Transformer end-of-life prediction (TREND)

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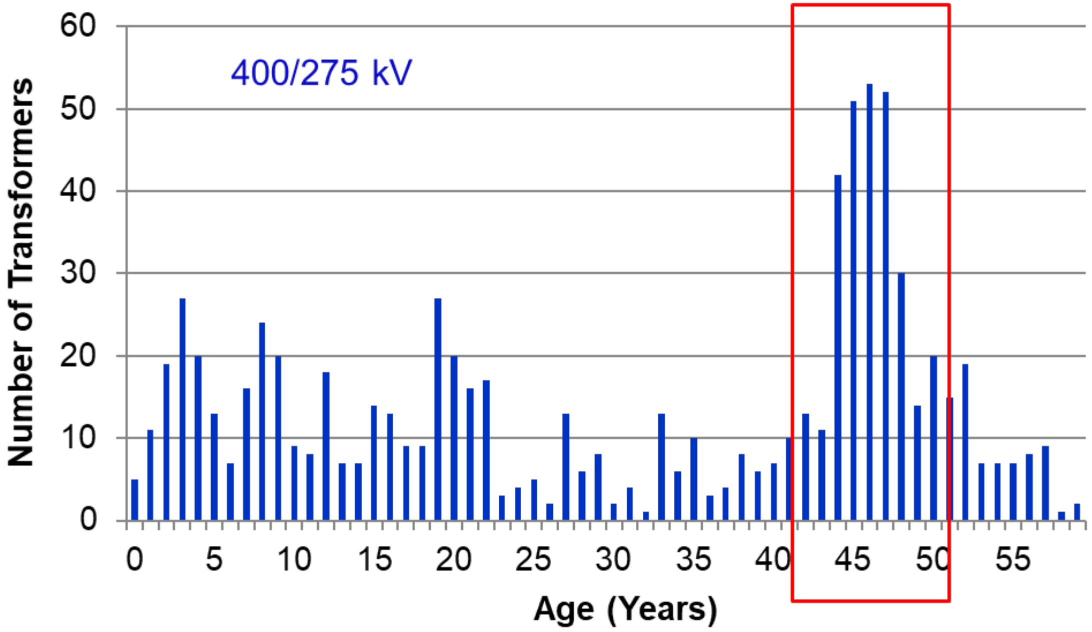
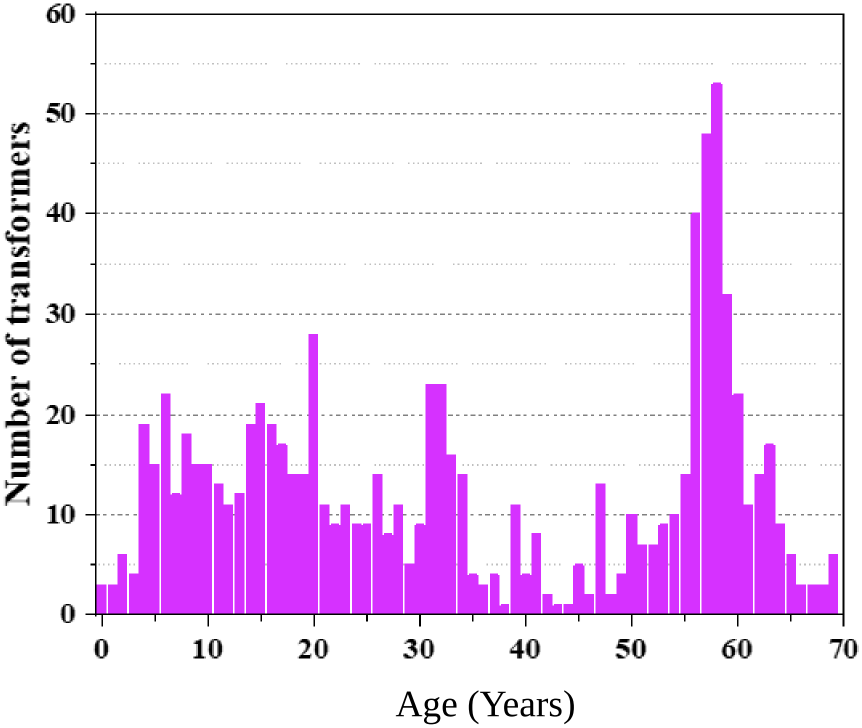
Contents

