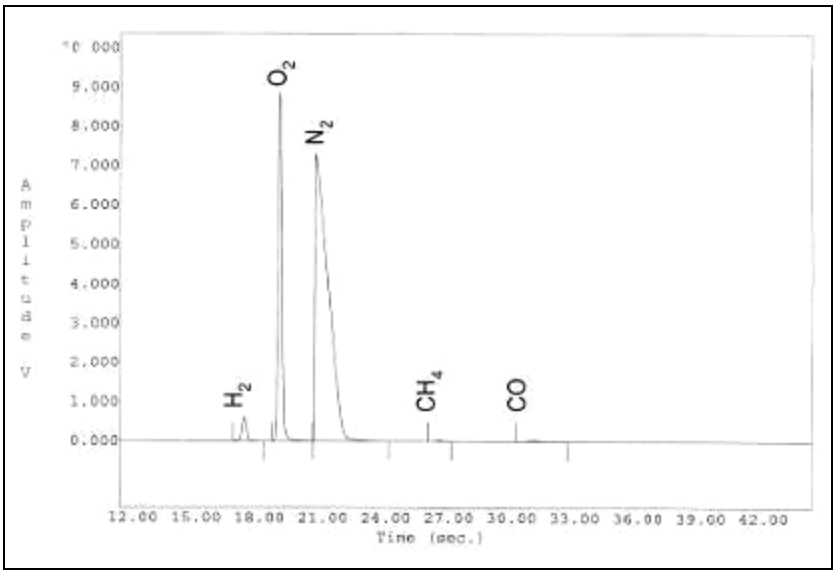


Figure 4-10
Portable GC- Spectrum- Channel A

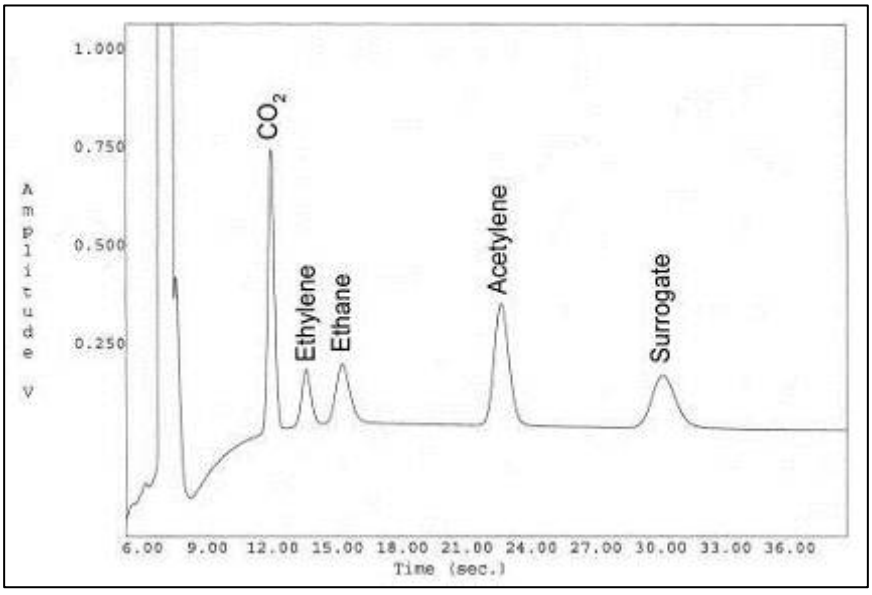


Figure 4-11
Portable GC-Spectrum – Channel B

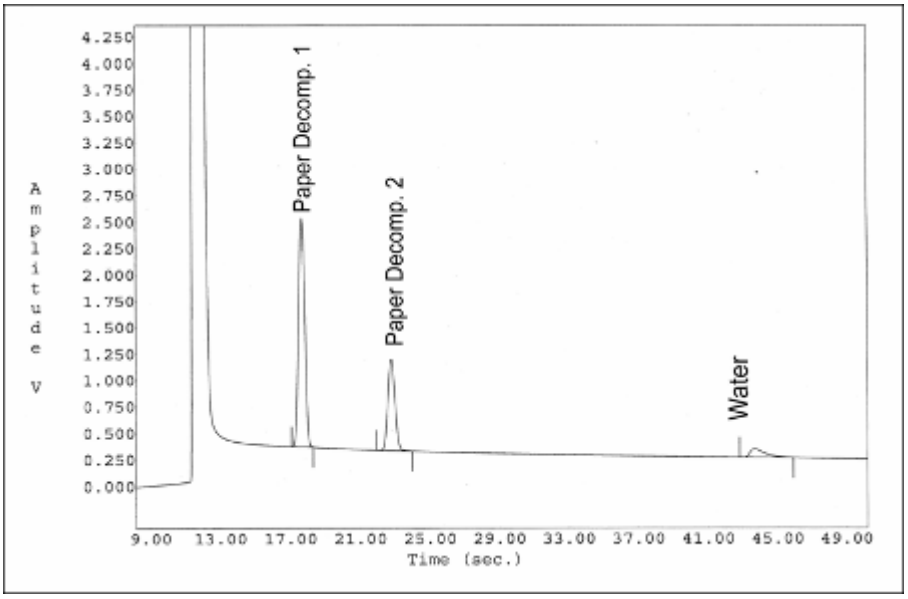


Figure 4-12
Portable GC-Spectrum- Column D

Equilibrium Time for Single Fiber

Experimental studies were performed to identify the length of time required for the oil and headspace to reach equilibrium in the single fiber set up. Oil with known concentrations of gases and volatiles were circulated through the a stainless tube containing the single strand hollow fiber as shown in Figure 4-14 and allowed to stand at 25 ^{o}C for different intervals of time, during which measurement of the headspace was taken. As shown in Figure 4-13, all the gases and volatiles reach equilibrium after 15 minutes at 25 ^{o}C. Hence, once the oil has circulated through the tube containing the hollow fiber, it was allowed to equilibrate for 30 minutes to allow for complete steady-state before taking any measurement.

