ELECTRIC POWER RESEARCH INSTITUTE

Transformer Aging as a Function of Temperature, Moisture, and Oxygen

1013931

Transformer Aging as a Function of Temperature, Moisture, and Oxygen

1013931

Technical Update, December 2007

EPRI Project Manager

L. Van der Zel

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Monash University

IntellPower Pty. Ltd.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

Monash University
Centre for Power Transformer Monitoring,
Diagnostics and Life Management
Department of Electrical and Computer Systems Engineering
Clayton 3800 Victoria
Australia

Principal Investigator
V. Davydov

IntellPower Pty. Ltd.
2/10 Warina Rd
Carnegie 3163 Victoria
Australia

Principal Investigator
O. Roizman

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Transformer Aging as a Function of Temperature, Moisture, and Oxygen. EPRI, Palo Alto, CA: 2007. 1013931.

PRODUCT DESCRIPTION

Work related to the EPRI-funded project Transformer Insulation Behavior During Overload has been underway since 1994. Results from the most recent stage of the project, designated as Part 5, are presented in this technical update. This work was conducted during 2007, based on a foundation laid by work that took place from 1994 through 2006 during project stages designated as Parts 1–4. Two main topics are covered in this technical update: (1) results of the experimental study into the aging of transformer paper-oil insulation systems under various temperature, moisture, and oxygen conditions; and (2) the development and field trial of new software tools.

Results and Findings

In 2007, the new laboratory test method developed by the research—a method for determination of the water-in-oil solubility parameter—was licensed by EPRI to TJ|H$_2$b Analytical Services, Inc. The Transformer Moisture Monitor (TMM) and Transformer Dryout Monitor (TDM) software tools underwent a field trial. Development of the other transformer condition assessment tool, the Transformer Moisture Assessor (TMA) workbook, is in progress. The combined effect of temperature, moisture, and oxygen on aging of paper insulation was experimentally assessed and quantified.

Challenges and Objectives

This report includes critical and practical information intended for engineering, maintenance, and laboratory personnel. Two primary topics are addressed: moisture measurement and on-line dryout of an operating transformer; and effects of moisture and oxygen on the aging of transformer insulation. Using the procedures described in this report will assist personnel in optimizing on-line treatment of transformers and conducting more-accurate assessments of transformer life expectancy.

Applications, Value, and Use

The tools developed during this research can be used to perform continuous monitoring of transformer insulation; to assess and rank transformers in terms of moisture content and life expectancy; and to facilitate the efficient dryout of insulation.

EPRI Perspective

Since the beginning of the transformer industry, the definition of nameplate current-carrying capacity has been related to temperature rise and ambient temperature, in recognition that operation beyond thermal limits jeopardizes transformer life. However, aging of transformer insulation is highly dependent on moisture and oxygen contents. If both are low, thermal degradation is minimal except with very high temperatures. The current report clearly shows that insulation degradation is most severe in paper-oil systems with high moisture and oxygen contents, which are a replica of air-breathing conservator units. Insulation degradation is somewhat less severe in oxygen-free paper-oil systems, and much less severe in dry and oxygen-free paper-oil systems, which are a replica of either conservator units with membranes or nitrogen-blanketed units. Maintaining low moisture and oxygen contents is an effective strategy for extending insulation life and reducing transformer operating risk. Monitoring and continuous oil filtration on-line are ways to address this.

Approach

The focus of the work in 2007 was to provide industry with practical tools for evaluating and improving moisture-related conditions of transformer insulation and for assessing life expectancy at various temperature, moisture, and oxygen levels. This was accomplished by developing new knowledge and software. These developments are based on previous EPRI research targeted at understanding the dynamic behavior and effects of moisture in transformer insulation systems.

Keywords

Transformer insulation
Paper
Oil
Aging
Moisture
Oxygen

ACKNOWLEDGMENTS

The work of the following university contributors to the contract is gratefully acknowledged:

- Prof. David Morgan
- Prof. Arthur Lowery
- Dr. Andrew Reykherdt
- Mr. Jaury Wijaya
- Mr. Nick Lelekakis
- Mr. Martin Linzner
- Mr. Ian Reynolds
- Mr. Geoff Binns
- Ms. Pam Dickinson.

The considerable assistance of the following external personnel is also acknowledged:

- Mr. Ross Polvere CitiPower, Melbourne, Australia

CONTENTS

1

EFFECT OF TEMPERATURE, MOISTURE AND OXYGEN ON LOSS OF INSULATION LIFE – UPDATE ON RESULTS

Introduction

The current report is a continuation of work reported in [1], [2] and [3] in March and December 2005 and November 2006 respectively.

To predict the insulation life of oil-immersed power transformers it is absolutely vital to understand the physics of aging of paper insulation under different conditions. The life of an oil-filled transformer depends on the life of its insulation system. This is defined by chemical processes occurred in the insulation under the influence of temperature, moisture, oxygen and other parameters.

The standards IEEE C57.91-1995 [4] and IEEE C57.100-1999 [5] give a life expectancy curve for oil-immersed transformers with a well dried, oxygen free insulation as a function of temperature only (see Figure 1-1).

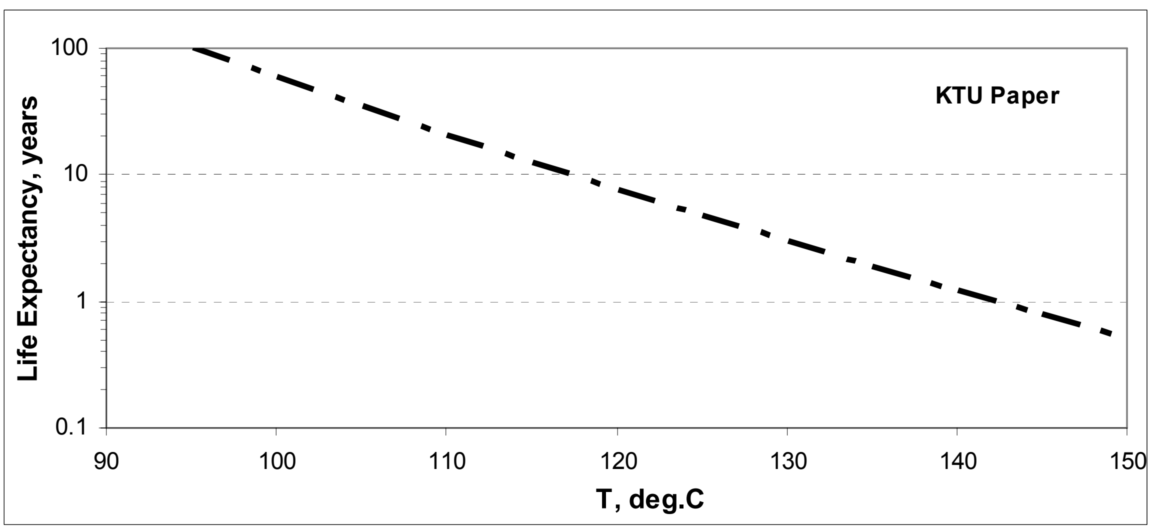


Figure 1-1
Life Expectancy Curve Determined by IEEE Standards for Transformers with 65°C Average Winding Temperature Rise

According to the standard [4], estimation of the Loss of Life (%LoL) is possible by using a minimum life expectancy parameter and a period of time during which the insulation is exposed to a particular temperature:

$$\%LoL = \frac{\sum_{n=1}^{N} F_{AA,n} \cdot \Delta t_n}{t_{\min LE}} 100\%, \quad \text{1-1}$$

where $t_{\min LE}$ is the minimum life expectancy of 180,000 hours (20.5 years) [4] & [5], N is a total number of time intervals and F_{AA} is an aging acceleration factor of the individual temperature during the time interval Δt_n.

The life expectancy (LE) can be described using the Arrhenius' chemical reaction rate theory in the form of an exponential reaction rate, as it was found by many researches in earlier studies [6-9]:

$$LE = A \exp\left(\frac{B}{T + 273}\right), \quad \text{1-2}$$

where A and B - constants of aging rate, T - winding hottest-spot temperature, °C.

The coefficient B in equation (1-2) represents a slope of the aging rate versus temperature. Most of the published values of B are in the range of 11,350 to 18,000 for non-thermally upgraded paper, and about 10,000 for thermally upgraded paper. The high level of deviations for the coefficient B values obtained by different investigators is a subject to variability in the materials and test conditions, which have been certainly not identical. Frequently, the results were obtained in the limited temperature range of approx. 135°C – 155°C. The standards [4, 5] adopted a value of B = 15,000 as an average value of research data obtained for a well-dried, oxygen-free transformer insulation.

Most of the experimental aging tests conducted world wide and their results presented in the standards have been carried out with low levels of moisture and oxygen contents, mainly in sealed tubes placed into an oven at a certain temperature. Apparently, the sealed tubes approach used in the aging studies does not allow controlling the levels of moisture and oxygen in the tubes. It is well known that chemical decomposition of paper and oil due to aging does lead to increase of the water content in the paper-oil system inside such sealed tubes, which in turn accelerates the rate of aging of paper insulation. Thus, the sealed tubes approach provides experimental data based on continuously increasing moisture content of the paper-oil system tested.

The Monash experimental study of insulation aging was conducted using the Monash test rig designed at the earlier stage of the project and described in detail in [1]. The 5-litre glass vessel was used to accommodate dry and degassed Shell Diala AX mineral oil, 1-mm thick pressboard and samples of Weidmann Kraft (K) and Kraft Thermally Upgraded (KTU) paper. To allow oil to expend and to contract, a pipe was connected to a 2-litre oil expansion conservator with an argon head space above the oil in the conservator; the head space was connected to a gas expansion rubber bag. The 5-litre test vessel was placed into an oven and kept at a dedicated temperature of the test conducted. Oil in the vessel was stirred continuously using a magnetic stirrer. To monitor the test parameters continuously, temperature and moisture sensors were placed in each test vessel and connected to a data acquisition (DAQ) system. Paper samples were regularly taken and tested for the DP. Oil samples were also tested for the DGA and other parameters during each run.

The oxygen level in the experiments was maintained at the following two levels: (1) low level, replicating transformers with a nitrogen head space or a conservator oil preservation system, and (2) high level, replicating free-breathing transformers.

The current report contains results of the experimental tests conducted at the low and high levels of oxygen and at various levels of the temperature and moisture. Also, the report includes descriptions of the ways of controlling the moisture and oxygen contents in each test. A combined effect of the temperature, moisture and oxygen on aging of paper insulation is demonstrated.

Objective

To develop new knowledge for more accurate estimation of the aging acceleration factor and life expectancy of paper insulation in mineral oil filled transformers under different temperature, moisture and oxygen conditions.

Preliminary Study into Moisture Equilibrium for New and Aged Paper

The moisture state of a paper-oil insulation system can be expressed using the following two parameters: (1) Active Water Content of Paper (WCPa) and (2) Water-in-Paper Activity (Awp). Figure 1-2 shows sorption curves relating WCPa and Awp for new paper, calculated for the range of temperatures from 0°C to 160°C.

A moisture sensor immersed in oil measures the oil Relative Saturation (RS) parameter. The RS is expressed in %. At the moisture equilibrium condition, the sensor measures the Equilibrium Relative Saturation (ERS), %. For a paper-oil physical complex, the Water-in-Paper Activity (Awp) can be calculated as Awp=ERS/100.

For new paper, the WCPa parameter can be estimated using the equilibrium chart shown in Figure 1-2 from the measured ERS and temperature.

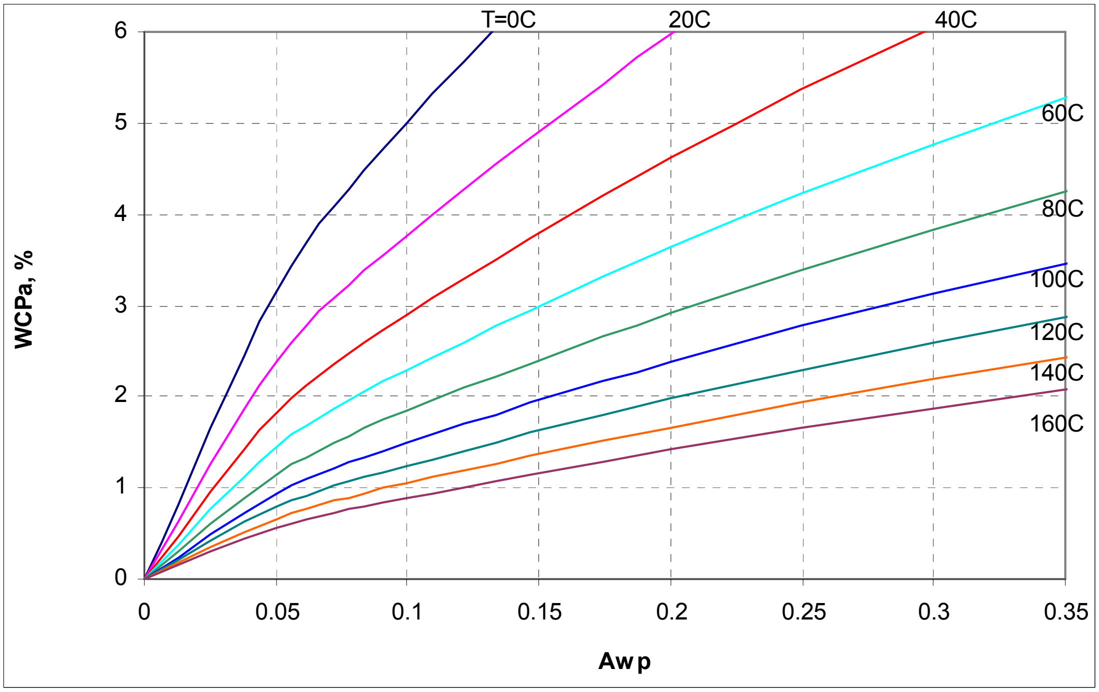


Figure 1-2
Moisture Equilibrium Sorption Curves for New Paper

However, for aged paper, the relationship between WCPa and Awp can differ to that for new paper.

A preliminary study was carried in a paper-air physical complex. Two paper samples, one with a high level of DP and the other with a low level of DP, were placed on a mash inside a vessel containing a saturated salt solution at the bottom of the vessel for establishing a known level of the Equilibrium Relative Humidity (ERH), %, in the complex. For continuous monitoring, a probe containing moisture and temperature sensors was installed in the vessel (see Figure 1-3).

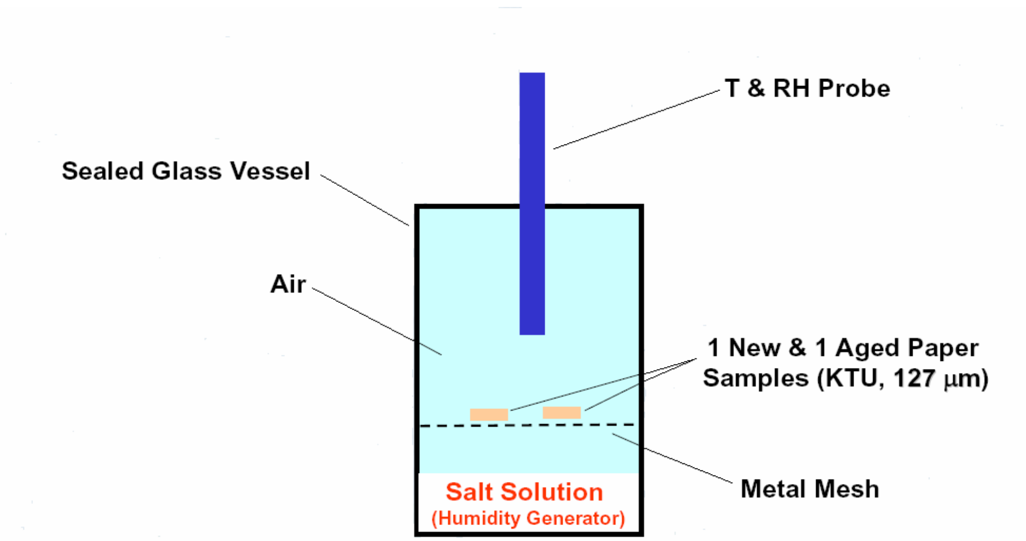


Figure 1-3
Study into Moisture Equilibrium for New and Aged Paper

Two non-oily KTU paper samples of 0.127 mm thickness each, new (DP=1148) and aged (DP=292), were used for the study. The tests were conducted at the constant temperature of 22°C using two salt solutions. For Salt Solution 1 the tests were conducted for one day, while for Salt Solution 2 – for two days. After keeping the paper samples in the vessel and establishment of the moisture equilibrium, the masses of the two samples were measured using an electronic balance. Using the known dry masses of each paper sample, the Water Content of Paper (WCP) was calculated for each test. The results of this study are shown in Figure 1-4.

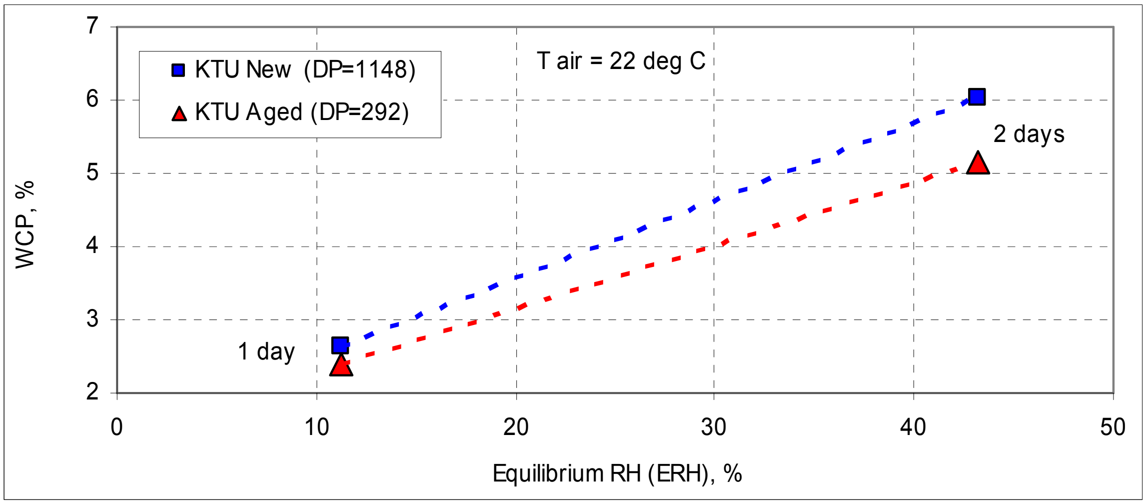


Figure 1-4
WCP versus ERH for New and Aged KTU Paper Samples

Figure 1-4 shows that the WCP of the aged paper sample was about 10-15% lower than the WCP of the new paper sample. This result suggests that, probably, a moisture equilibrium chart for aged paper is different to that for new paper.