Age Profile of UK Transmission Transformer Fleet

- The UK power utilities are facing a fleet of ageing high voltage assets.
- A large population of both transmission transformers are in the age above 50 years.

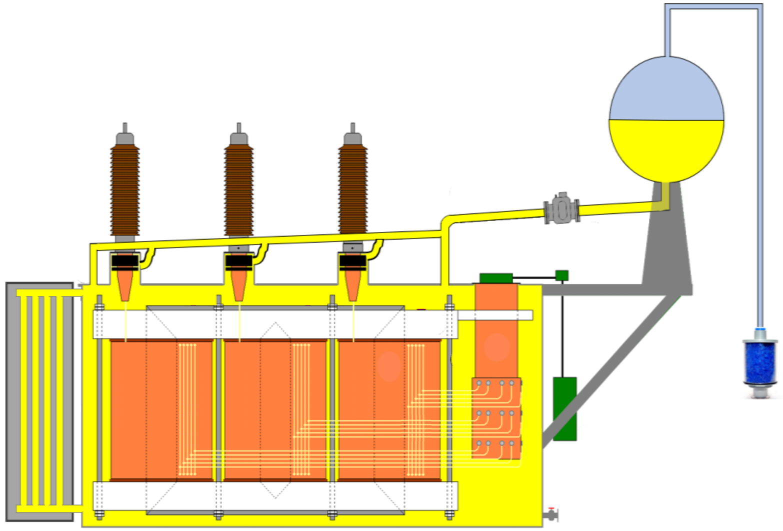


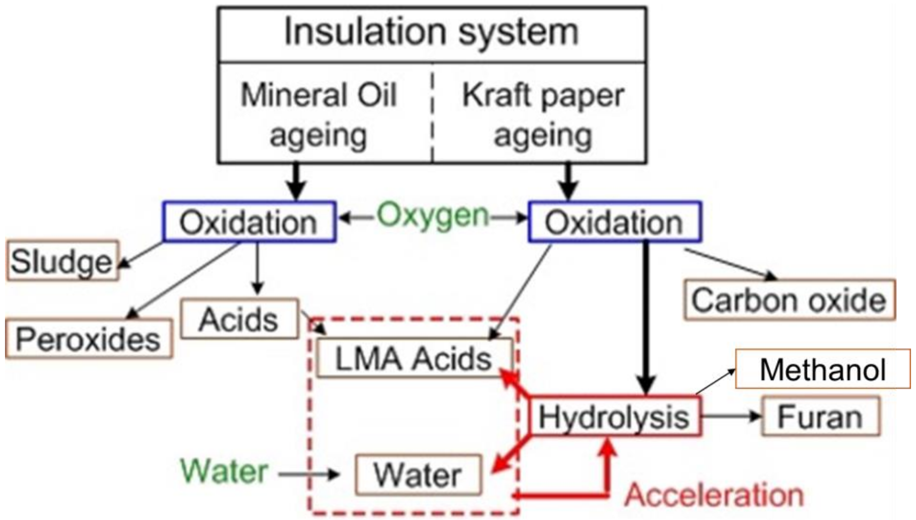
Age profile of UK transmission system transformers in 2012