The same experiment was repeated at a higher temperature of 70 ^{o}C. The oil was passed through a stainless steel tube that contained the hollow fiber**.** The tube was heated at 70 ^{o}C for different periods of time using an external heater as shown in Figure 4-14. Concentrations of gases and volatiles were measured using GC-QUAD and it was observed that equilibrium occurs within 10 minutes at 70 ^{o}C. Hence in the transformer model, the oil was allowed to equilibrate for 20min to allow for complete steady-state before any measurement.

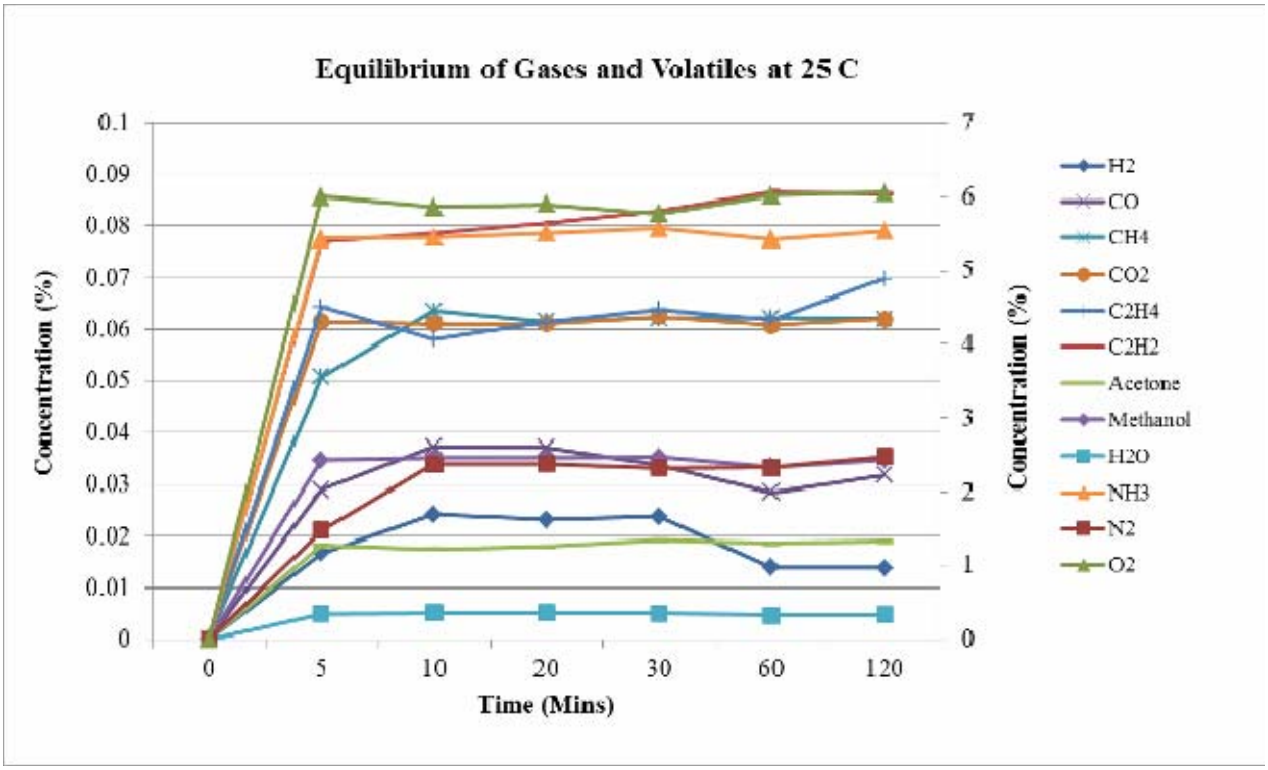


Figure 4-13
Equilibrium of Different Gases and Volatiles in Single Hollow Fiber at 25 °C

Figure 4-14
Stainless Steel Tube with Single Hollow Fiber with an External Heater Block