The above conclusion has a direct impact on the way the aging study is being conducted at Monash. During the study, the test temperatures varied between 100 and 160 °C and the thickness of the paper insulation tested did not exceed 1 mm. For these two reasons, the temperature and moisture equilibrium conditions were present in the test vessels for the most duration of each test run. This means, that the moisture sensor in each test vessel was measuring the Equilibrium Relative Saturation (ERS) for most of the time, and the Water-in-Paper Activity was calculated from this directly measured parameter as Awp=ERS/100.

We can assume that keeping a constant level of the ERS in the oil would result in the WCPa gradually changing with the changing DP. At this stage, it is roughly estimated that with the DP decreasing to less than 300, the WCPa decreases by approx 10-15% (see Figure 1-4). For a more accurate conclusion, a proper equilibrium chart for aged paper is needed to be developed.

It appears that the Awp is the only controllable parameter of the moisture state of a paper-oil system.

To account for the effect described above, the moisture state of the paper-oil complex was expressed using the following two moisture parameters: (1) Initial Active Water Content of Paper ($WCPa_i$) and (2) Water-in-Paper Activity (Awp) – refer to reports [1], [2] and [3].

Continuation of Experimental Runs with Low Level of Oxygen

Summary of Experimental Design and Tests Conducted

The experimental design of the test runs for the low level of oxygen is shown in Table 1-1.

Table 1-1
Values of Temperature and Moisture (Expressed in $WCPa_i$) Considered for Experimental Design at Low Oxygen Level

Factors	Tests / Runs								
	1(L)	**2(L)**	**3(L)**	**4(L)**	**5(L)**	**6(L)**	**7(L)**	**8(L)**	**9(L)**
T, °C	140	100	140	100	140	100	120	120	120
$WCPa_i$, %	2.7	2.7	0.5	0.5	1.6	1.6	2.7	0.5	1.6
O2 Level	Low								

Two extra tests at 130°C and 160°C were conducted in order to validate some of the obtained results and reported in [3] (see Table 1-2 below).

Table 1-2
Life Expectancy of Paper (DP = 200) for Two Additional Tests

Parameters		Runs	
		130(L)	**160(L)**
T, °C		130	160
$WCPa_i$, %		1.6	0.5
LE, years	KTU	0.44	0.21
	K	0.22	0.08

The following test runs have been completed at the low level of oxygen and reported in [3]:
Runs 2(L), 3(L), 5(L), 7(L) and 160(L).

Test 130(L) was also reported in [3], however, it was not completed prior to submitting report [3] in 2006. The test was continued and completed in 2007. The final results are reported below.

The other tests listed in Table 1-1 were extrapolated using the Arrhenius' chemical reaction rate theory, as such long tests require years to complete [3].

Final Test Results for Run 130(L)

The test was started in 2006 and completed in 2007. The conditions of the test were:

- T = 130 °C
- $WCPa_i$ • 1.6%
- O2: Low Level.

During Run 130(L) moisture level in the paper-oil system was decreasing. To compensate for the moisture loss and to keep the level of moisture in the system at a desired level, water was periodically added to the oil. Oxygen in the paper-oil system was kept at a low level.

Figure 1-5 shows the dynamics of the temperature and relative saturation during Run 130(L).

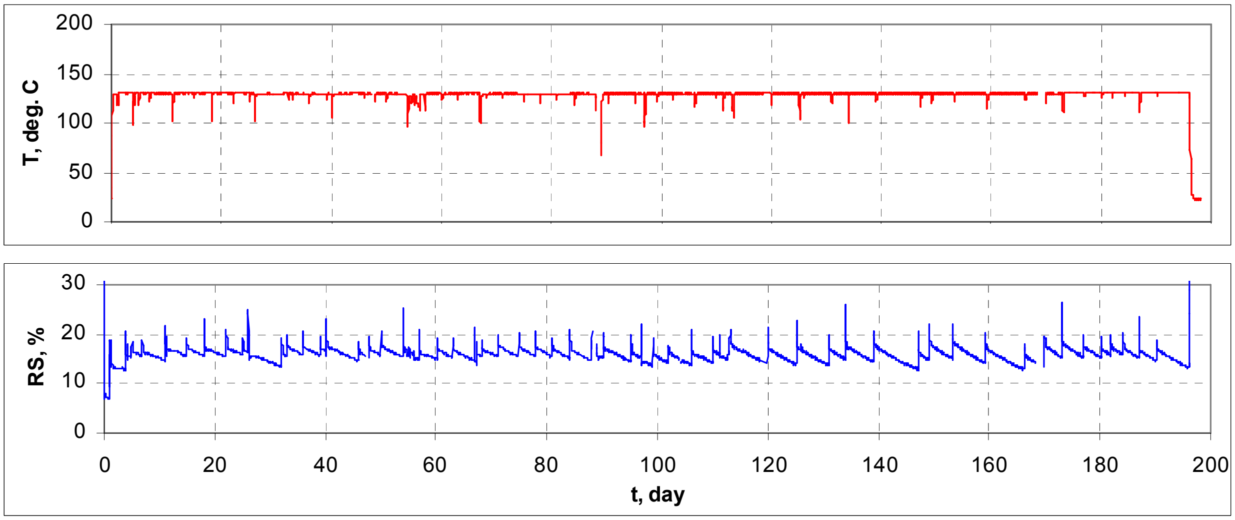


Figure 1-5
T and RS during Run 130(L)

Because the test did not require keeping a high level of O2, only a few samples of oil were taken for the dissolved gas analysis. The levels of O2 and N2 and other gases are shown in Figure 1-6 and Figure 1-7 respectively.

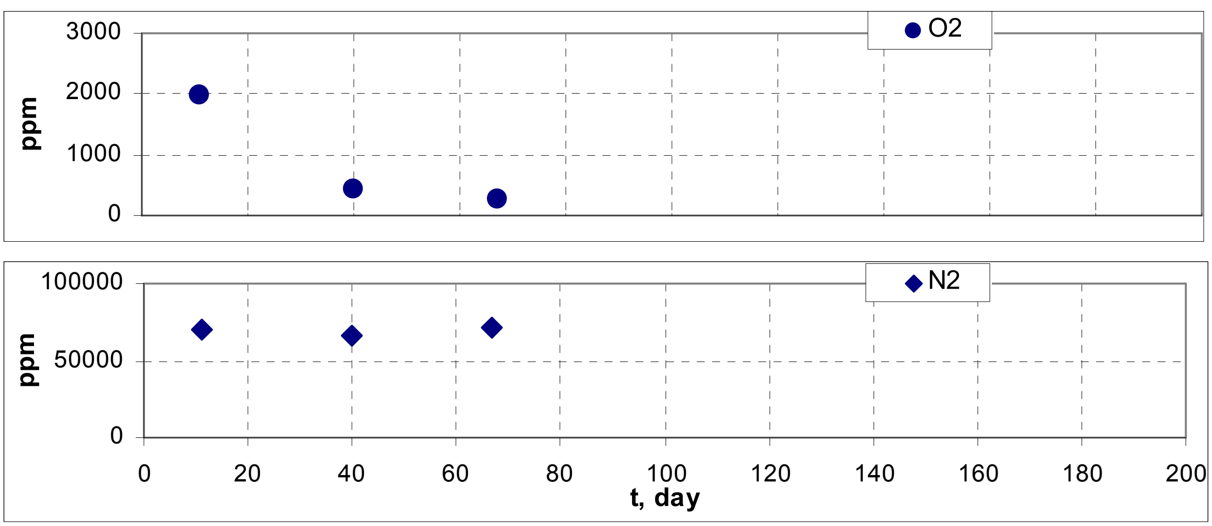


Figure 1-6
Level of O2 and N2 during Run 130(L)

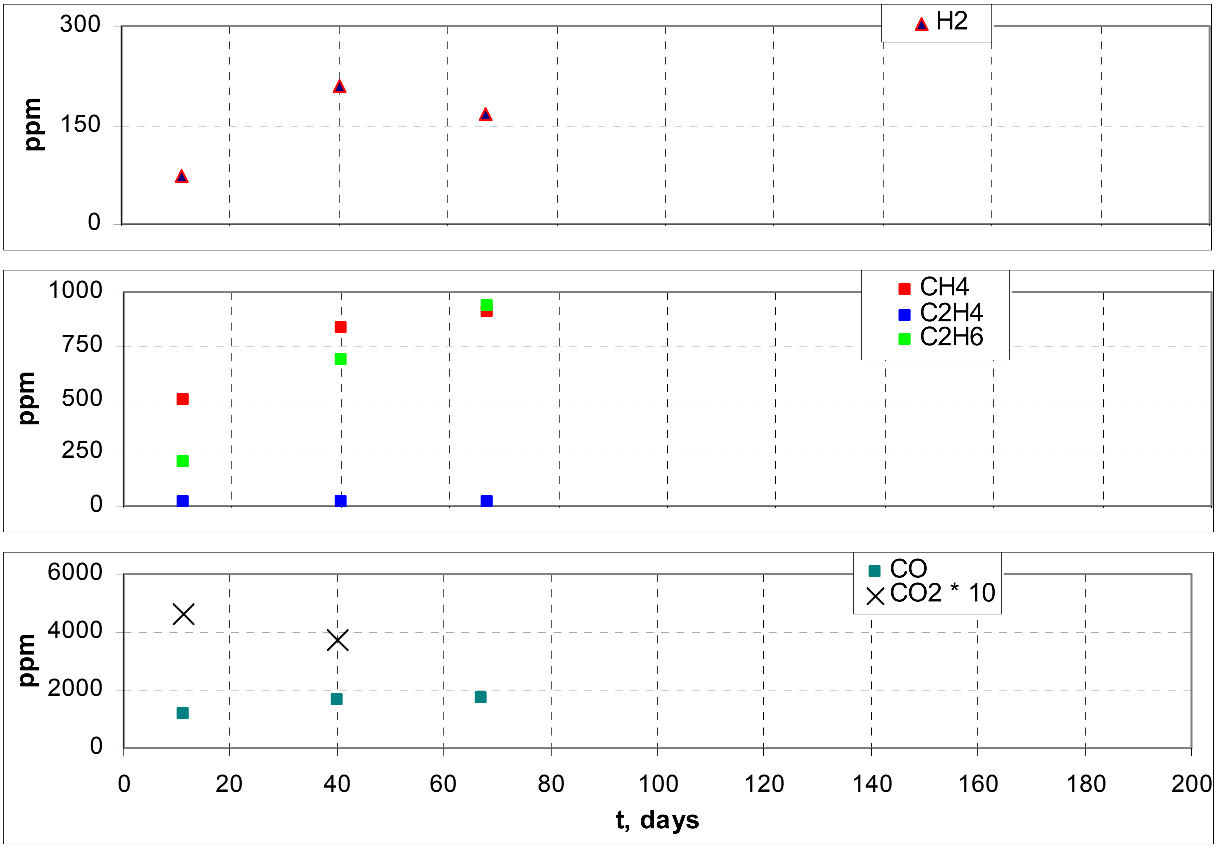


Figure 1-7
Concentrations of H2, CH4, C2H4, C2H6, CO and CO2 during Run 130(L)

Figure 1-8 shows the values of DP for the K & KTU paper samples taken during the test.

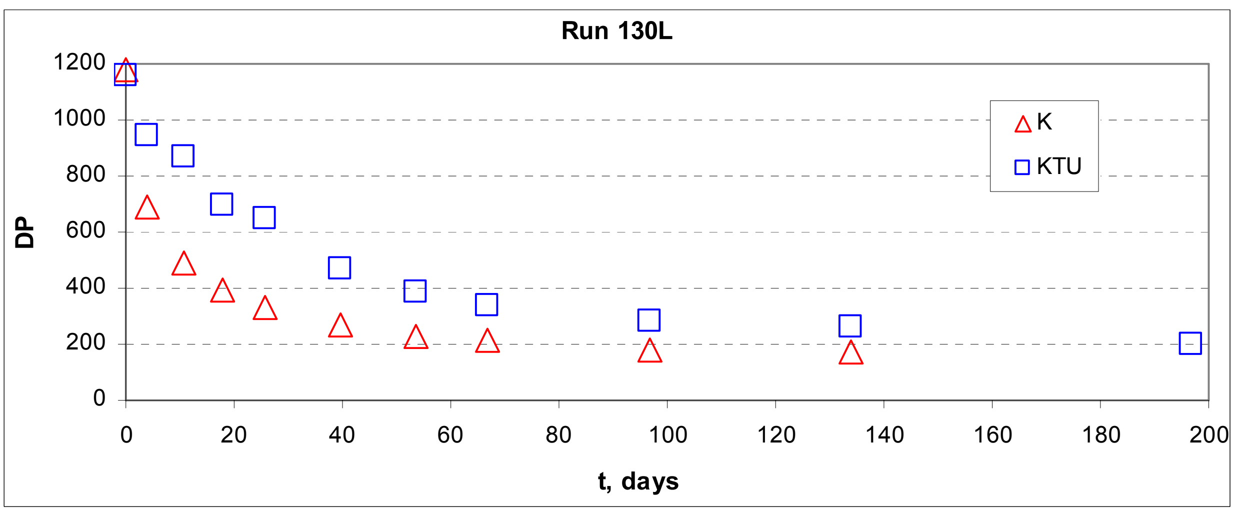


Figure 1-8
DP for Paper Samples during Run 130(L)

In the 2006 report [3], an attempt to predict the life expectancy for K and KTU paper at DP = 200 was made, while Run 130(L) was still in progress. The prediction for K and KTU paper was made when the DP level was 213 and 341 respectively. The test was continued in 2007 and the final results were re-calculated on the completion of the test. The experimentally obtained figures gave the life expectancies of 79 days (K) and 160 days (KTU) against the initially predicted values of 69 days (K) and 121 (KTU) days, which gave approx. 14% and 32% deviations between the predicted and experimentally obtained values.

The above analysis shows that the prediction of the life expectancy for the test with the higher DP gave a higher error.

It should be noted, that Run 130(L) was conducted at the moisture level slightly lower than the level of $WCPa_i$ • 1.6% required. Because of this, the obtained life expectancy was longer than it was expected. For this reason, the result of this test was slightly outstanding compare to the experimental results obtained from the other tests.

Table 1-3 summarizes the results of physicochemical analysis tests conducted for oil with the low level of oxygen at the end of each aging test.

Table 1-3
Changes of Physicochemical Characteristics of Mineral Oil during Aging Tests with Low Level of Oxygen

Test	Test Parameters			Furans Generation Rate, ppm/day	Inhibitor Consumption Rate, ppm/day from 0.19% =1900ppm	Interfacial Tension Reduction Rate, (Dynes/cm)/day from 47 Dynes/cm	Oil Color from L0.5
	T, deg C	WCP, %	O2 level				
2(L)	100	2.7	Low	0.055	2.15	0.055	L5.5
3(L)	140	0.5	Low	0.161	2.38	0.065	L6.0
5(L)	140	1.6	Low	0.700	2.04	0.184	L3.5
7(L)	120	2.7	Low	0.627	3.66	0.122	L4.5
130(L)	130	1.6	Low	0.141	1.52	0.056	L5.0
160(L)	160	0.5	Low	1.063	5.00	0.250	L4.0

Figure 1-9 illustrates the generation rate of furan compounds versus temperature and water content of paper insulation of results obtained during the aging tests.

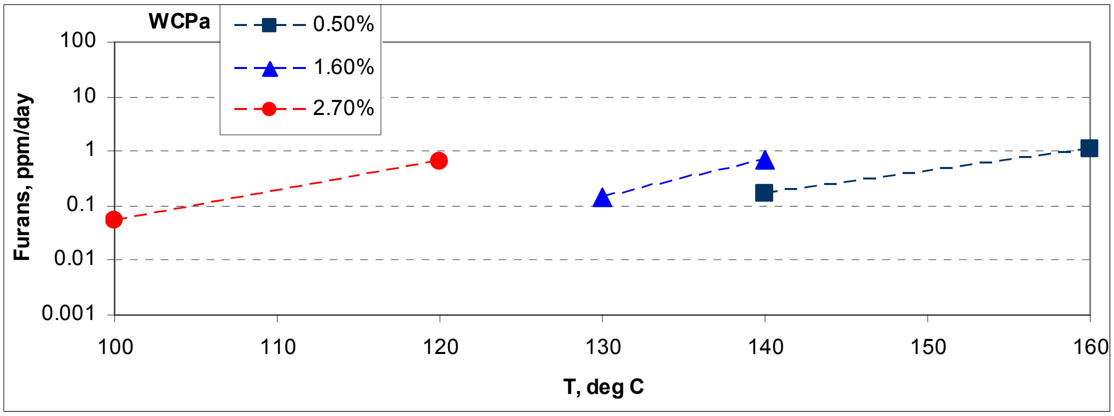


Figure 1-9
Generation Rate of Furan Compounds in Aging Tests at Low Oxygen

As it can be seen from Table 1-3 and Figure 1-9, the rate of furans generation, reduction of oil inhibitor content and reduction in interfacial tension, all depend exponentially on the temperature of the oil-paper complex. We can predict that changing the moisture condition from dry (0.5%) to wet (2.7%) at the same temperature would increase the rate of furans generation by an order of magnitude or even higher (see Figure 1-9).

Test Results for Runs with High Level of Oxygen

The experimental design for high oxygen content is shown in Table 1-4.

Table 1-4
Values of Temperature and Moisture (Expressed in $WCPa_i$) Considered for Experimental Design at High Oxygen Level

Factors	Tests / Runs								
	1(H)	**2(H)**	**3(H)**	**4(H)**	**5(H)**	**6(H)**	**7(H)**	**8(H)**	**9(H)**
T, °C	140	100	140	100	140	100	120	120	120
WCPai, %	2.7	2.7	0.5	0.5	1.6	1.6	2.7	0.5	1.6
O2 Level	High								

The runs with the high level of oxygen are more sophisticated compare to the runs with the low oxygen level, because they require adding oxygen to the paper-oil systems tested.

Test Results for Run 2(H)

Run 2(H) was reported in 2005 as Run 3. During the initial stage of testing in 2005, the DP level did not reach 200. To bring the DP to 200, Run 2(H) was continued in 2007. The test conditions were as following:

- T = 100 °C
- $WCPa_i$ • 2.7%
- O2: High Level.

Figure 1-10 shows the dynamics of the temperature and relative saturation during the test.