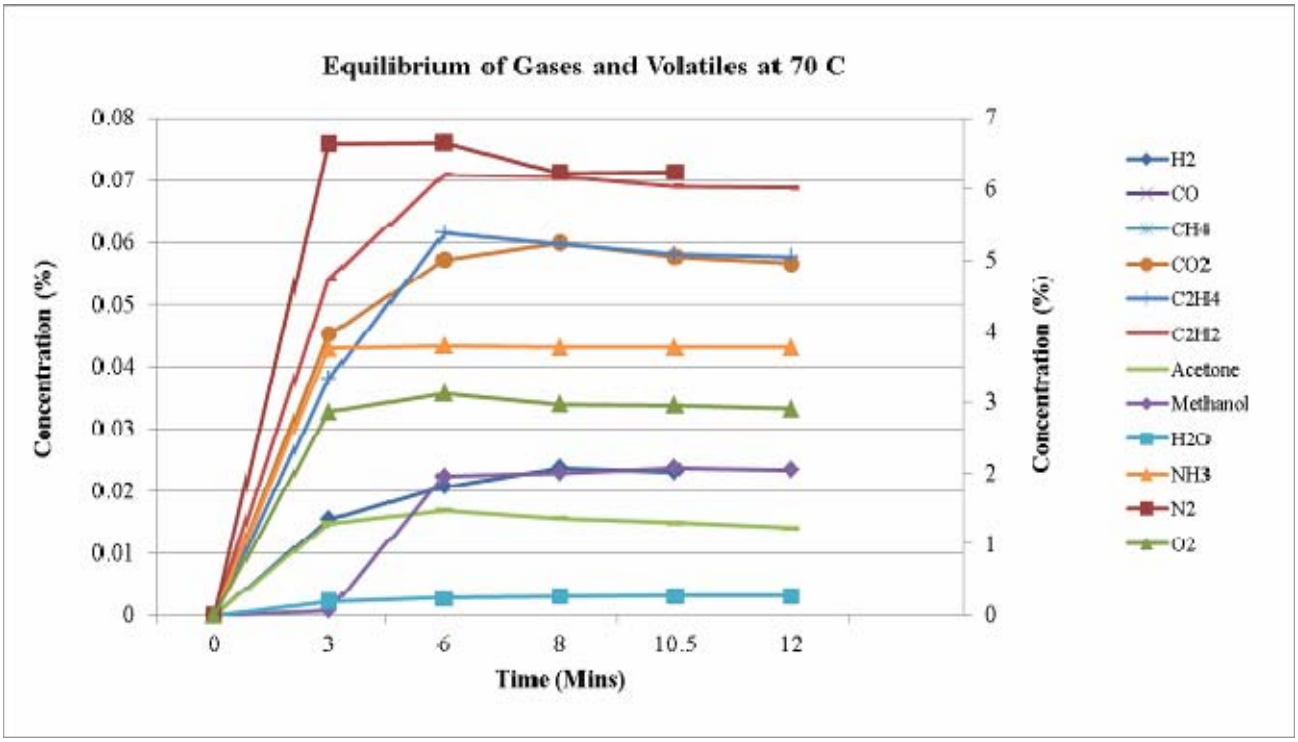


Figure 4-15
Equilibrium of Different Gases and Volatiles in Single Hollow Fiber at 70°C

Conclusion

Both HFE; the bundle and the single stand hollow fiber were used on the online set up for the separation of gases and volatiles. Each Hollow Fiber Extractor presented different opportunities and advantages over the other. With the single strand hollow fiber, a maximum of 0.30mL of gases was collected in the Hollow Fiber tube, which was enough to be analyzed by the GC-QUAD, however not enough to detect the level of ammonia using the commercially available ammonia sensor. Hence both HFEs were set up in parallel to measure the level of gases, volatiles and moisture using the single strand hollow fiber and in order to measure the level of ammonia, the ammonia sensor was attached on the shell side of the HFE bundle as shown in the next chapter.

5
TRANSFORMER MODEL SET UP

Laboratory Scale Prototype

A series of experiments was performed to test the effectiveness of the identified online method and the HFE at a larger scale. The goal was to analyze the marker compounds identified on bench top experiments in a setup that more closely resembled field conditions. A schematic of the equipment is shown in Figure 5-1 and more details are provided in the Appendix section. The HFE extractor and Membrane/Gas Chromatography system were set up as shown in Figure 5-2. The transformer model was set up with:

- Oil tanks (84 L)
- Free-breathing conservator vessel for oil expansion
- Thermally Upgraded Paper-insulated windings and spacers
- Paper in-between disks for DP_v measurement
- Current supply for the resistive heating of windings
- Pump for the forced oil circulation
- Sensors for the oil, paper and winding temperatures
- PC with data acquisition and control programs