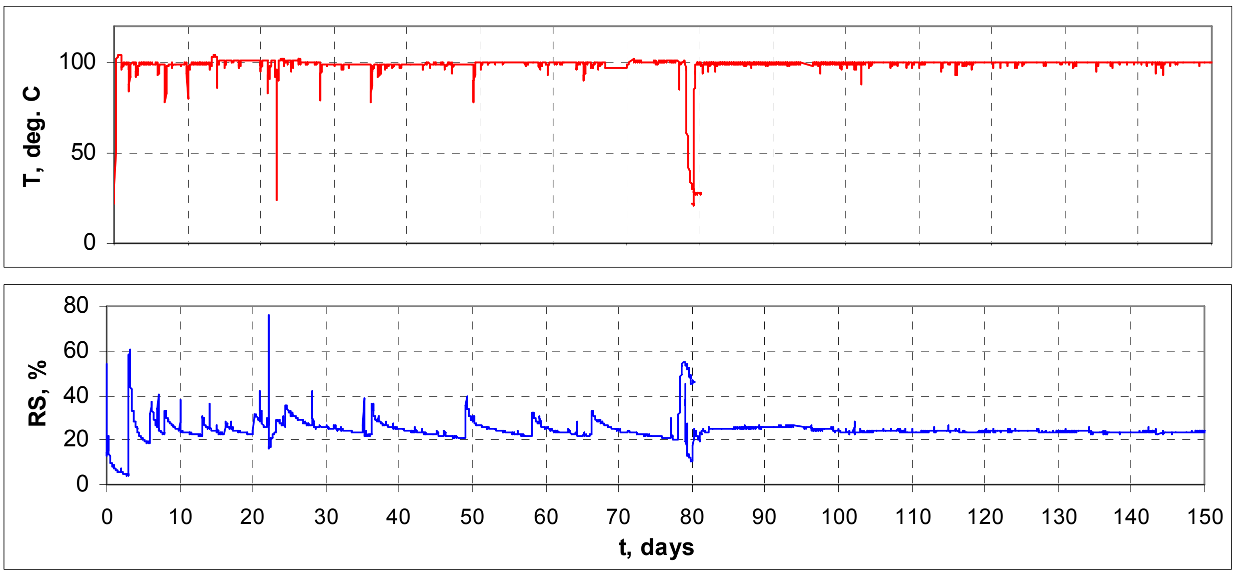


Figure 1-10
T and RS during Run 2(H)

As it can be seen from Figure 1-10, after the initial 80 days of aging, the test was restarted and a different approach of controlling moisture in the test rig was implemented. Dry 1mm-thick pressboard strips fixed to a paper-holder were immersed in the oil in the test vessel. The strips were replaced periodically with the recycled dry strips.

Figure 1-11 shows the amount of oxygen injected into the rig to keep the high level of oxygen.

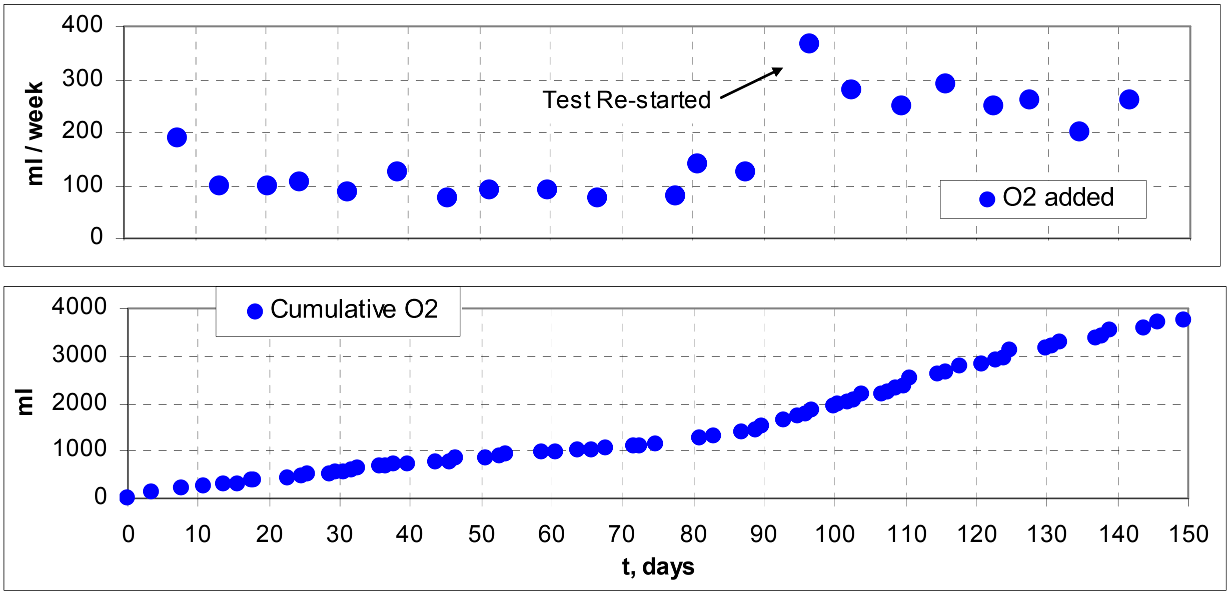
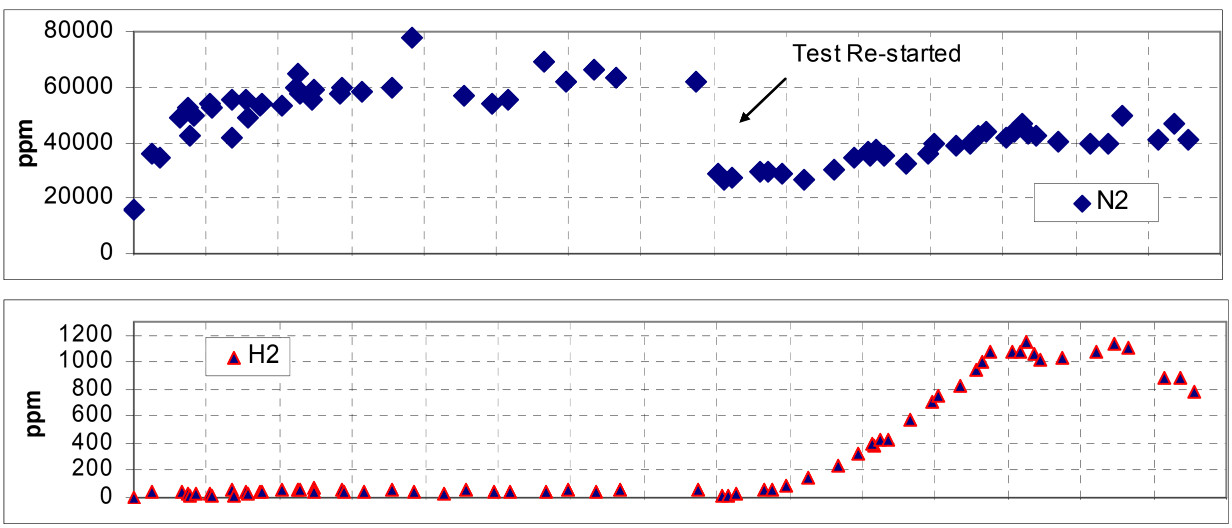


Figure 1-11
Amount of Oxygen Added into Test Rig of Run 2(H)

Figure 1-12 shows the dynamics of the other dissolved gases in the test, including N2.



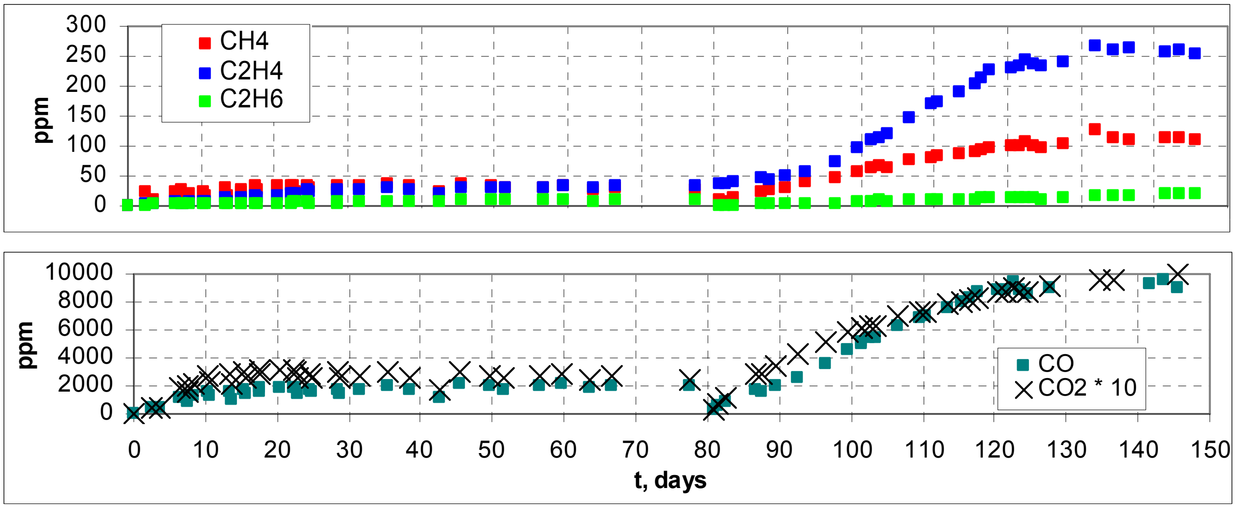


Figure 1-12
Concentrations of N2, H2, CH4, C2H4, C2H6, CO and CO2 in Run 2(H)

Figure 1-13 shows the values of the DP for the K & KTU paper samples taken during Run 2(H).

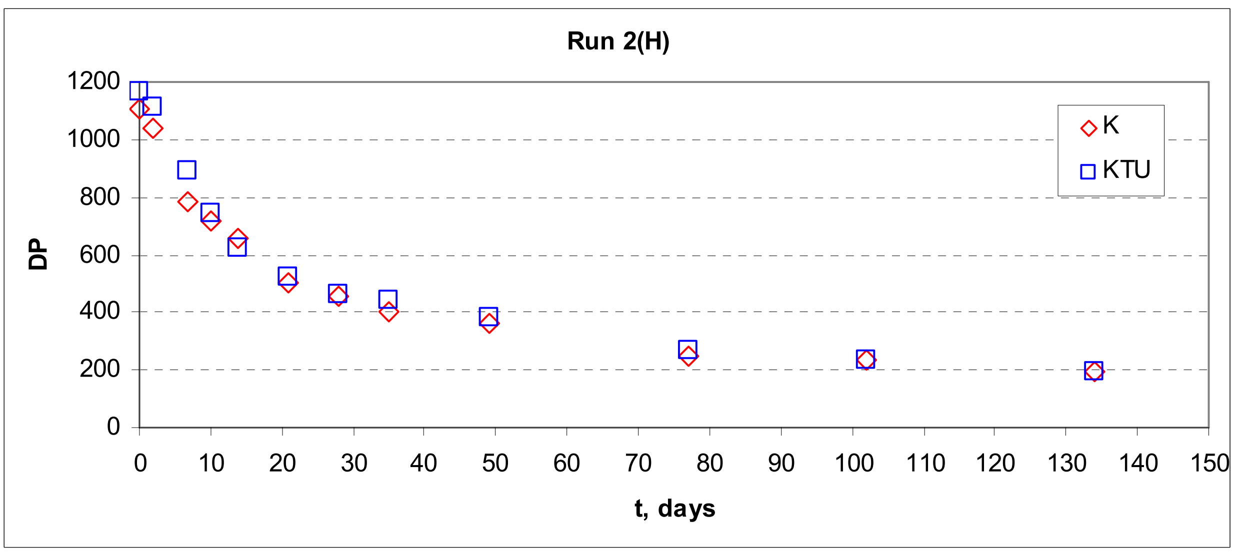


Figure 1-13
DP of Paper Samples in Run 2(H)

Physicochemical tests of oil samples were conducted following completion of the test. The results are shown in Table 1-5.

Table 1-5
Results of Furans and Physicochemical Analyses of Oil for Run 2(H)

Day of sampling	Furan Compounds, mg/kg (ppm)					Acidity mgKOH/g	Interfacial Tension Dynes/cm	Inhibitor %	Color
	2-FAL	5HF	2-FOL	2AC	5MF				
148	ND	0.846	14.1	0.081	0.116	0.08	35	0.14	L2.5

Test Results for Run 3(H)

Run 3(H) was conducted at the following conditions:

- T = 140 °C
- $WCPa_i$ • 0.5%
- O2: High Level.

During the test run, moisture was generated at a high rate. At the initial stage of the test, the moisture content of the paper-oil system was controlled by replacing a wetter pressboard coil with a drier one (two times). After 32 days of the run, the approach was changed. Periodically, vacuum was applied to the hot oil for a short period for removing the excessive moisture from the system – for keeping moisture a desirable level. The application of vacuum has affected the DGA signatures of the run. Oxygen was added to the oil regularly.

Figure 1-14 shows the level of temperature and relative saturation during the test.

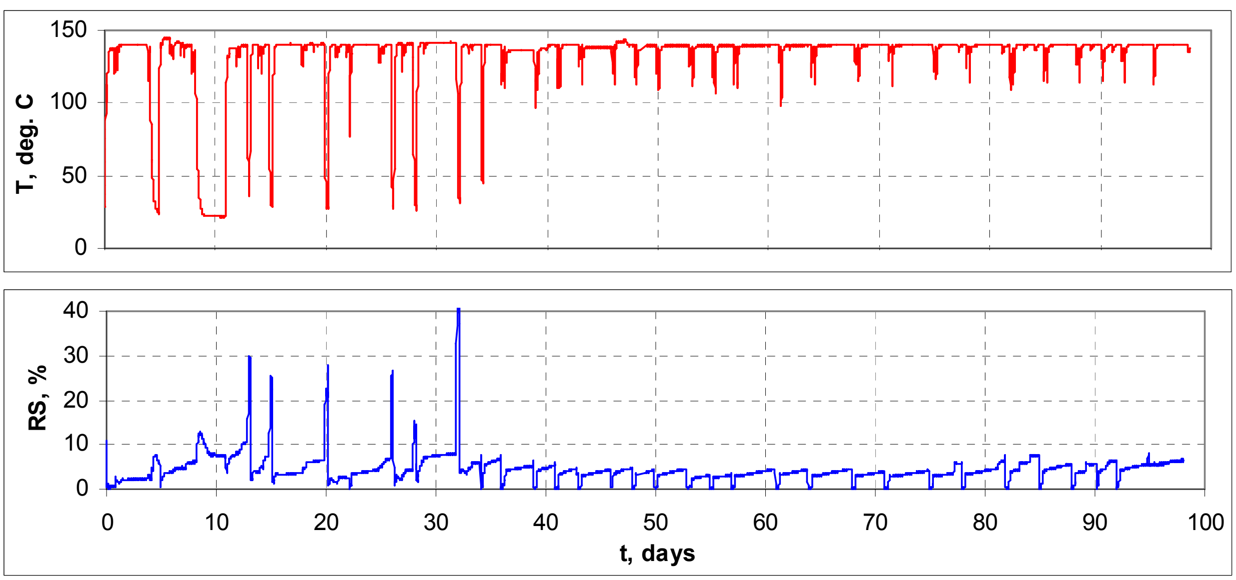


Figure 1-14
T and RS in Run 3(H)

Figure 1-15 shows the amount of oxygen added into the test rig of Run 3(H).

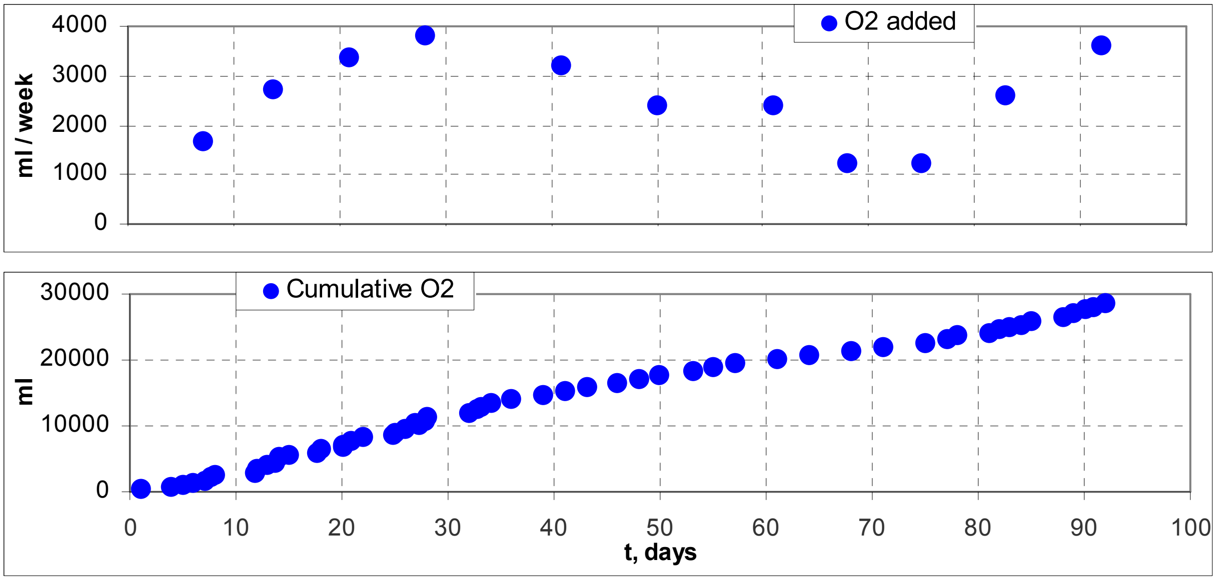


Figure 1-15
Amount of Oxygen Added into Test Rig during Run 3(H)

Figure 1-16 shows concentrations of other gasses measured during Run 3(H).

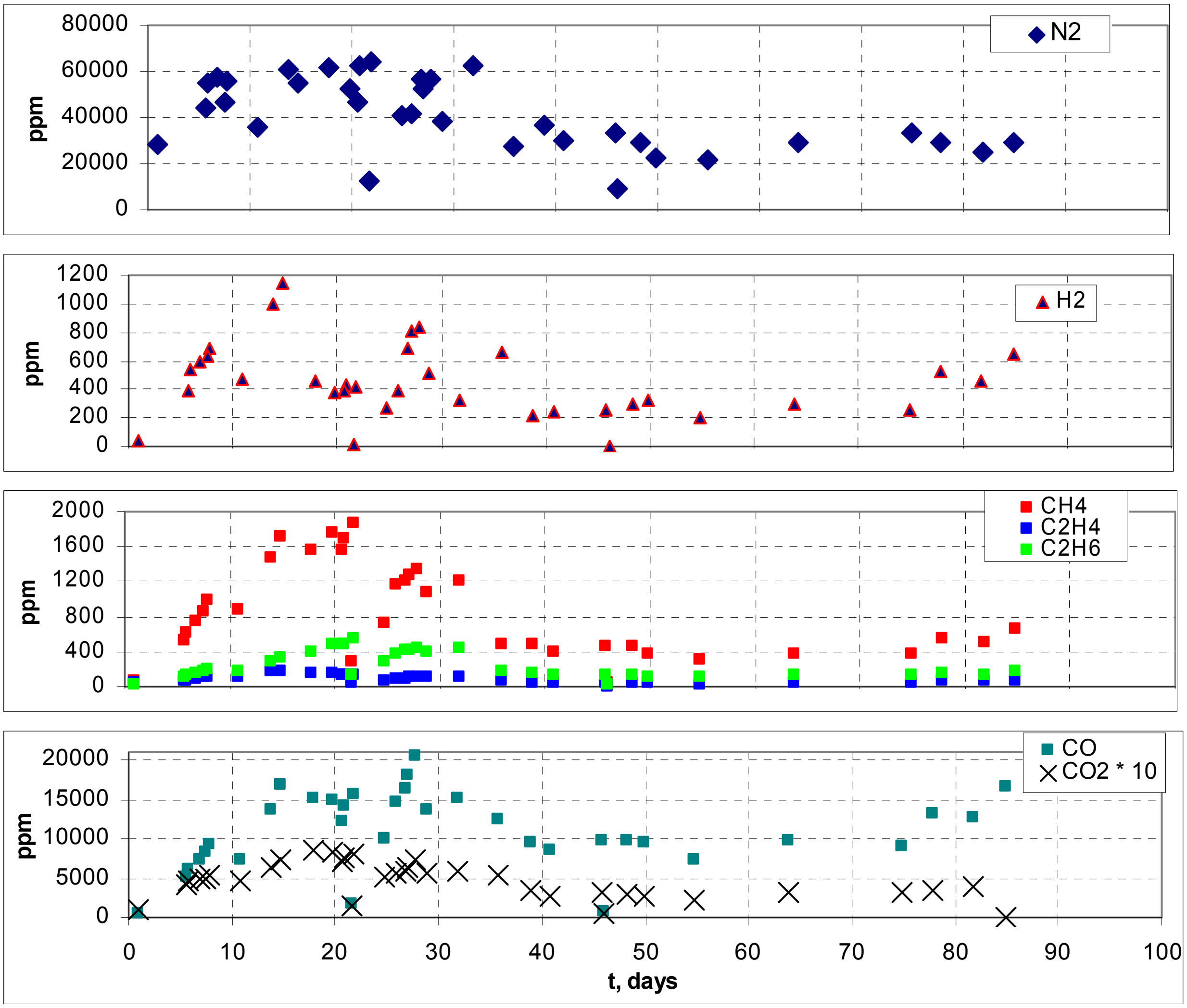


Figure 1-16
Concentrations of N2, H2, CH4, C2H4, C2H6, CO and CO2 during Run 3(H)

Figure 1-17 shows the values of DP for the K & KTU paper samples taken during Run 3(H).

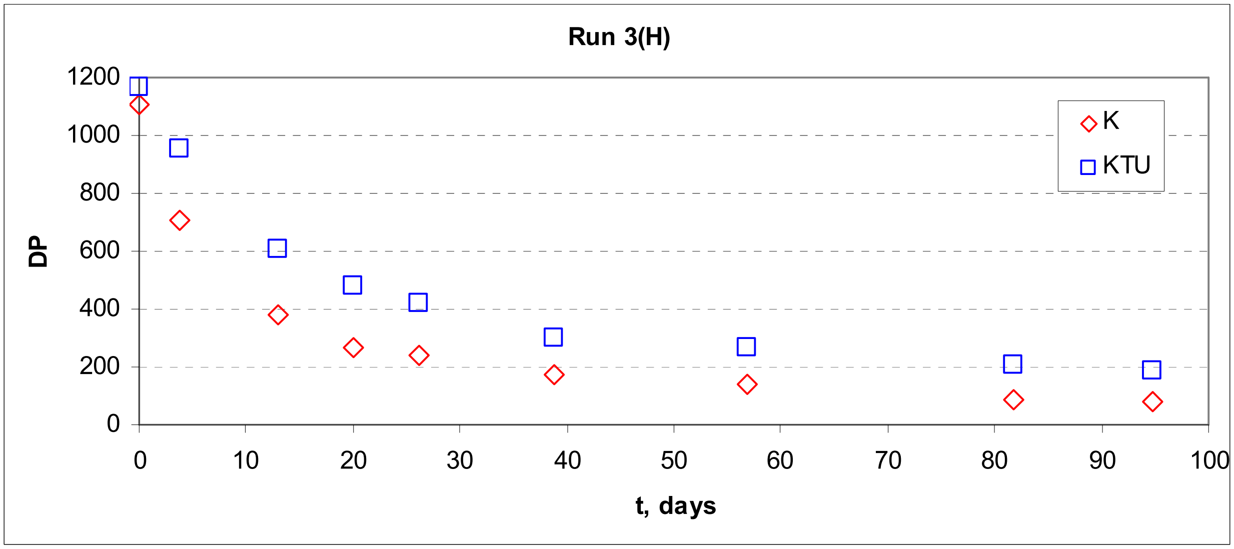


Figure 1-17
DP of Paper Samples for Run 3(H)

The results of physicochemical tests of oil samples taken after completion of the test are shown in Table 1-6.

Table 1-6
Results of Furans and Physicochemical Analyses of Oil for Run 3(H)

Day of sampling	Furan Compounds, mg/kg (ppm)					Acidity mgKOH/g	Interfacial Tension Dynes/cm	Inhibitor %	Color
	2-FAL	5HF	2-FOL	2AC	5MF				
84	ND	2.31	19.9	0.484	0.842	0.53	18	ND	8.0

Test Results for Run 5(H)

Run 5(H) was conducted at the following conditions:

- T = 140 °C
- $WCPa_i$ • 1.6%
- O2: High Level.

During this test run, moisture in the paper-oil system was generated at a high rate. One or two times a week, vacuum was applied to the hot oil for a short period for removing the excessive moisture from the system – for keeping moisture at a desirable level. The application of vacuum has affected the DGA signatures of the run. Oxygen was added to the oil regularly.

The temperature and relative saturation of oil during the test are shown in Figure 1-18.

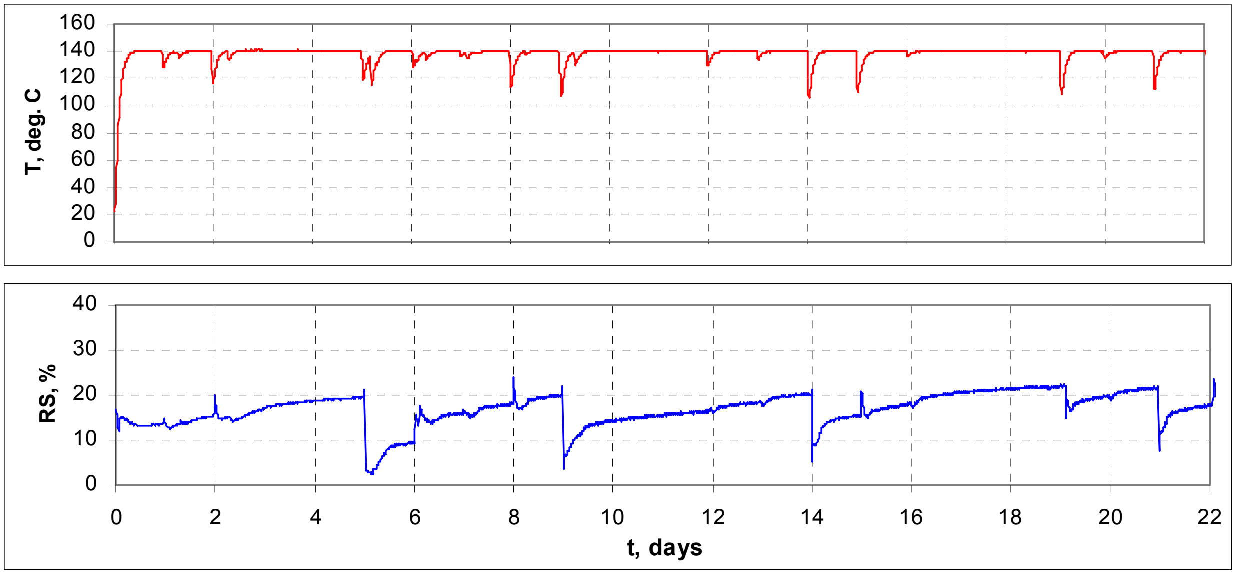


Figure 1-18
DP for Paper Samples in Run 5(H)

Figure 1-19 shows the amount of oxygen added into the test rig of Run 5(H).

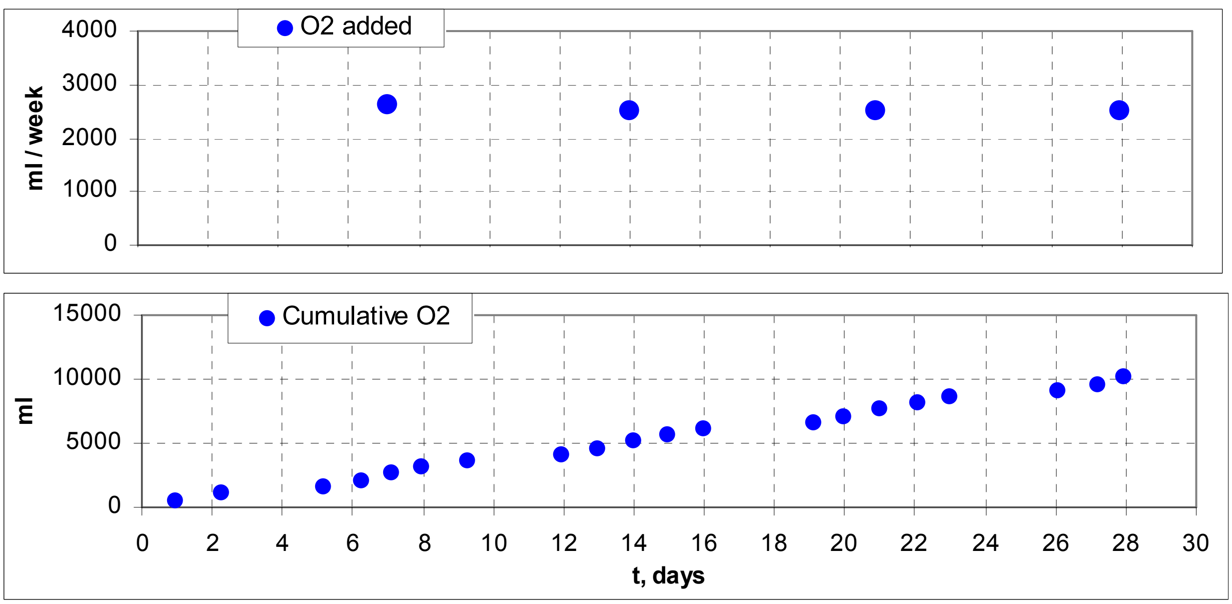


Figure 1-19
Amount of Oxygen Added into Test Rig of Run 5(H)

The dissolved gas analysis of other gases during the test is shown in Figure 1-20.

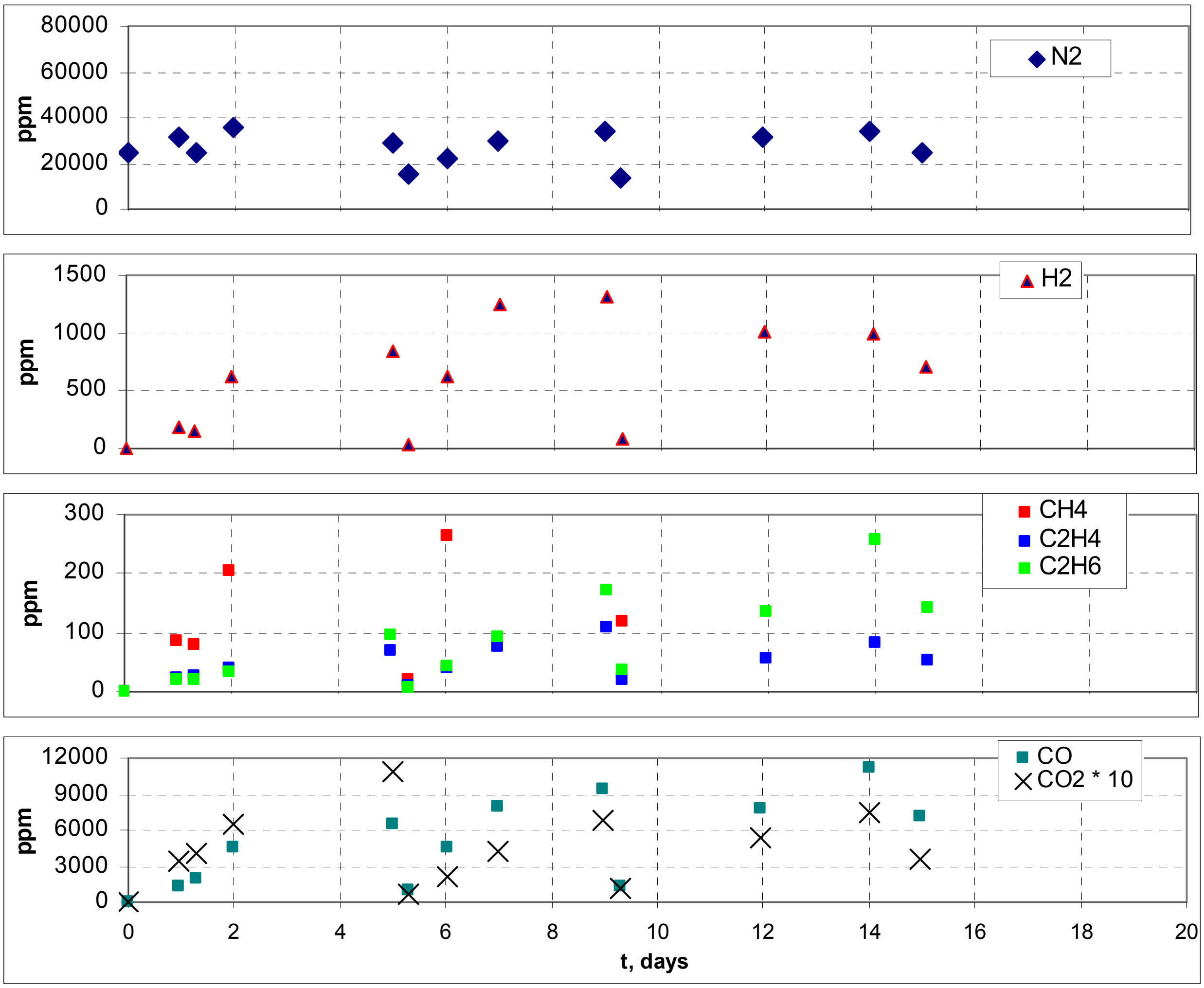


Figure 1-20
Concentrations of N2, H2, CH4, C2H4, C2H6, CO and CO2 during Run 5(H)

Paper samples were taken for the DP measurements. The results of these tests are shown in Figure 1-21.

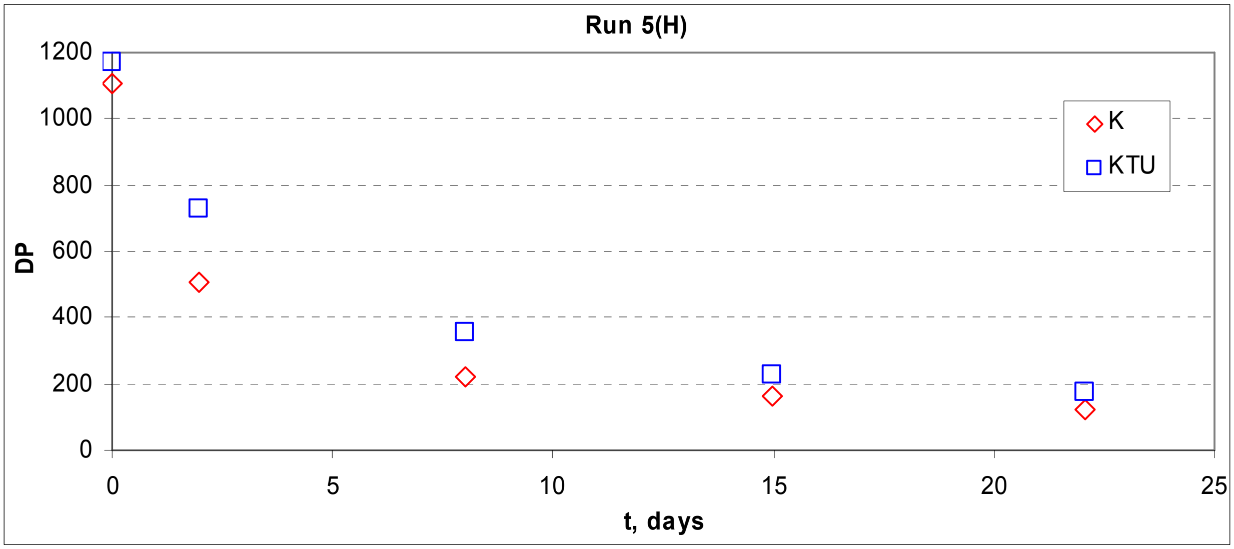


Figure 1-21
DP of Paper Samples during Run 5(H)

The results of physicochemical tests of oil samples taken after completion of the test are shown in Table 1-7.

Table 1-7
Results of Furans and Physicochemical Analyses of Oil for Run 5(H)

Day of sampling	Furan Compounds, mg/kg (ppm)					Acidity mgKOH/g	Interfacial Tension Dynes/cm	Inhibitor %	Color
	2-FAL	5HF	2-FOL	2AC	5MF				
29	ND	7.57	110.0	1.68	3.38	0.28	26	0.06	L8.0

Test Results for Run 8(H)

Run 8(H) was conducted at the following conditions:

- T = 120 °C
- $WCPa_i$ • 0.5%
- O2: High Level.

During this test run, moisture was generated at a moderate rate. The moisture content of the paper-oil system was controlled by replacing wetter pressboard coils with drier ones periodically. Oxygen was added to the oil regularly.

The temperature and relative saturation of oil during the test are shown in Figure 1-22.

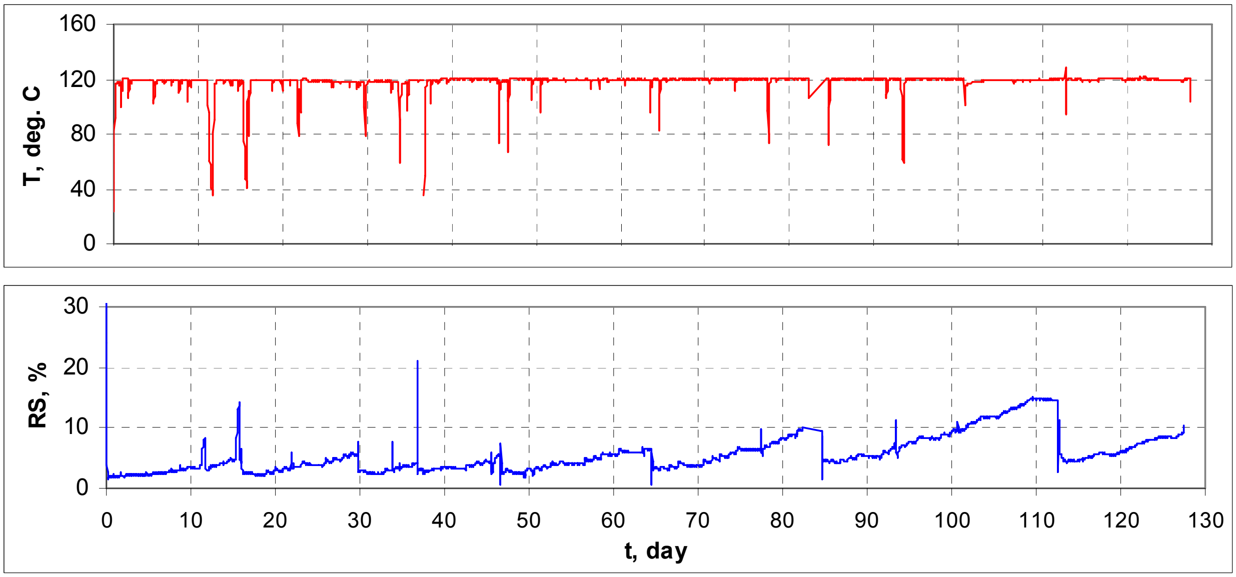


Figure 1-22
Temperature and RS during Run 8(H)

Figure 1-23 shows the amount of oxygen added into the test rig of Run 8(H).