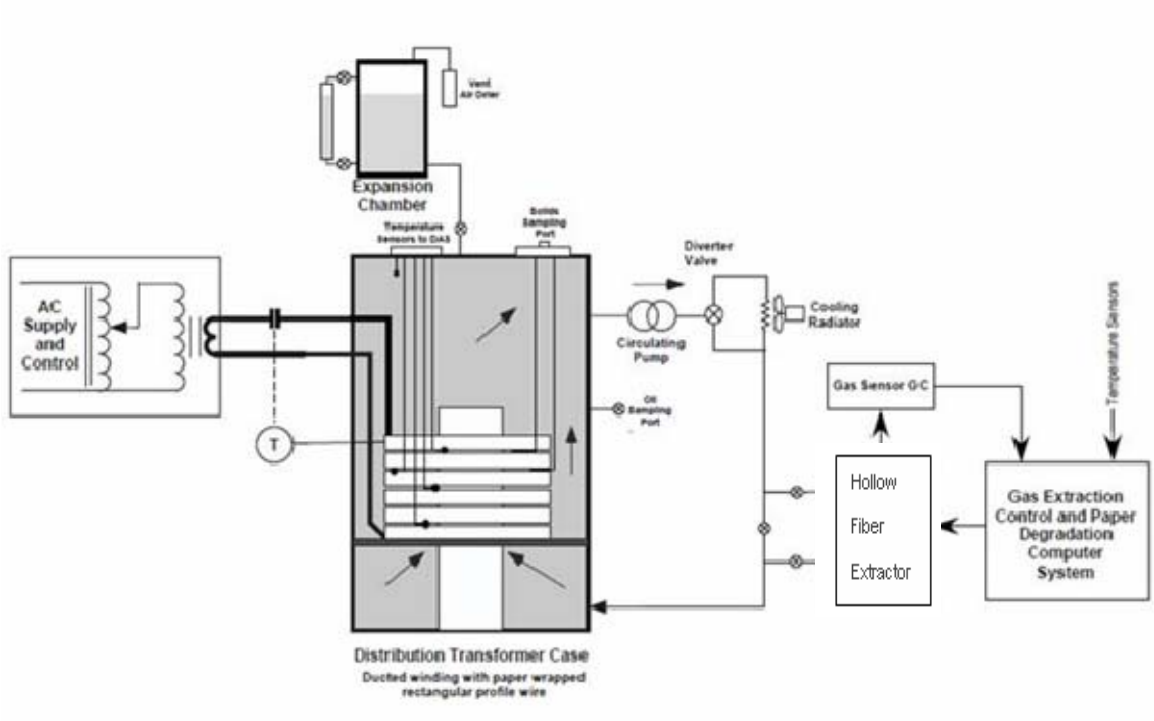
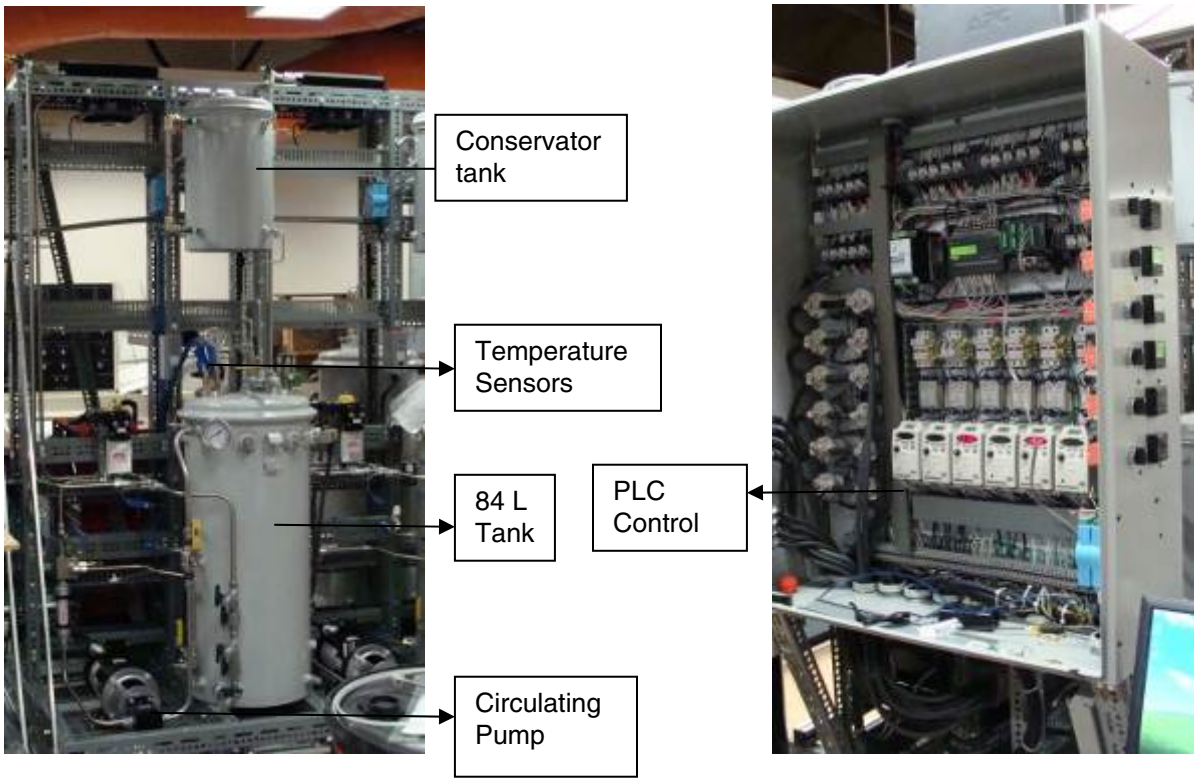
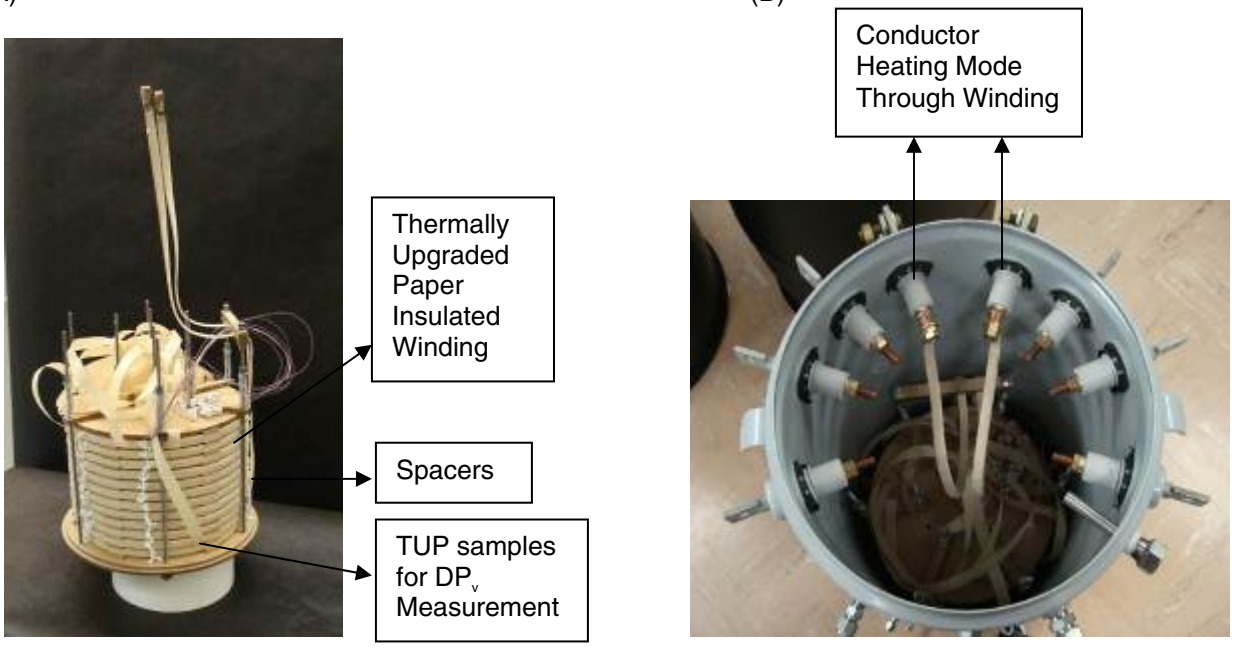