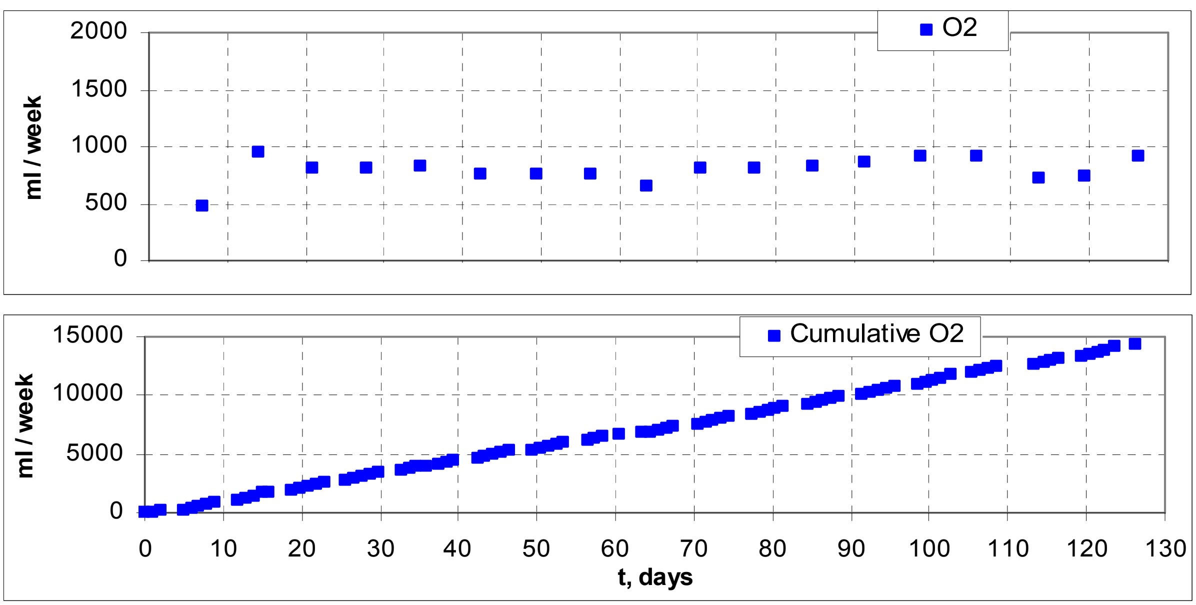


Figure 1-23
Amount of Oxygen Added into Test Rig during Run 8(H)

The dynamics of the dissolved gases during the test is shown in Figure 1-24.

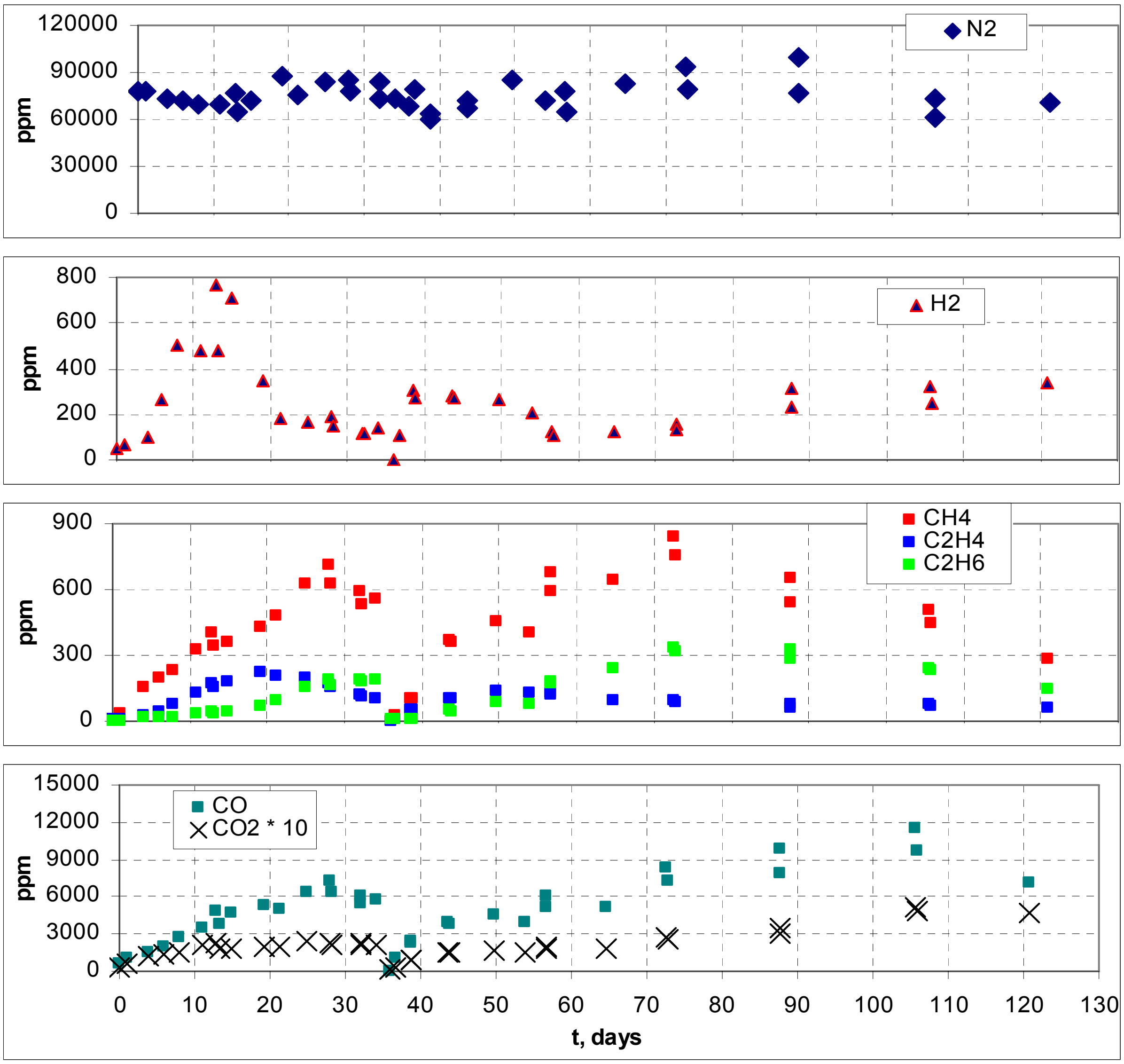


Figure 1-24
Concentrations of N2, H2, CH4, C2H4, C2H6, CO and CO2 during Run 8(H)

A few oil samples were taken during the test and sent to an external laboratory for testing of Inhibitor Content, Interfacial Tension, Acidity and Furans. The results of these tests are shown in Figure 1-25.

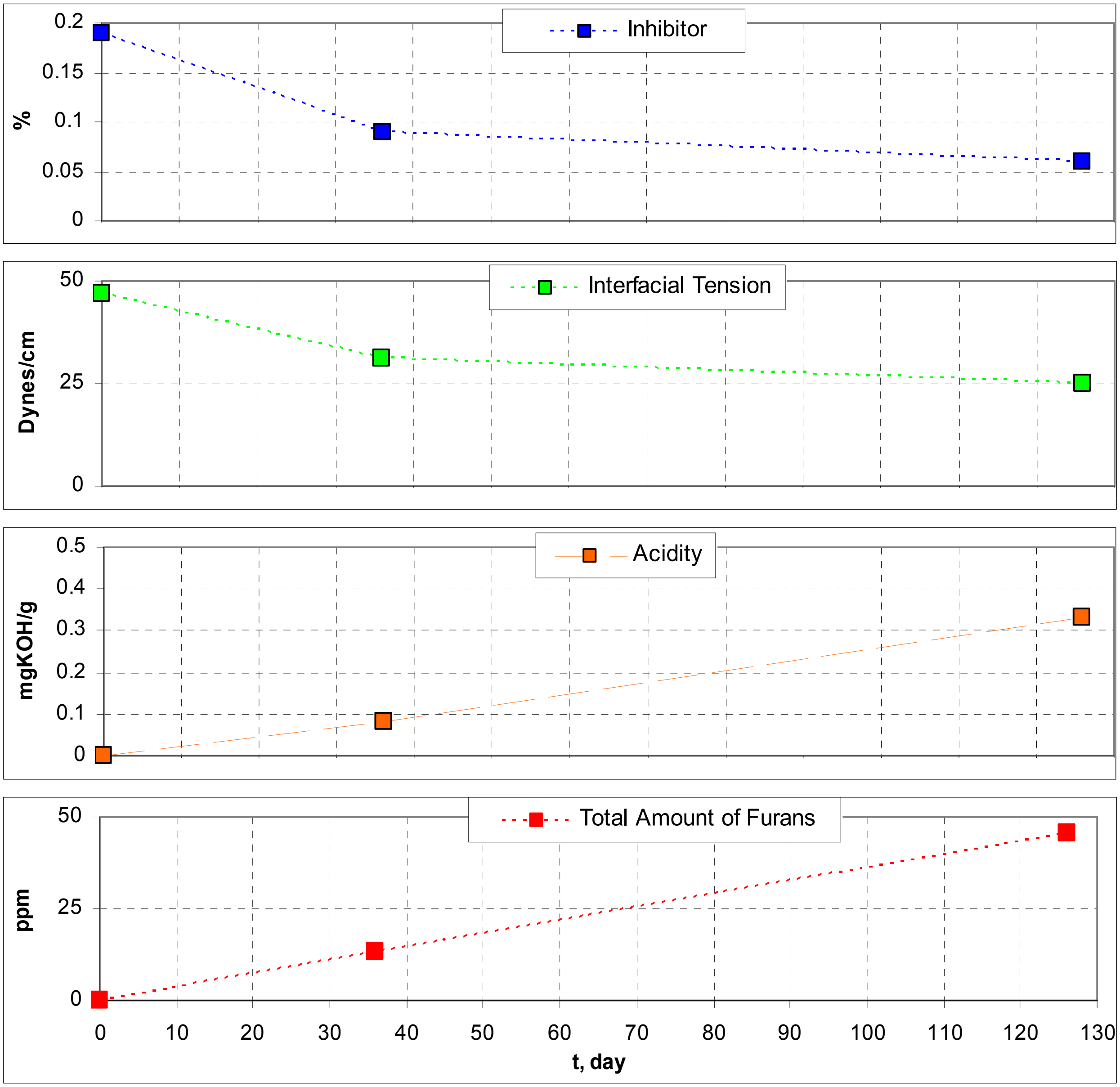


Figure 1-25
Physicochemical Analysis Results for Oil during Run 8(H)

Paper samples were taken for the DP measurements. The results of these tests are shown in Figure 1-26.

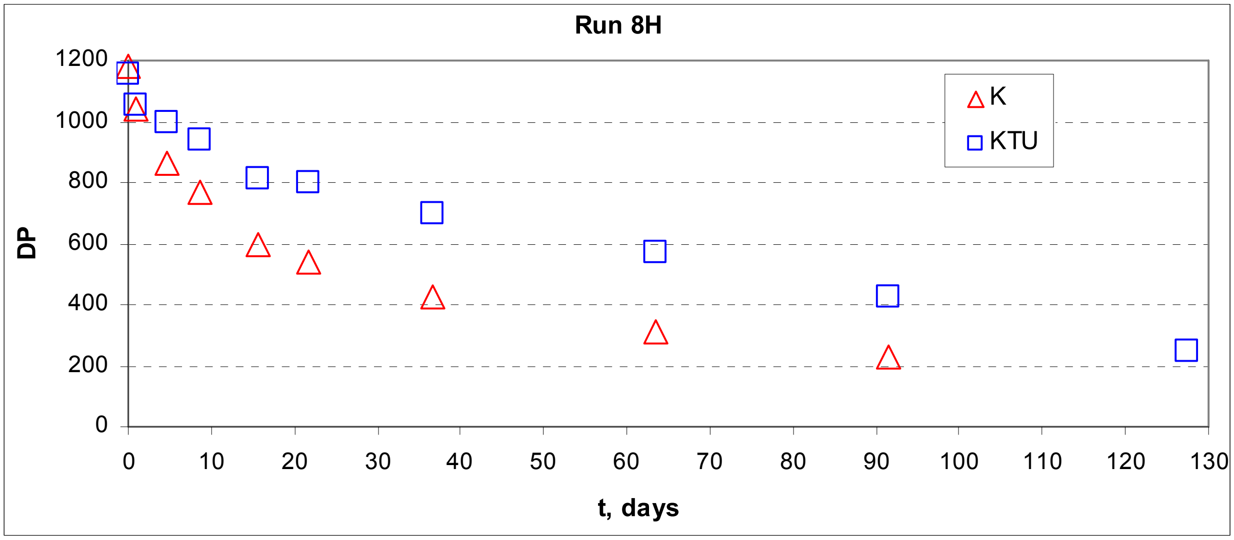


Figure 1-26
DP of Paper Samples during Run 8(H)

The results of physicochemical tests of oil samples taken at the end of the test are shown in Table 1-8.

Table 1-8
Results of Furans and Physicochemical Analyses of Oil at End of Run 8(H)

Day of sampling	Furan Compounds, mg/kg (ppm)					Acidity mgKOH/g	Interfacial Tension Dynes/cm	Inhibitor %	Color
	2-FAL	5HF	2-FOL	2AC	5MF				
127	ND	0.86	43.80	ND	1.02	0.33	25	0.06	7.0

Comparison of Test Results with Low and High Levels of Oxygen

A comparison of various test results with the low and high levels of oxygen was performed in order to illustrate an effect of oxygen, moisture and temperature on aging of K and KTU types of paper insulation.

Three levels of moisture were used to compare the rate of aging of paper insulation at 100°C and 140°C at the two levels of oxygen.

The effect of Oxygen on aging of K and KTU paper at T = 100°C and $WCPa_i$ = 2.7% can be seen in Figure 1-27.

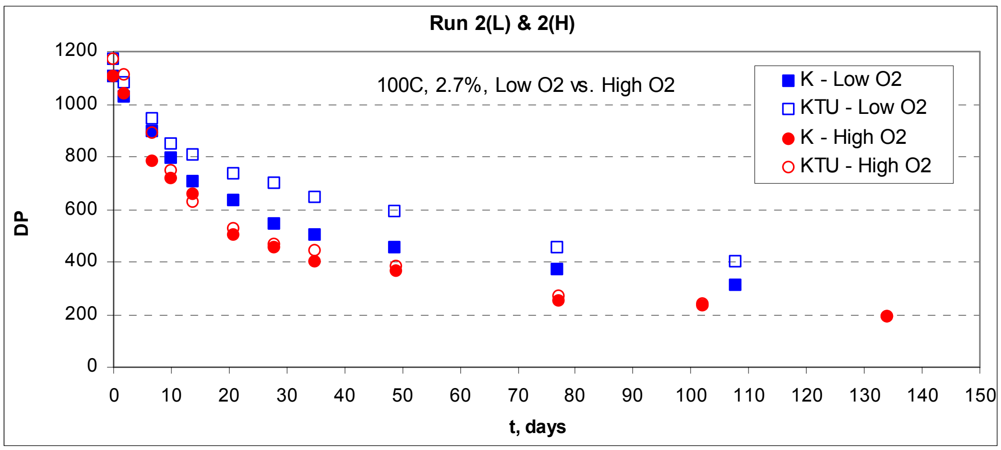


Figure 1-27
Effect of Oxygen on Aging of K and KTU Paper at 100°C and $WCPa_i$ of 2.7%

The combined effect of Oxygen and Moisture on aging of K and KTU paper at 140°C can be seen in Figure 1-28.

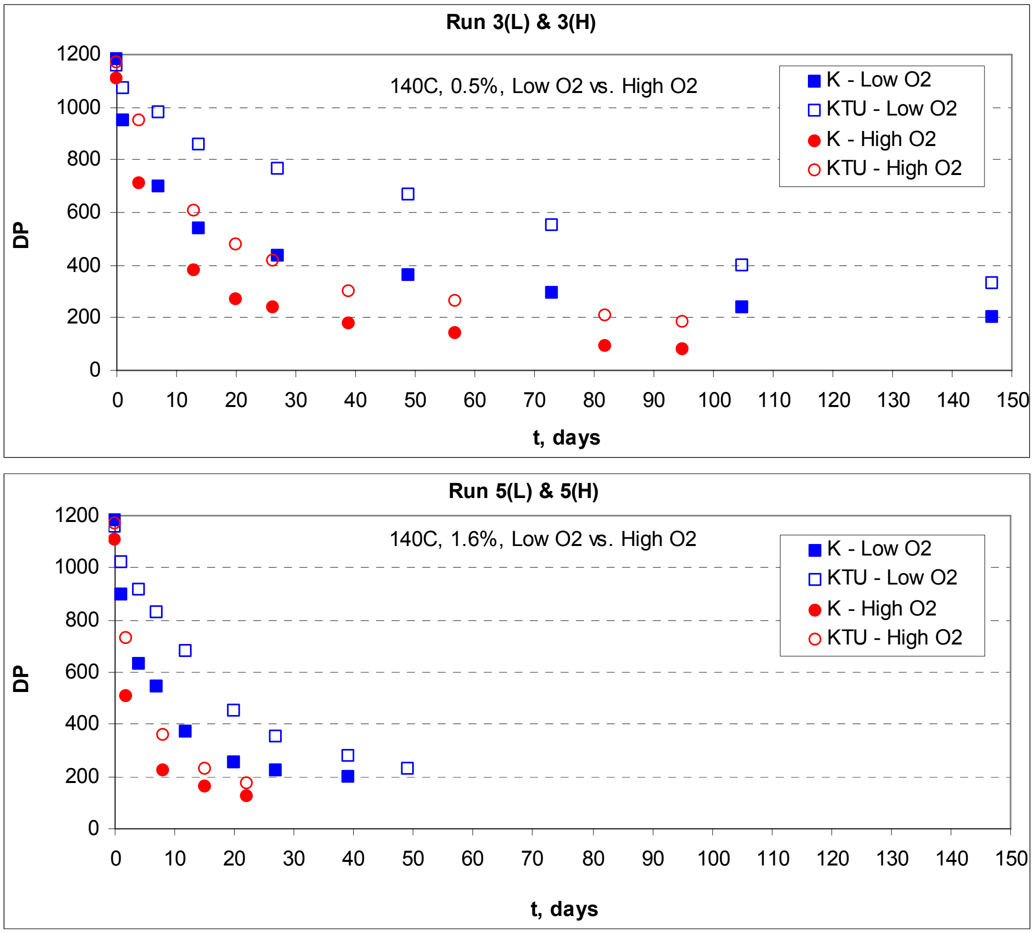


Figure 1-28
Effect of Oxygen and Moisture on Aging of K and KTU Paper at 140°C for $WCPa_i$ of 0.5% & 1.6%

The effect of temperature on aging of paper insulation at the high levels of both oxygen and moisture is shown in Figure 1-29.

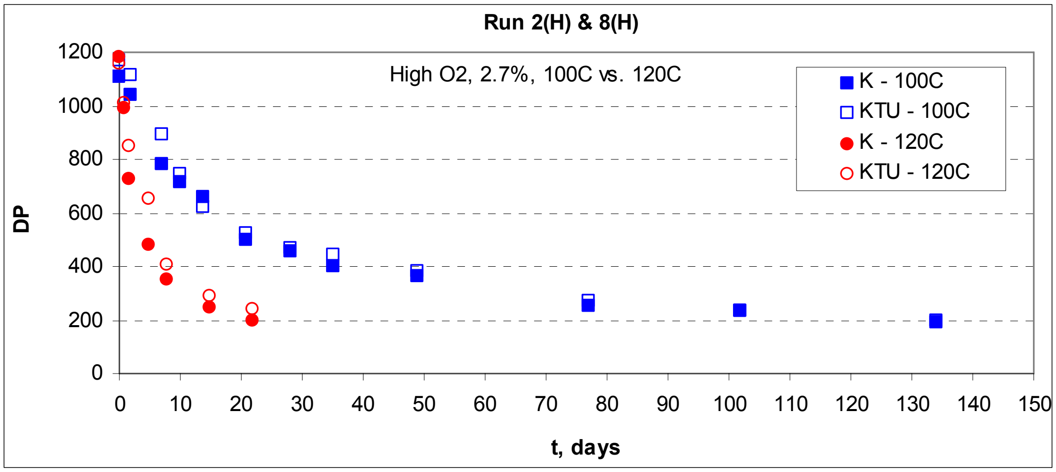


Figure 1-29
Effect of Temperature on Aging of Paper at 100°C and 120°C at High O2 and WCPa$_i$ of 2.7%

The above comparison shows that the presence of oxygen in transformer oil accelerates the aging of paper insulation at a rate of two and higher. A high level of moisture and oxygen gives the aging rate of thermally upgraded paper (KTU) similar to the normal Kraft paper (Figure 1-27 and 1-29).

Conclusions

A preliminary study has demonstrated that the relationship between WCPa and Awp for new and aged paper can be different. It was assumed that keeping a constant level of the ERS in the oil would result in the WCPa gradually changing with the changing DP.

The experimental runs into the combined effect of temperature, moisture and two levels of oxygen on the aging of Kraft (K) and Kraft Thermally Upgraded (KTU) types of paper were completed.

Increase in moisture content accelerates the aging of paper dramatically. Increase in oxygen content accelerates the aging even further.

A combined effect of the temperature, moisture and oxygen on aging of paper insulation was quantified.

For a wet and oxygen reach paper-oil complex, the KTU and K types of paper degrade at the same rate. Thus, to utilize a full advantage of the KTU winding insulation, it is vital to keep transformers with the KTU paper dry and oxygen free.

References

1. "Transformer Operating Risk Assessment: Development of Models", EPRI, Palo Alto, CA: 2005. 1008671.
2. "Operating Risk Assessment – Update on Results", EPRI, Palo Alto, CA: 2005. 1010584.
3. "Operating Risk Assessment – Update on Results", EPRI, Palo Alto, CA: 2006. 1012348.
4. IEEE Guide for Loading Mineral-Oil-Immersed Transformers, IEEE Std C57.91-1995.
5. IEEE C57.100-1999, IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers.
6. V.M. Montsinger and P.M. Ketchum, "Emergency Overloading of Air-Cooled Oil-Immersed Power Transformers by Hot-Spot Temperatures", AIEE Transactions, vol.61, 1944.
7. T.W. Dakin, "Electrical Insulation Deterioration Treated as a Chemical Reaction Rate Phenomenon", AIEE Transactions, vol.66, 1947.
8. A.M. Emsley, G.C. Stevens, "Review of Chemical Indicators of Degradation of Cellulosic Electrical Paper Insulation in Oil-filled Transformers", IEE Proc.-Science. Meas. Technol., Vol.141, No.5, September 1994.
9. Lars E. Lundgaard and others, "Aging of oil-impregnated paper in power transformers", IEEE Trans. on Power Delivery, Vol.19, No.1, Jan. 2004.

2

FIELD TRIAL OF TRANSFORMER MOISTURE MONITOR (TMM) AND TRANSFORMER DRYOUT MONITOR (TDM) SOFTWARE APPLICATIONS

Introduction

The Transformer Moisture Monitor (TMM) and Transformer Dryout Monitor (TDM) software applications are being developed by Monash University under the current EPRI supported project. In early 2006, the TDM was tested and validated in the laboratory at Monash. Later in 2006, both the TMM and TDM were tested in the field at a Melbourne based power utility. The two software applications were used for on-line assessment of the initial moisture state of an operating transformer, followed by on-line dryout of the transformer. The trial was conducted on an old 10 MVA underground substation transformer.

The project was jointly conducted by CitiPower and the Centre for Power Transformer Monitoring, Diagnostics and Life Management (CPTM) of Monash University, under the Science and Technology Innovation (STI) Program supported by the State Government of Victoria, Australia, and the industry sponsors of the Centre. A special portable hardware unit for monitoring and control of the effectiveness of the dryout process, being developed by the CPTM under the STI Program, was housing a portable data acquisition system, monitoring devices and other hardware. A locally installed computer was running the TDM in real time on-line, while the TMM was used at a later stage for analysis of the on-line data collected.

A number of publications on on-line dryout (e.g.: [2-1]…[2-5]) has appeared in recent years, which indicates a high level of interest to this topic in the industry. The CPTM-CitiPower on-line dryout project was designed in the way that a transformer under study will undergo a few rounds of dryout, each followed by a stage of moisture recovery in oil of the transformer. This approach was adopted to gain a better understanding of the moisture dynamics in the paper-oil physical complex of the transformer before, during and following its on-line dryout. By the time of the report preparation, the project was in the middle of the research program. This chapter describes the first stage of this field project.

The aims of this stage of the project were:

- To assess the initial moisture state of the transformer, and to monitor the moisture dynamics in its paper-oil complex following the dryout using the TMM
- To assess the effectiveness of on-line dryout using the TDM
- To establish an impact of on-line dryout on mechanical integrity of the windings using the FRA signatures of the transformer
- To test and improve the monitoring hardware and software being developed at Monash University.

Description of Transformer and Equipment Used

Transformer and Moisture Transmitters Installed

The 10 MVA transformer under study is located at of CitiPower's Russel Place (RP) underground substation. Nameplate and other data of the transformer are given in Table 2-1 below.

Table 2-1
Transformer Data

Parameter	Description
Transformer name	Tx1 (RP)
Transformer location	Underground
Manufacturer	Australian General Electric PTY LTD
Year of manufacture	1952
Years in operation	55
Rating, MVA	10
Loading	10-40%
Voltage (HV/LV), kV	22 / 6.6
HV power supply	22 kV 3-phase underground cable
HV/LV winding connections	Δ/Y
Core or Shell type	Core type
Cooling type	ONAN
Oil preservation	Free breathing conservator
Oil type	Unknown
Oil Volume	2295 gallons UK (approx. 10430 litres)

Two moisture transmitters were installed in the transformer in 2006: one at the top of the transformer tank and the other in the return cooler pipe (Figure 1, a and b).

a) Top of Transformer

b) Cooler Return Pipe

Figure 2-1
Positioning of Two Moisture Transmitters in Transformer

A third transmitter was installed in free air in the transformer enclosure approximately one meter from the transformer tank and approximately half way up to the height of the ceiling. The three transmitters have been connected to SCADA in September 2006. Since then, the temperature and moisture of the transformer oil has been continuously monitored as well as the air temperature and relative humidity.

Vacuum Dryout Unit

On-line dryout has commenced in November 2006. A vacuum dryout unit was used for this purpose. The dryout system consisted of a dehydration vacuum unit (with the vacuum level down to –100 kPa or 1 Bar) to remove to some extent moisture and gases from the oil, and a 5-micron filter unit to remove particles from the oil. During dryout, oil was heated by a built-in heater. The unit has a flow rate of up to 500 liters per hour.

Figure 2-2 depicts the vacuum dryout unit in operation at the substation.

Figure 2-2
Vacuum On-line Dryout Unit in Operation

Monash Portable Dryout Monitoring Unit (PDMU)

A device called Portable Dryout Monitoring Unit (PDMU) has been designed and developed under the STI Project at Monash University and field tested as part of this CPTM-CitiPower project. The purpose of this device was to provide a portable unit fitted with all necessary monitoring and communication hardware for the unmanned remote monitoring of on-line dryout.

The Monash PDMU was connected to the transformer and the vacuum dryout unit using flexible hoses for oil circulation. Oil was drawn from the bottom of the transformer by a pump of the dryout unit and circulated through the PDMU and dryout unit, and then returned back to the top of the transformer. The first field version of the PDMU is shown in Figure 2-3.

Figure 2-3
Monash Portable Dryout Monitoring Unit in Operation

The version of the portable monitoring unit used in this project contained on-line monitors and an on-board data acquisition system. Data in real time was transferred to a computer running the Transformer Dryout Monitor (TDM) software application, used for assessment of the effectiveness of the dryout.

Positions of the hardware items listed above and the oil flow diagram during dryout are shown in Figure 2-4.

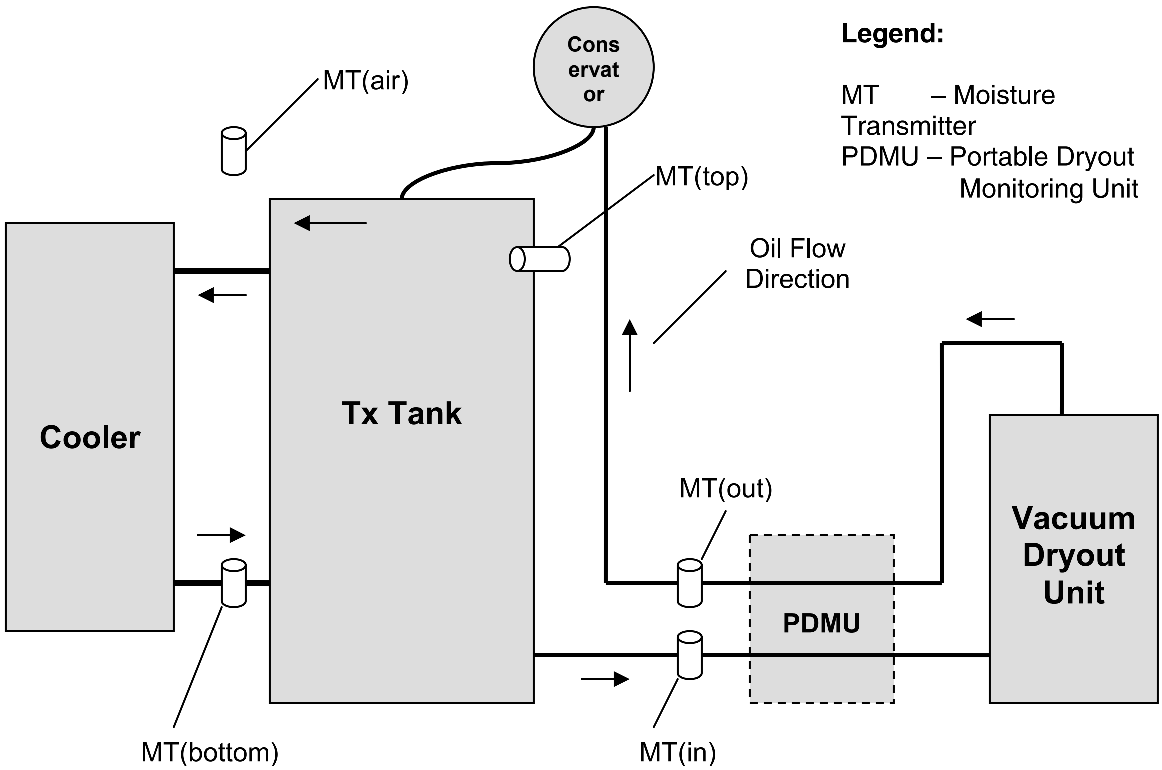


Figure 2-4
Schematic Diagram of Oil Flow during Dryout including Hardware Items

Assessment of Transformer Condition prior to Dryout

As part of initial oil quality assessment, a few oil samples were taken from the transformer and sent to a few laboratories for testing. Some of the oil samples were sent to Monash for the moisture, DGA and water-in-oil solubility testing.

Water in Oil Solubility Test Results

The water solubility of oil is expressed as S(T)=exp(A-B/T), where T is the oil temperature in Kelvin, A and B are the constants, which were determined at Monash experimentally as A=14.60, B=2899 for Tx1 (RP) transformer. The water solubility curve for this oil is compared with that for new oil in Figure 2-5.

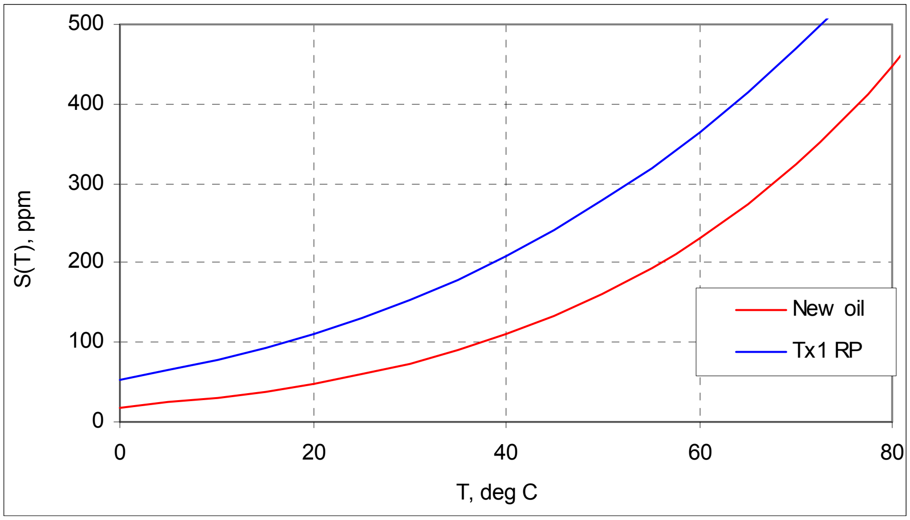


Figure 2-5
Water Solubility Curves for Tx1 RP Transformer and New Oils

The comparison of the water-in-oil solubility curves in Figure 2-5 indicates a very poor condition of the oil tested.

Moisture Assessment of Transformer Prior to Dryout

Variations in the load, temperature (T), relative saturation (RS) and water content of oil (WCO) recorded prior to dryout are shown in Figure 2-6.

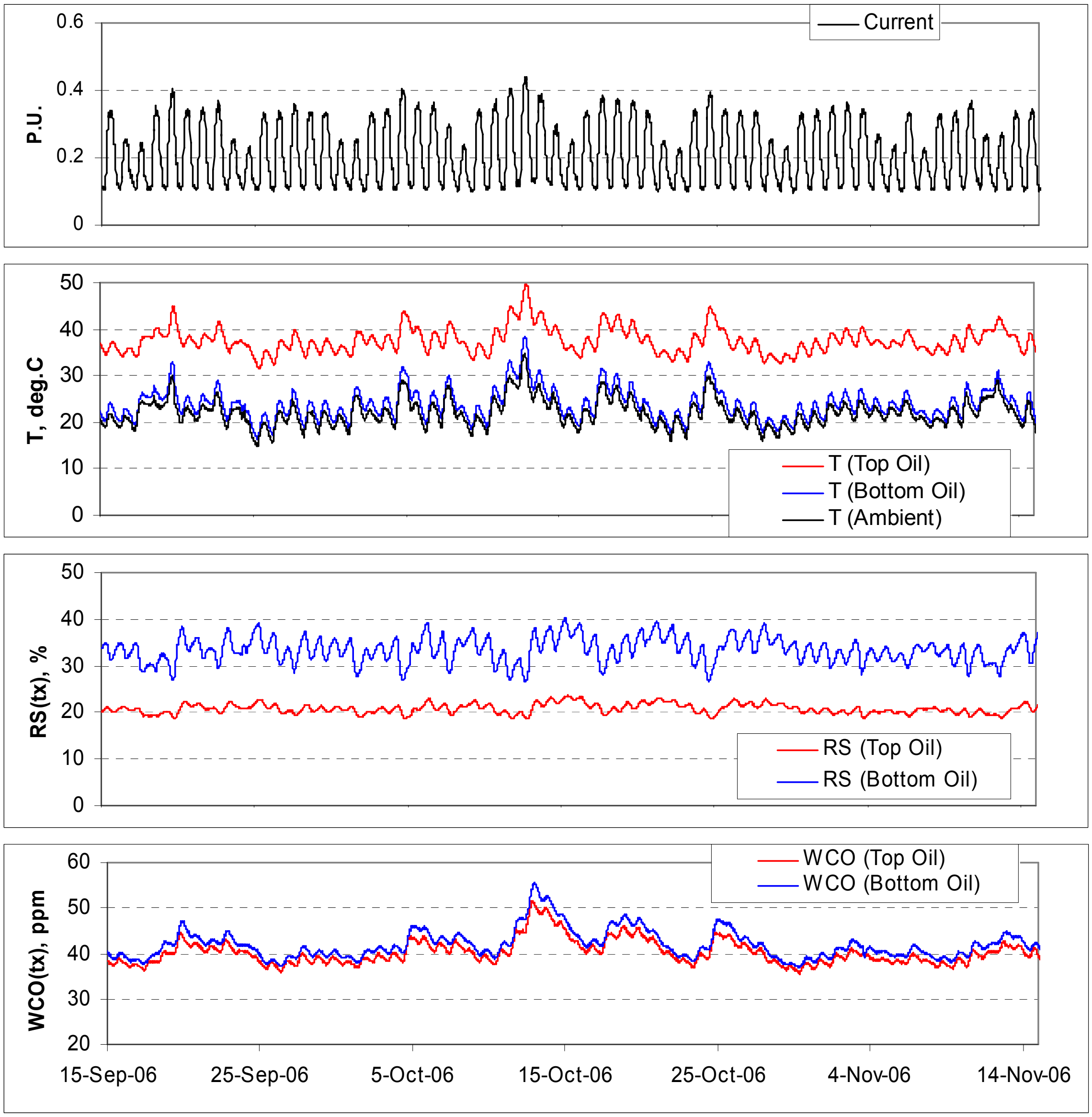


Figure 2-6
Load, T, RS and WCO in Transformer prior to Dryout

For the data recorded prior to dryout (see Figure 2-6), the active water content of paper (WCPa) was evaluated using the Transformer Moisture Monitor (TMM) software as follows:

- Top Tank: WCPa = 3.6% at Confidence Level of 0.60;
- Bottom Tank: WCPa = 5.4% at Confidence Level of 0.38.