Figure 5-1
Schematic of Transformer Model for On-Line Assessment of Paper Degradation by-Products



(A) (B)



(C) (D)

Figure 5-2
(A) Transformer Model Set Up; (B) PLC Control for the Transformer Set Up; (C) Thermally Upgraded Paper Insulated Winding with Spacers; (D) Transformer Model Tank with Insulated Windings with Current Supply for Resistive Heating of Windings.

The system was instrumented with pressure and temperature gauges and plumbed with by-pass and diverting valves to allow independent operation of degassing of the oil through the hollow fiber and analyzing the gases and volatiles. The hollow fiber bundle and the single strand of hollow fiber were used for two different purposes. On the outside shell of the bundle of hollow fiber an ammonia sensor was attached as shown in Figure 5-3 to measure the level of ammonia in the oil. Both the GC-QUAD and the ammonia sensor will be used to measure the level of ammonia in oil. The GC-QUAD has a detection limit of 500 ppm in oil at 25 ^{o}C whereas the ammonia sensor has 41 ppm in oil at 25^{o}C, allowing the use of the bundle of hollow fiber for the analysis of low level of ammonia and the single strand hollow fiber GC-QUAD set up for high level of ammonia. At 70 ^{o}C, the sensitivity of both the hollow fiber extractor set up and the single strand hollow fiber GC-QUAD set up increases.

Figure 5-3
Ammonia Sensor on the Outside Core of the Hollow Fiber

Oil was passed through the hollow fiber bundle at two different flow rates (0.05 and 0.10 USGPM). It was observed that the rate of diffusion of ammonia was dependent on the flow rate and that at lower flow rate (0.05 USGPM), a shorter equilibrium time of 40 minutes is required as shown in Figure 5-4.

The single strand hollow fiber was used to extract other gases and volatiles present in oil. The oil was circulated from the tank to a reservoir which is attached to a fan as shown in Figure 5-5 where the oil was cooled down below 70 ^{o}C. The oil was then circulated on the outside of the single strand hollow fiber in the stainless steel tube and allowed to stand still. The tubing containing the single strand hollow fiber and oil was then heated at 70 ±1 ^{o}C using an external programmable heater as shown in Figure 4-14. Once the reading on the thermocouple reached 70 ^{o}C, the system is allowed to reach equilibrium for 20 minutes to allow the gases and volatiles to move from the oil to the headspace. One end of the single strand hollow fiber is connected to the GC-QUAD which is the technique used to measure the level of gases and marker compounds for paper degradation.