Results of First Round of Dryout

Transformer Dryout Monitor (TDM)

The TDM software is being developed at Monash University under the EPRI funded project. The software performs a number of functions: it assesses the initial values of the active water content of paper (WCPa) in % and the Water-in-Paper Activity (Awp) parameter, calculates the water content of oil (WCO) in ppm, predicts the optimum remaining time of dryout, calculates the moisture extraction rate and the amount of water, in grams, extracted during dryout. A screenshot of the interface of the TDM is given in Figure 2-7.

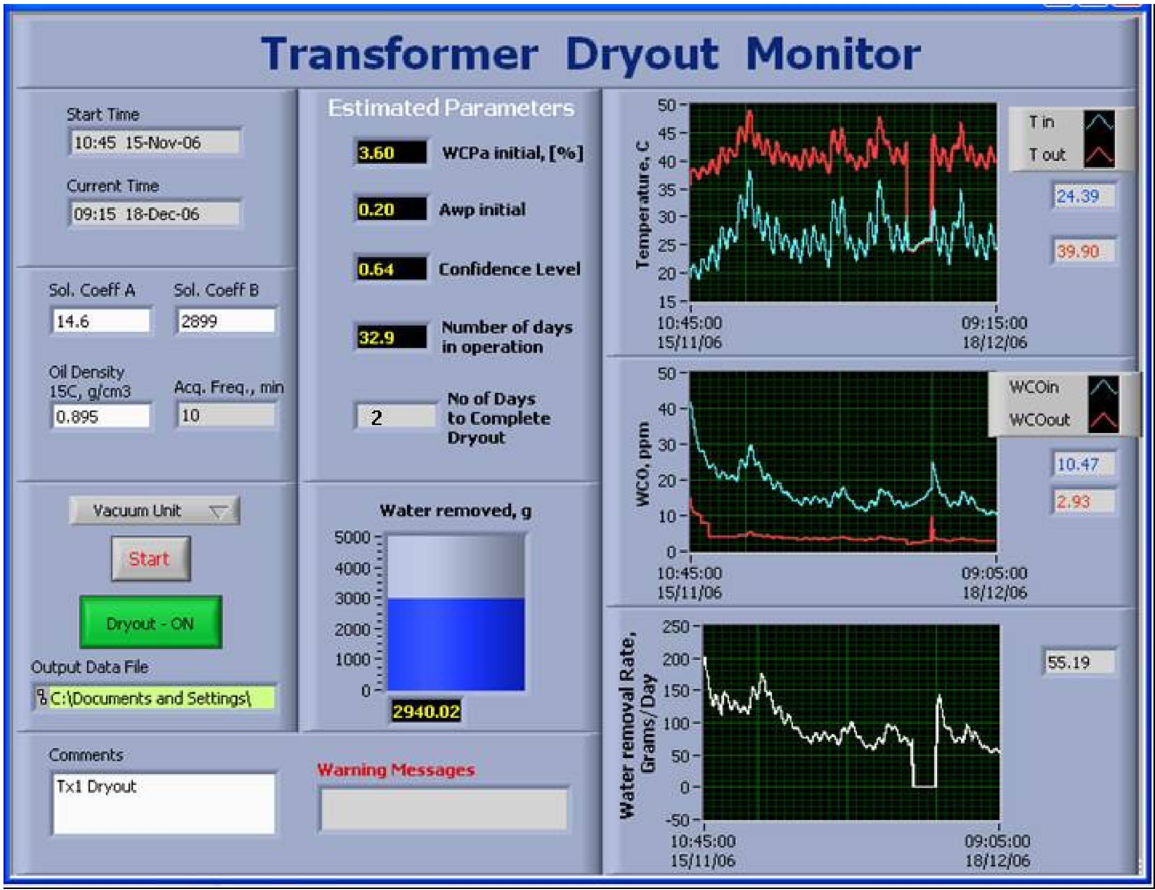


Figure 2-7
TDM Interface Showing First Round of Dryout

Using the TDM, the total mass of water removed from the oil and paper during the first round of dryout of approx. five weeks was calculated as 2,940 g (see Figure 2-7).

Moisture Dynamics in Transformer during Dryout

Variations in the load, temperature, relative saturation and water content of oil recorded during dryout are shown in Figure 2-8.

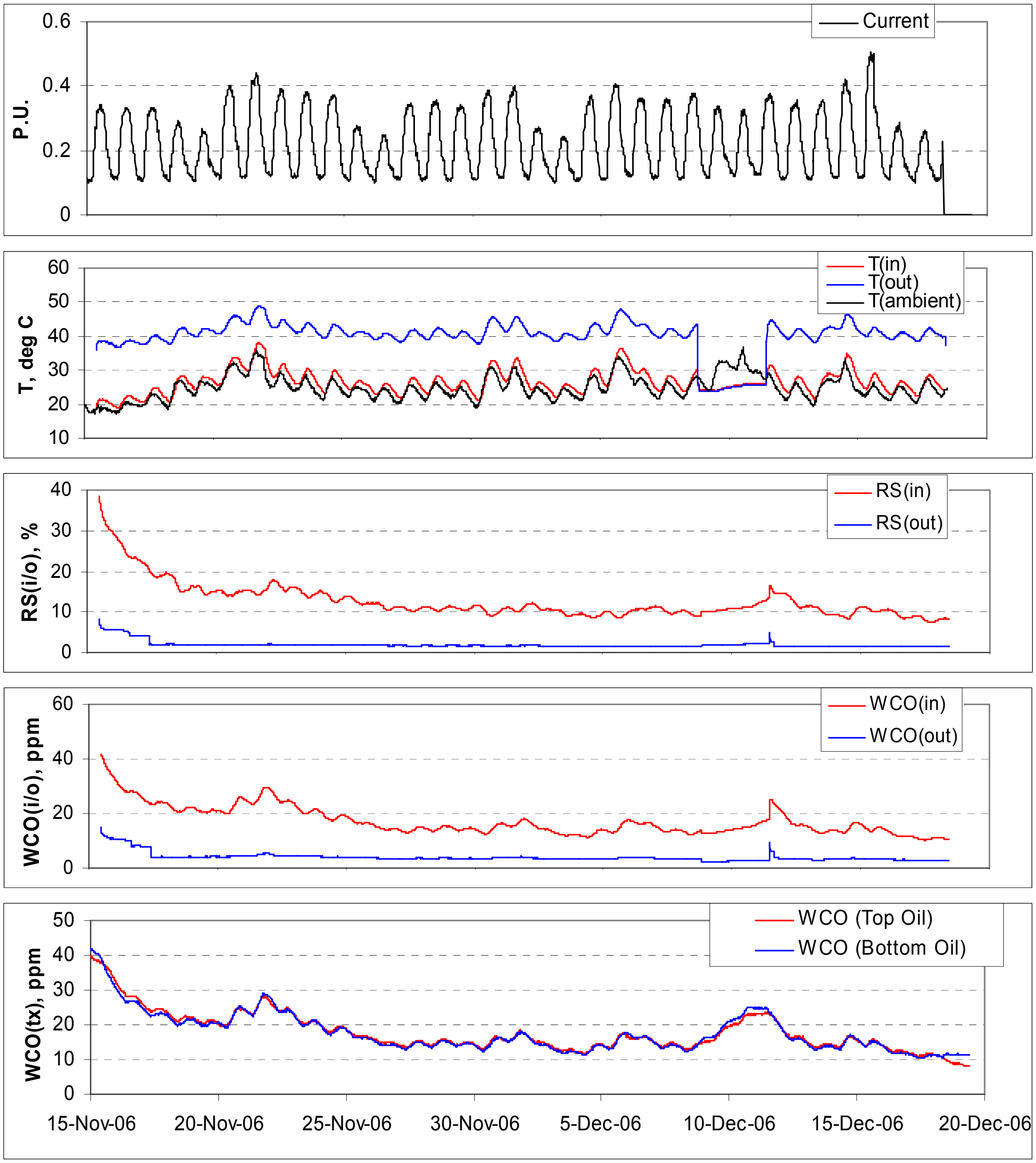


Figure 2-8
Load, T, RS, WCO at Inlet and Outlet of Dryout Unit, and WCO in Tx during Dryout

As we can see from Figure 2-8, in the few days after the dryout had commenced, the WCO(out) has dropped to 4-5 ppm, and stayed at this level for the whole duration of this round of dryout. The difference between each reading of the WCO(in), WCO(top) and WCO(bot) was close to zero for most of the dryout duration. When for a technical reason the dryout was stopped on 8 December for three days (refer to the T graph), the WCO at the top of the transformer increased from 12 to 23 ppm, while the WCO at the bottom of the transformer increased from 12 to 25 ppm (see the last WCO graph). At the end of dryout the WCPa was evaluated using the TMM software as follows:

- Top Tank: WCPa = 1.6% at Confidence Level of 0.46;
- Bottom Tank: WCPa = 2.4% at Confidence Level of 0.30.

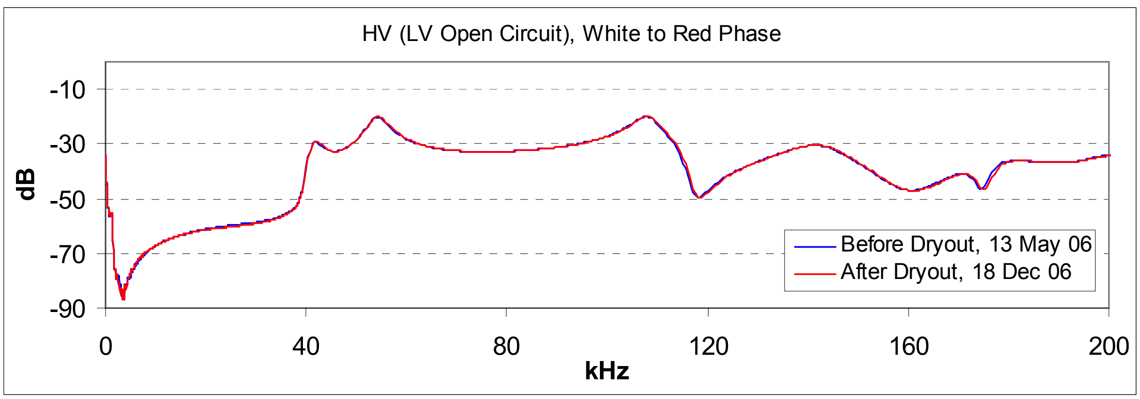
Comparison of FRA Signatures before and after First Round of Dryout

The authors of paper [2-6] have shown that changes in the frequency response analysis (FRA) plots below 1 MHz indicate mechanical changes in the windings.

In practice there are a number of parameters influencing FRA signatures. In addition to a mechanical change, the FRA response could be affected by changes in moisture and temperature of the transformer [2-2]. Moreover, the FRA response could be affected by changes in a test configuration, i.e. settings of the FRA measurement instrument and length, layout and grounding of the FRA measurement cables [2-7].

Effects of the moisture and temperature on FRA signatures have been found from tests of winding models at Monash [2-2].

The FRA signatures of Tx1 (RP) transformer, taken before and immediately after the first round of dryout, are shown in Figure 2-9 for the same windings for the frequency range of 0-200 kHz and 0-2000 kHz.



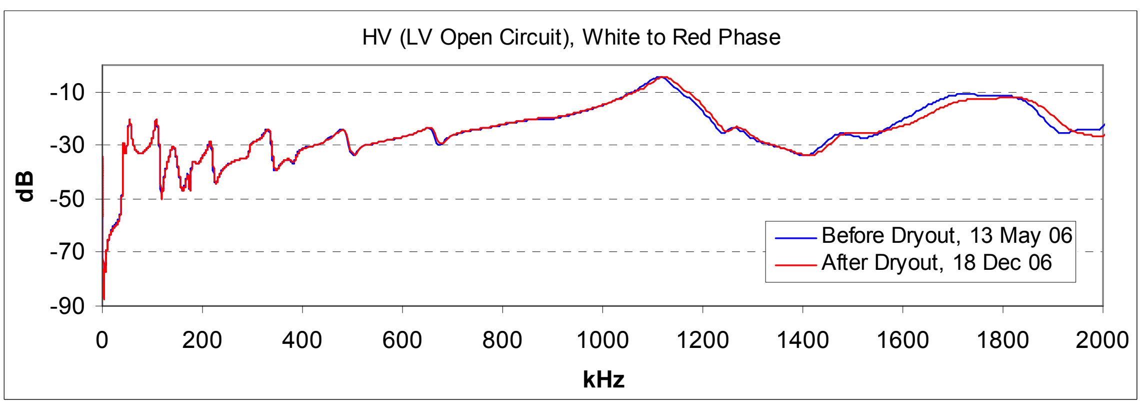


Figure 2-9
Comparison of FRA Signatures before and after Dryout

The FRA signatures taken before and after dryout show that no changes have occurred in the frequency range below 1 MHz. This fact confirms that no winding looseness was introduced by dryout.

In contrast, in the frequency range above 1 MHz some changes in the FRA signatures were observed. Because the top oil temperature in the transformer during the both FRA measurements was in the same range of 35-38 °C, the effect of temperature on the FRA response can be eliminated. The effect of the test configuration was eliminated too – the same measurement gear, cables and connections were used during the two FRA tests. Thus, the only factor affecting the FRA response after dryout was the change in the moisture content of paper insulation. The Monash experience reported in [2-2] shows that as dryout progresses the FRA curve shifts to the right. The same effect has been observed with Tx1 (RP) (see Figure 2-9). This fact tends to indicate that some moisture was removed from paper.

Comparison of Oil Quality Parameters before and after First Round of Dryout

For the assessment of the effect of dryout on the oil quality parameters, a few oil samples were taken from the transformer before and after the first round of dryout. The oil was sampled from the top sampling port and the bottom drain valve of the transformer. The test results are shown in Tables 2-2, 2-3 and 2-4.

Table 2-2
Oil Quality Parameters before and after Dryout for Top and Bottom of Transformer

No	Parameter	Prior to Dryout: 26 Sep 06		After Dryout: 18 Dec 06	
		Top	**Bottom**	**Top**	**Bottom**
1	Oil Sample Temperature, °C	33.4	20.8	36.0	24.0
2	Moisture (Karl Fischer), ppm	38.6	38.4	-	-
3	Breakdown Voltage, kV	44	63	67	67
4	DDF at 25 °C, %	0.209	0.210	0.215	0.220
5	Resistivity (90 °C), GOhm.m	95.0	82.0	73.0	73.0
6	Acidity, mgKOH/g	0.53	0.51	0.51	0.50
7	Interfacial Tension (IFT), mN/m	17.1	16.8	18.1	17.5
8	Color	3.0	3.0	3.0	3.0
9	Inhibitor, %	0	0	0	0
10	Corrosive Sulphur	Non-corrosive	Non-corrosive	Non-corrosive	Non-corrosive
11	Furan Compounds, ppm:				
	5 hydroxymethyl-2-furaldehyde	0.002	<0.001	<0.001	<0.001
	2 furaldehyde	0.254	0.520	0.317	0.314
	2-acetylfuran	<0.001	0.003	0.003	0.003
	5 methyl-2-furaldehyde	<0.001	<0.001	0.011	0.011
	2 furfural	<0.001	<0.001	<0.001	<0.001
	Total Furans, ppm:	0.256	0.523	0.331	0.328

Table 2-3
Particle Counts before and after Dryout for Top and Bottom of Transformer

Particle Counts per 100 ml for:	Prior to Dryout: 26 Sep 06		After Dryout: 18 Dec 06	
	Top	**Bottom**	**Top**	**Bottom**
Particles 5-15 µm	17,305	68,110	4,190	201,760
Particles 15-25 µm	590	2,670	525	15,975
Particles 25-50 µm	75	695	55	2,650
Particles 50-100 µm	0	30	25	85
Particles >100 µm	0	0	5	0

Table 2-4
DGA before and after Dryout for Top and Bottom of Transformer

No	Dissolved Gas, ppm	Prior to Dryout: 26 Sep 06		After Dryout: 18 Dec 06	
		Top	Bottom	Top	Bottom
1	Hydrogen	14	14	0	0
2	Oxygen	27,314	27,826	2,459	1,570
3	Nitrogen	79,041	78,031	16,492	16,391
4	Methane	4	3	0.4	0.4
5	Carbon Monoxide	195	193	19	28
6	Carbon Dioxide	2,675	2,643	95	124
7	Ethylene	2	2	0	0
8	Ethane	1	1	0	0
9	Acetylene	0	0	0	0

Analysis of data in Tables 2-2, 2-3 and 2-4 shows the following. In both cases, prior to and after the dryout, the particle counts at the bottom of transformer were much higher than that at the top (see Table 2-3). Initially the higher concentration at the bottom was probably due to the fact that particles were too heavy to be taken up by the natural oil flow, and for this reason concentrating at the bottom of the transformer.

After dryout, the particle counts at the bottom were significantly higher than before dryout (see Table 2-3). These higher particle counts could be due to the following possible reasons. (1) The particles from the bottom of the transformer were lifted up into the bulk oil by the oil stream forced by the pump of the dryout unit not long before the oil sample was taken. However, these additional heavy particles did not reach the top oil sampling port – for this reason the particle counts at the top after dryout were low. (2) Dryout process breaking down bits of insulation and hence adding to the particle count – if there have not been additional particles created, one would have expected a more uniform spread of the particles in the oil. (3) It could be due to some of the "sludge" being dissolved and adding to the particle count as a result of the additional heating during the process. (4) Alternatively, the filter itself added the particles.

Surprisingly, prior to dryout the breakdown voltage for the top oil was much lower than that for the bottom oil, despite the fact that DDF and Resistivity did not support the trend (see Table 2-2). Given that the moisture content of the top and bottom oil samples was almost the same, and the particle counts at the top were lower than at the bottom, there was no explanation to the discrepancy observed between the top and bottom oil breakdown voltages of 44 and 63 kV.

The dryout has resulted in some increase of the breakdown voltage for both top and bottom oil samples.

However, the dryout did not affect the other two important oil quality parameters such as Acidity and IFT (see Table 2-2). The Acidity level of 0.5-0.53 and the IFT level of 17-18 indicate an extremely deteriorated oil condition, which supports the conclusion made on the basis of the water-in-oil solubility test (see Figure 2-5).