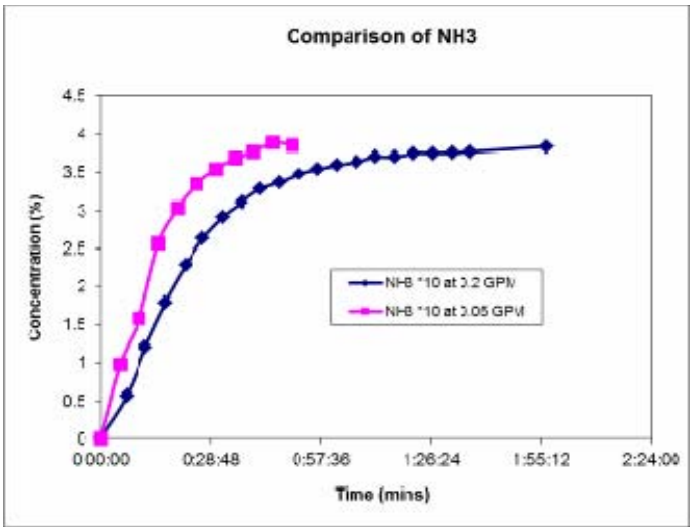


Figure 5-4
Equilibrium Time of Ammonia between Headspace and Oil in the HFE at Different Flow Rates

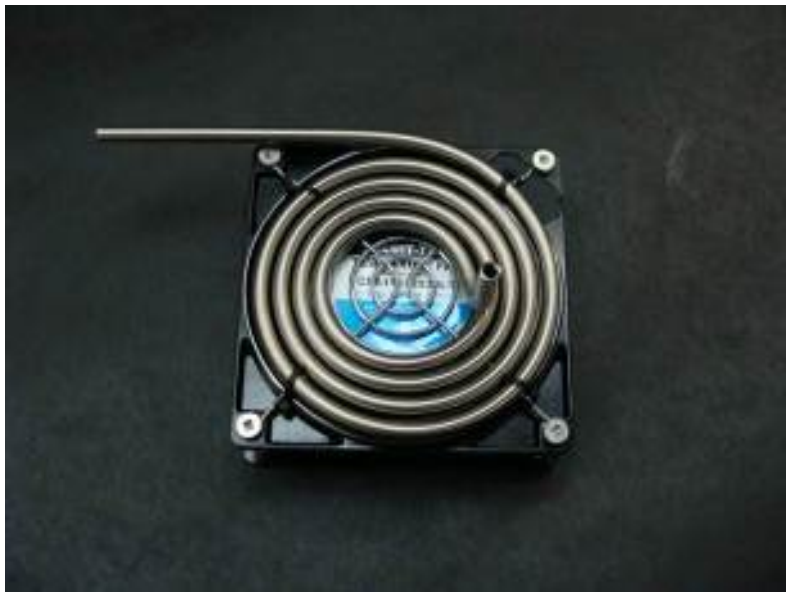


Figure 5-5
Reservoir to Cool the Oil before Passing through the Single Strand Hollow Fiber

Control of the GC and acquisition of the chromatograms were carried out using a dedicated PC. A separate PC was used for controlling the flow of the oil in the HFE and single strand hollow fiber and the temperature of the oil. The equipment set up is shown in Figure 5-6.

Figure 5-6
Complete Transformer Model with Sensors

Initial Equilibration of Oil and Paper

Two similar test chambers were built; one for this project and one for the online degassing and dehydration project which is also sponsored by EPRI as shown in Figure 5-6. The paper insulating system was heated in the chamber at elevated temperature of up to 120 ^{o}C. As shown in Figure 5-7, there is a temperature gradient between the disk at the top of the tank and the one at the bottom of the tank. With the oil circulating at a rate of higher than 5 L/min, the top and bottom oil temperatures were only 5^{o}C apart. To equilibrate the oil and the paper in the system, the chamber was heated by applying a variable load to the windings of up to 120 ^{o}C for a 3 hour period and then allowing to cool down to 70 ^{o}C for 30 minutes followed by cool down to room temperature as shown in Figure 5-7.

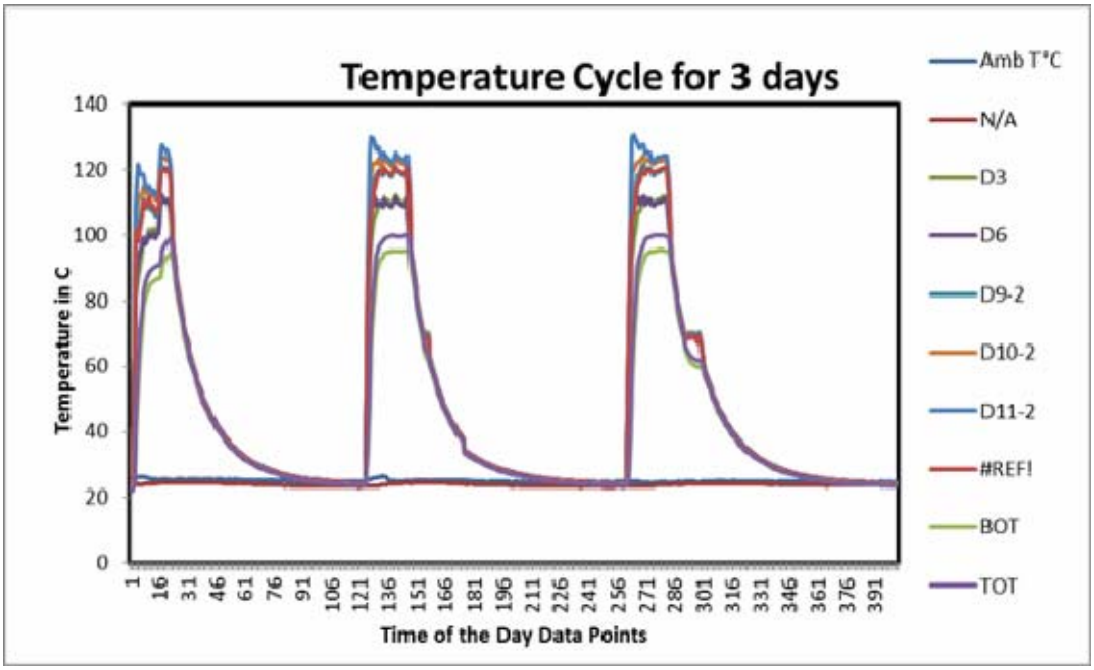


Figure 5-7
Initial Equilibration of the oil and paper; BOT = Bottom Oil Temperature; TOT= Top Oil Temperature, temperature at the top of the disk; D= Disk with D-1 being Disk 1 at the bottom of the Tank.

This cycle was repeated for three days and the oil samples were taken out for analysis at room temperature before switching the current on in the morning. The level of gases, volatiles and moisture in the oil were recorded and plotted as shown in Figure 5-8. A linear increase in the level of O_2, N_2, CO_2, H_2, CO, CH_4, H_2O and methanol was observed versus interval of heating at 120 ^oC. There was no C_2H_2, C_2H_4, C_2H_6 gases produced during the 582 minutes of heating at 120 ^oC.

As shown in Figure 5-8 above, only a gradual production of the fault gases does occur under moderate overload ($T_{winding}$ =120 ^oC and T_{oil} = 90 ^oC), making such gassing difficult to measure. Therefore, several overload tests at higher temperatures will be applied.