Prior to dryout, the furan content at the bottom of transformer exceeded the furan content at the top by the factor of 2, which is an interesting observation on its own. After dryout, the furans were distributed evenly, and, more importantly, were not removed by the vacuum treatment from the oil (see Table 2-2). The laboratory reports state that from these furan measurements the Degree of Polymerization (DP) of paper insulation was assessed as approx. between 500 and 600.

The concentrations of dissolved gases prior to dryout were characteristic for an old free-breathing transformer and did not indicate any abnormality; the differences between the gas concentrations at the top and bottom were negligible. As expected, the vacuum dryout removed the most of the dissolved gases from the oil. For example, the oxygen content has dropped by an order of magnitude (see Table 2-4).

Recovery of Moisture in Oil following Completion of First Round of Dryout

On 20 December 2006, on completion of the FRA testing, the transformer was energized and placed on load without on-line dryout, with the aim to monitor the dynamics of moisture recovery in the transformer oil. Data on moisture recovery recorded for the first seven weeks after dryout is shown in Figure 2-10.

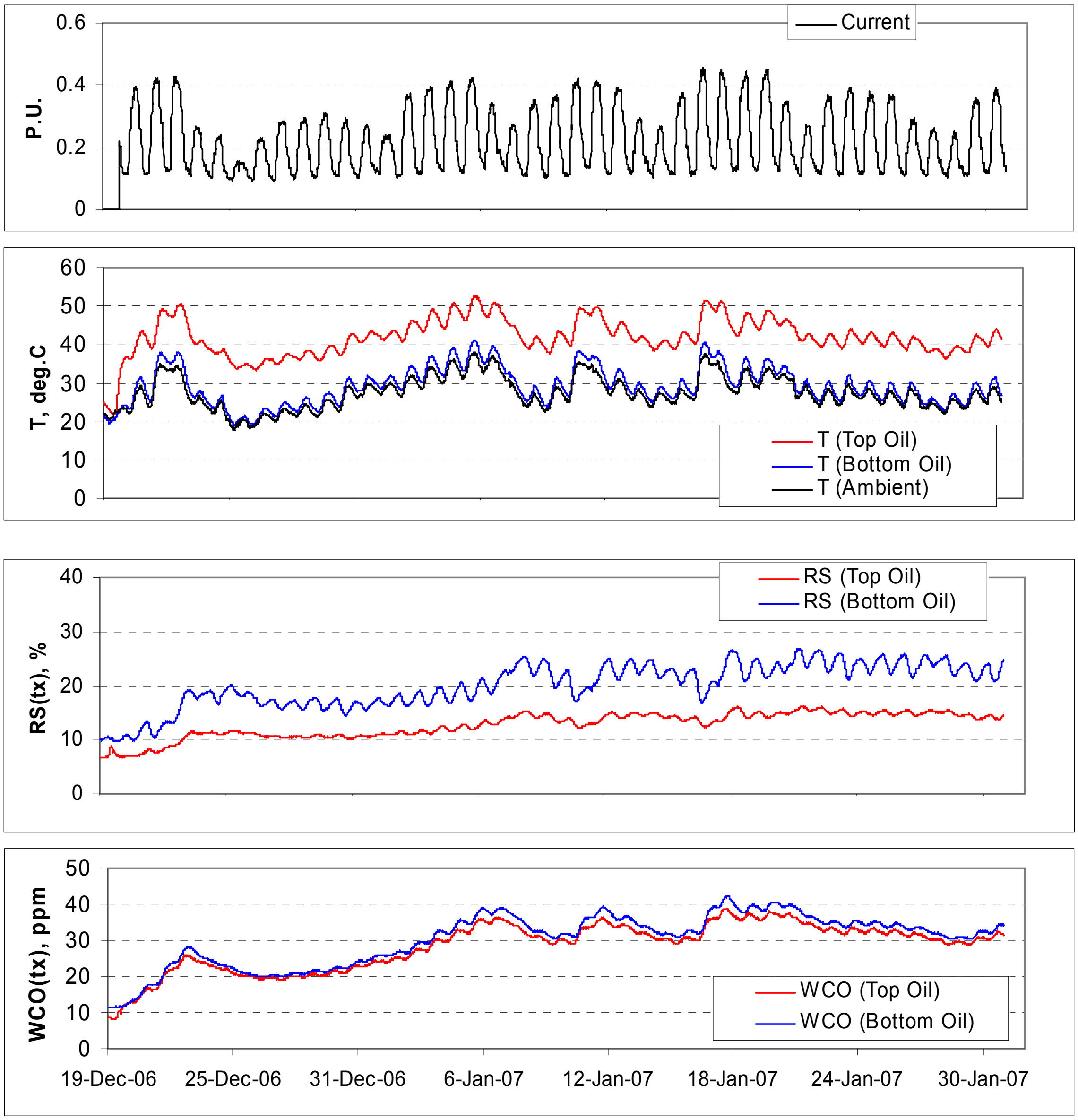


Figure 2-10
Load, T, RS and WCO in Transformer after Dryout

It is apparent from Figure 2-10 that within the first two weeks, for the T(top) fluctuating around 40°C, the WCO(top) reached 25 ppm and within approx. one more week reached 30 ppm. For comparison, prior to dryout the WCO(top) fluctuated around 40 ppm at the temperature of 40 °C.

In nine weeks after the termination of dryout, the active water content of paper (WCPa) was evaluated using the Transformer Moisture Monitor (TMM) software as follows:

- Top Tank: WCPa = 3.0% at Confidence Level of 0.64;
- Bottom Tank: WCPa = 4.4% at Confidence Level of 0.44.

Two main sources for the increase in the WCO of the transformer after dryout should be considered:

- Moisture being released into oil from paper insulation
- Moisture being absorbed by oil from atmospheric air.

As it was shown in [2-3], during on-line dryout moisture is removed form the outer layers of winding paper and surfaces of thick insulation. After completion of dryout, moisture diffuses from inner layers towards the surface of solid insulation and then appears in the oil, thus providing the first source (of the two listed above) for the WCO increase.

We know that the atmospheric moisture does represent the other source for the WCO increase. However, with the free breathing conservator it was not possible to distinguish between the two.

Discussion

It is well known that in a vessel containing oil and a gaseous headspace (e.g. air) above it, moisture migrates between the oil and the air and tends to establish equilibrium at constant temperature and constant pressure [2-8]. In other words, at T(oil)=T(air) we should have RS(oil)=RH(air).

If it were possible to have the condition of T(oil)=T(air) at a location in the transformer, and also to monitor the RS(oil) in that location for a period of time, the comparison of the RS(oil) with RH(air) versus time would provide valuable knowledge on the moisture state of the oil-paper complex against the moisture state of the atmospheric air.

Given that the oil temperature in the cooler return pipe is the closest one to that of the surrounding air (the oil temperature in the cooler return pipe is higher than the air temperature by about 2 °C), we were able to compare the humidity levels in the two media, oil and air, with an acceptable degree of inaccuracy. As it was mentioned before, such comparison would be absolutely valid only for the condition when the oil temperature equals the air temperature: in this case the RS(oil) values in our transformer would be higher then the recorded in the cooler return pipe by a few per cent only.

The comparison of the ambient temperature and humidity with that for the cooler return pipe oil prior to dryout is shown in Figure 2-11, and after dryout – in Figure 2-12.

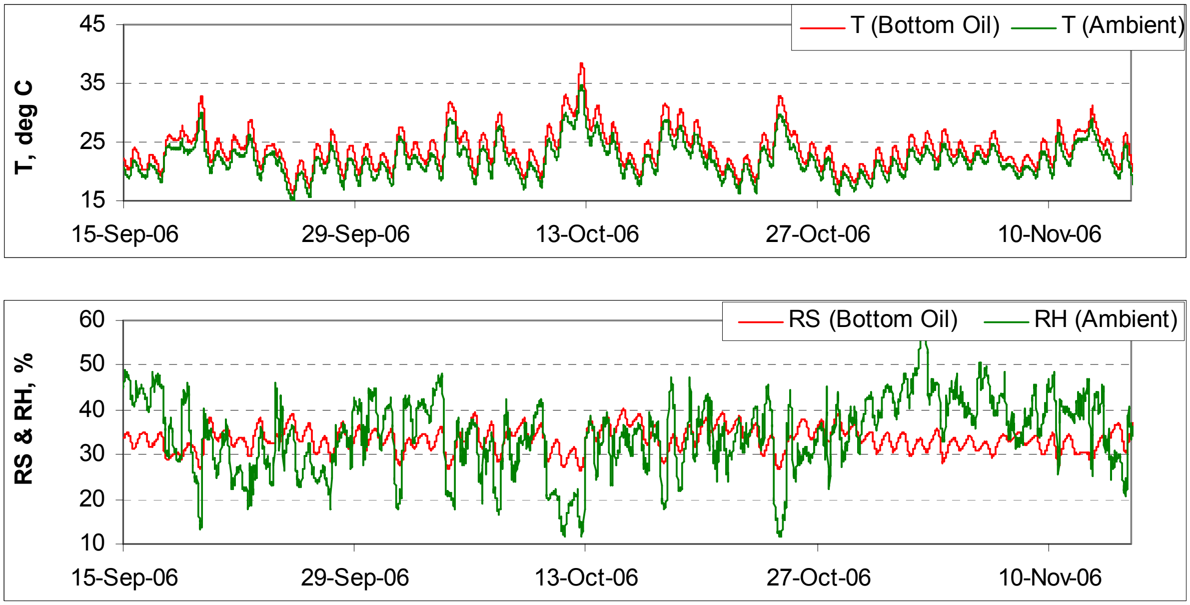


Figure 2-11
Comparison of Temperature and Humidity of Air and Oil in Return Cooler Pipe before Dryout

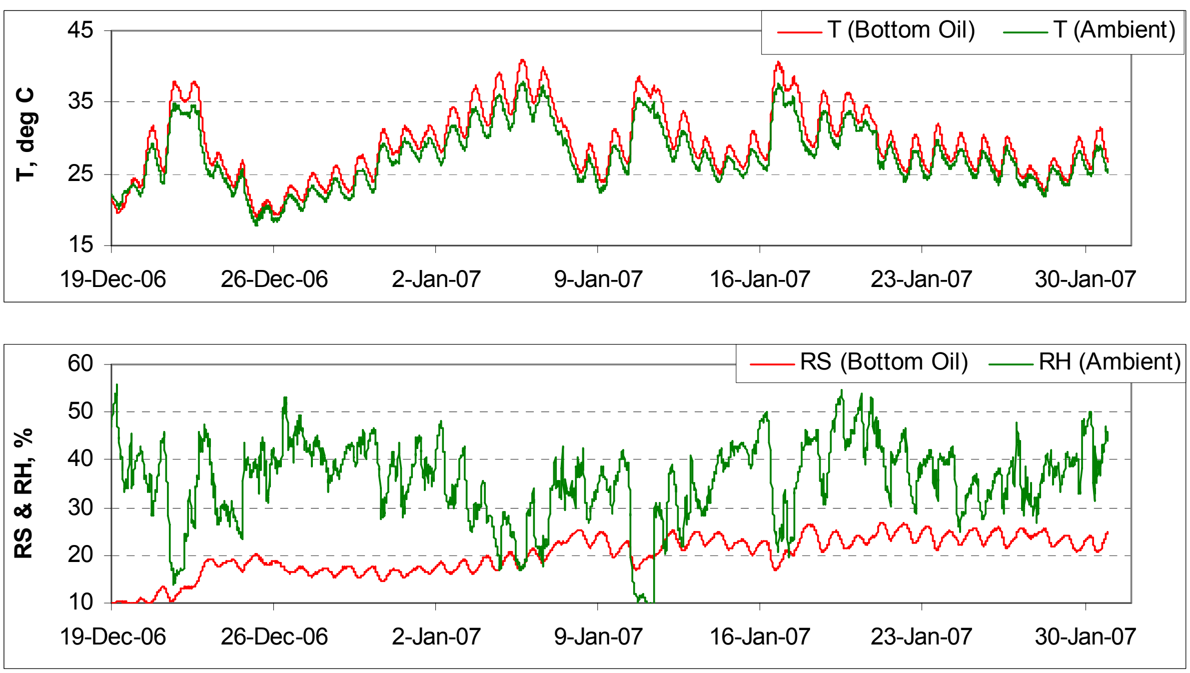


Figure 2-12
Comparison of Temperature and Humidity of Air and Oil in Return Cooler Pipe after Dryout

From Figure 2-11 we can see that before dryout the RS(oil) and RH(air) values were varying within the same range. After dryout, Figure 2-12 shows how the gap between the RS(oil) and RH(air) reduces with time; no doubt, with time the picture will look as in Figure 2-12.

From the observation provided in Figures 2-11 and 2-12 we can conclude that the oil and air are not far from establishing dynamic moisture equilibrium.

Absorption of moisture from the air in a free breathing transformer occurs at the interface between the air and the oil in the conservator. In the free-breathing conservator, the temperatures of oil and air at the oil-air interface are equal. Thus, in the conservator, in periods when RS(oil)<RH(air), oil absorbs moisture from air. Daily, as a result of thermal cycling, this portion of wet oil from the conservator enters the main tank during the cooling period, where the excess of moisture is absorbed by the insulation. The bigger portion of this additional moisture from oil is absorbed by the cooler insulation of the transformer (e.g. paper wraps of the bottom windings and thick pressboard and wooden constructions in the bulk oil), while the smaller portion of this additional moisture from oil is absorbed by the hotter insulation (e.g. paper wraps of the top windings and thick insulation supporting active parts of the transformer).

Because the absorption of moisture by oil from the atmosphere is a continuous process that took place in T1 (RP) transformer for the 55 years of its life, the moisture content of the transformer insulation was close to its ultimate level. For example, for the bottom transformer insulation, at the RS varying in the range of 30-40%, and at the bottom oil temperature varying in the range of 15-35°C, the ultimate level of water content of paper insulation can be assessed as between 7% and 9%. For the top transformer insulation, at the RS varying in the range of 20-25%, and at the top oil temperature varying in the range of 30-50°C, the ultimate level of water content of insulation can be assessed as between 4.5% and 5.5%. The assessments of the WCPa values at the top and bottom before and after dryout were given in the relevant sections above.

Proposed Round Two of On-line Dryout

In order to eliminate the effect of atmospheric moisture described above, it is proposed to install an oil preservation system on the transformer prior to the second round of its on-line dryout. This should allow a clearer observation of the dynamics of moisture between the insulation and oil. The authors hope to report these new future findings in another paper.

Conclusions

The TMM and TDM software developed under the EPRI research at Monash - and on-line monitoring hardware used allowed more effective management of assets.

On-line monitoring allowed more effective analysis of the dryout process, thus optimizing moisture removal and duration of dryout. Also, the on-line monitoring was vital for observing moisture coming from paper back to oil after dryout.

The short-term effectiveness of on-line dryout has been demonstrated as the transformer became dryer than it was before.

Dielectric strength of oil has improved: the breakdown voltage has increased from 44/63 kV (top/bottom oil samples) before dryout to 67/67 kV after dryout.

Absence of a mechanical change following the first round of dryout has been proven by the FRA plots reported.

References

2-1. Tenbohlen S. at al., “New Concept for Prevention of Aging by Means of On-line Degassing and Drying and Hermetically Sealing of Power Transformers”, Paper A2-204, Paris CIGRE Session 2004

2-2. P. Guuinic, M. Pristchepa, B. Ward, V. Davydov, A. Reykherdt and O. Roizman, “On-line Dryout of Transformer Insulation at EdF: Lessons Learned”, Proceedings of EPRI Substation Equipment Diagnostics Conference XII, 18 p., New Orleans, LA, February 2004

2-3. V.G. Davydov and O.Roizman, “Experience with On-line Drying of Two Power Transformers”, Proceedings of TechCon2005 Asia-Pacific, p. 3-24, Sydney, 4-6 May 2005

2-4. M. Cropp, “Managing Water Levels in Dielectric and Transformers using On-Line Drying Systems”, Proceedings of TechCon2005 Asia-Pacific, p. 105-117, Sydney, 4-6 May 2005

2-5. C. Feely, “Transformer Moisture Monitoring and Dehydration – Powercor Experience”, Proceedings of TechCon2005 Asia-Pacific, p. 239-254, Sydney, 9-10 May 2006

2-6. B. Finlay, “Transformer Condition Diagnosis using Frequency Response Analysis”, Proceedings of TechCon2005 Asia-Pacific, p. 141-157, Sydney, 9-10 May 2006

2-7. P. Picher and C. Rajotte, “Comparison of FRA and FRSL measurements for the detection of transformer winding displacement”, CIGRE Transformer Colloquium, Merida, Mexico, 2003

2-8. R. B. Kaufman, E. J. Shimanski, and K.W. MacFadyen, "Gas and Moisture Equilibriums in Transformer Oil". Trans. AIEE, vol. 74, 1955.

3
DEVELOPMENT OF TRANSFORMER MOISTURE ASSESSOR (TMA) WORKBOOK

General Description of TMA

The **Transformer Moisture Assessor (**TMA), a Microsoft Excel workbook, is a collection of spreadsheets dedicated to analysis of moisture state of power transformers.

The current version of the TMA, a description of which is presented in this section, is not the final version. The description given below outlines a prototype of the on-going development.

The TMA workbook consists of the following spreadsheets:

1. **GUI Spreadsheet** is a spreadsheet where a user can navigate different tasks related to moisture assessment.
2. **Transformer Nameplate Data** is a spreadsheet containing transformer details.
3. **Raw Data** is the spreadsheet containing historical data extracted from a data acquisition system or SCADA.
4. **Classification Procedure** is a spreadsheet for ranking power transformer in terms of moisture. Also, this spreadsheet is used to generate the Color Classification Chart for transformer diagnostics.
5. **WCPa Calculator** is a handy calculator allowing assessment of the Active Water Content of Paper (WCPa) based on the measurement of the Water Content of Oil (WCO) and Temperature using a moisture equilibrium chart**.**
6. **Water Solubility Chart** is a spreadsheet comparing the water-in-oil solubility curves when the solubility coefficients are known. The solubility coefficients for oil from a particular transformer are evaluated by testing in a chemical laboratory of an oil sample taken from this transformer.
7. **Isotherm** is a spreadsheet to calculate a graphical relationship between the Active Water Content of Paper (WCPa) in 1-mm-thick pressboard and the Water-in-Paper Activity (Awp) at a constant temperature. Both BET and GAB formulations are offered.
8. **On-line Transformer Moisture Assessment** is a spreadsheet allowing determination of the Water-in-Paper Activity (Awp) and Active Water Content of Paper (WCPa) corresponding to the predicted Water-in-Paper Activity and other statistical parameters based on the historical data of the oil Temperature and Relative Saturation (RS).

Each spreadsheet can be used as a standalone module to perform specific analysis and calculations.

In 2008 EPRI utilities will be involved in trials of this first release – and the feedback from the members will aid in the development of the final product.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1013931

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com