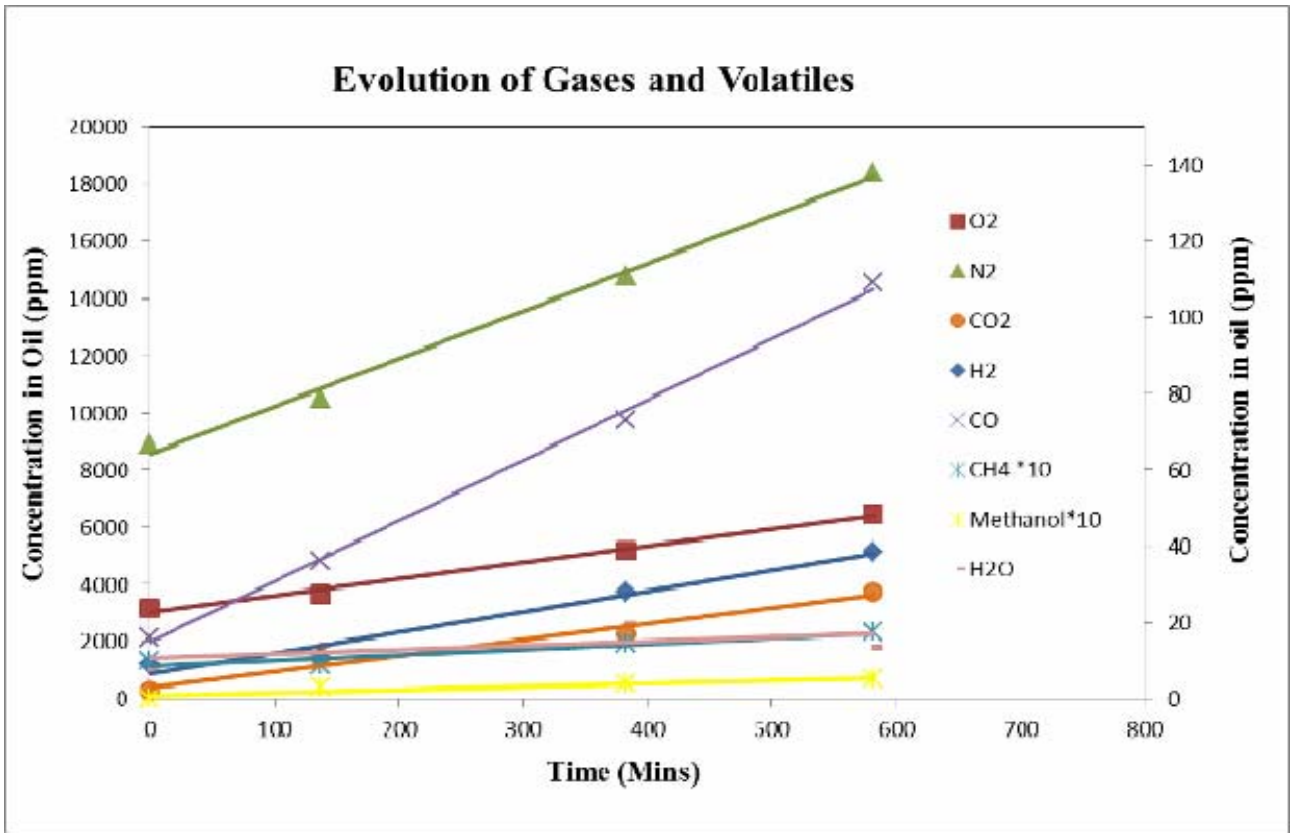


Figure 5-8
Rate of Formation of Gases and Volatiles during Initial Equilibrium of Oil and Paper. N_2, O_2, and CO_2 are plotted with respect to the left hand side y-axis, whereas CO,H_2, H_2O, CH_4 and methanol are plotted with respect to the right hand side y-axis.

6
NEXT STEPS

The research is advancing towards a better assessment of transformer aging. This answer is vital to the cost effective management of transformer fleets within a utility.

In summary, online commissioning tests were performed on one of the transformer model unit which was filled with used mineral oil and windings. Known amounts of gases and volatiles were added to the system and then the Hollow Fiber extraction and online monitoring techniques were tested. These tests were necessary to validate the proper function of many of the components and the set of initial conditions - as well as the use of the online monitoring techniques. The hollow fiber extraction was tested at variable oil flow rates as well as variable temperature.

The next stage will be to set up the validated online monitoring system on the transformer model built for this project and perform thermal runs at different temperatures. During the accelerated aging studies, temperature data at specific winding locations will be collected continuously. The temperature data will be used to calculate the loss of life of the paper using an IEEE function or similar. The results will be compared to the DPv of the paper from the same location as the temperature. Online measurement of the level of gases and low molecular weight compounds will also be collected and a relationship between the level of the marker compounds, temperature and DPv will be investigated. The goal is to develop relationships helpful to estimating the remaining life of the transformer. To validate the approach, offline analysis of the oil will also be performed for comparison with the online measurement of gases and volatiles.

A
APPENDIX

Specifications of Transformer Model

The transformer model consists of the following

- Main Tank
- Tank Lid
- Expansion Tank
- Windings
- Thermocouples
- Paper Strips

Main Tank

The main tank as shown in Figure A- 1 is representative of the distribution style transformers modified with additional main tank and lid ports. The inside diameter of the main tank is 31 “High x 14.22” Wide and can hold a total volume of 84.2 L of oil. The main tank is comprised of 8 Low Voltage Bushing Ports with 4 – ¼ “FNPT and 4-1/2”FNPT ports.

Figure A- 1
Main Tank with LV Bushing Ports.

Tank Lid

The tank lid is comprised of 2 high voltage bushing ports and 2 1-1/2 “FNPT ports with a Buna N Square Cut Ring gasket with V clamp as shown in Figure A- 2.

Figure A- 2
Tank Lid

Expansion Tank

The expansion tank is similar to a small distribution tank with additional ports with inside diameter of 10.25 “x 16”High. The expansion tank can hold up to 22.9 L of oil with 4 – ¼”FNPT ports and 2 - 1-1/2”FNPT ports located on the lid. A tube is attached to the outside of the expansion tank to allow introduction of air and a mixer is introduced in the expansion tank to allow thorough mixing of oil with air as shown in Figure A- 3.

Figure A- 3
Expansion Tank

Windings

The copper conductor winding is wrapped with five layers Thermally Upgraded paper from Manitherm D. The size of the conductor is 0.5 “x 0.070”. The Thermally Upgraded Paper is 0.75 “W x 0.0025” Thick. The transformer model core is made up of 12 disks winding with each coil having 22 turns. The disk windings are separated by disk spacers made of transformer board of 2. “L x 1.24” W x0.164” T. The core is supported by the transformer board tube of 6.25” OD 6.75”ID x 11”L.

Figure A- 4
Copper Windings with Thermally Upgraded Paper with Coils Separated by Disk Spacers.

Table A- 1
Overall System and Winding Specifications

Overall Winding Specification	
Total Volume of Bulk Insulation	216 cubic inch
Volume of Hot Insulation	176 cubic inch
Volume of Conductor	298 cubic inch
Winding Volume	5751 Cubic inch or 11.23 L
System and Oil Volume	
Total System Volume	115.5 L
Expansion Space Volume	10 L
Sampling Volume Allowance	5 L
Reserve Head Space	2 L
Winding Volume	11 L
Miscellaneous Volume Displaced	1 L
Oil Volume	90 L at beginning of test run

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