Age profile of UK transmission system transformers in 2024

Ageing of Transformer Insulation





- Transformer paper insulation undergoes ageing through a combination of mechanisms including, oxidation, hydrolysis and pyrolysis
- Temperature, water and low molecular weight acids are the main factors affecting the ageing of paper insulation
- Paper ageing by-products in oil such as furanic compounds and alcohols are used to assess the ageing state of paper insulation
- The complexity of transformer ageing including non-uniform temperature distribution, stability of chemical markers, their partitioning between liquid and solid insulation, pose challenges in estimating the remaining life of transformer paper insulation

Lifetime Estimation of Transformer Paper Insulation

Life estimation of transformer insulation

Statistical modelling

- Mostly related to population analysis
- Utilises scrapped, failed and in-service transformer data
- Probability based approaches are used
- Large number of random failures compared to age related failures is a key issue

Degradation modelling

- Considers the ageing as a chemical process
- Estimated or measured temperature, water, acidity is utilised in predicting the degradation of paper insulation
- Accurate measurement or estimation of the inputs as well as selecting the kinetic model parameters are challenges

Chemical marker-based modelling

- Furanic compounds and low-molecular-weight alcohols are commonly used aging markers
- Partitioning and stability issues cause challenges in interpreting the results

Methods utilised to Study different aspects related to Chemical Markers

Chemical marker generation

- Studies with cellulose, hemicellulose and lignin compounds
- Laboratory ageing studies with oil paper insulation systems
- Molecular dynamic simulation studies

↓

Partitioning among liquid, solid and headspace

- Small scale experiments varying different conditions such as temperature, material types, water content, acidity, etc.
- Large scale experiments using transformer/winding models
- Macroscopic modelling combining diffusion and convective transfer
- Molecular dynamic simulation studies

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Stability of markers

- Small scale experiments with liquid utilising different temperature, and oil conditions
- Molecular dynamic simulation studies

Origin of Chemical Marker through Experiment

- Kraft paper consists of mainly cellulose, hemi-cellulose and lignin
- Laboratory ageing experiments are conducted with cellulose, hemi cellulose and lignin compounds as well as ageing by products of cellulose such as glucose, and levoglucosan
- Mechanisms of chemical marker generation are proposed based on the results

Yield of furanic compounds during ageing in mineral oil at 130 °C for one week (a-0.5 g , b-0.3 g)

	2-FAL
Cellulose[a]	176
Pentosans[a]	600
Lignin[a]	1.1
Levoglucosan[b]	28

Yield of methanol during ageing in mineral oil at 130 °C for one week

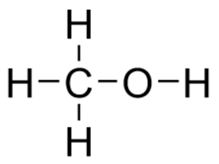
	Model compounds studied	CH_3OH μg/kg of oil/g of component
Components of Kraft paper		
α-cellulose	Microcrystals from cotton linters	8940
	Whatman paper No. 41	1730
lignin	Alkali Kraft lignin	153200
hemicelluloses from softwoods	Mannan isolated from *Saccharomyces cerevisiae*	<D.L.[b]
Hemicelluloses from hardwoods	Xylan isolated from birch	227500
Major by-product from α-cellulose hydrolysis	D-(+)-glucose	<D.L.
Major by-product from α-cellulose pyrolysis	1,6-anhydro-β-D-glucopyranose	1750
Blank oil		440

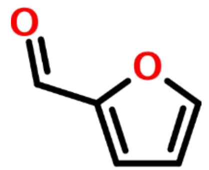
1. J. Scheirs, G. Camino, M. Avidano, and W. Tumiatti, "Origin of furanic compounds in thermal degradation of cellulosic insulating paper," Journal of Applied Polymer Science, vol. 69, no. 13, pp. 2541-2547, 1998
2. J. Jalbert, R. Gilbert, P. Tétreault, B. Morin, and D. Lessard-Déziel, "Identification of a chemical indicator of the rupture of 1,4-β-glycosidic bonds of cellulose in an oil-impregnated insulating paper system," Cellulose, vol. 14, no. 4, pp. 295-309, 2007

Methanol and 2-FAL as Ageing Indicators

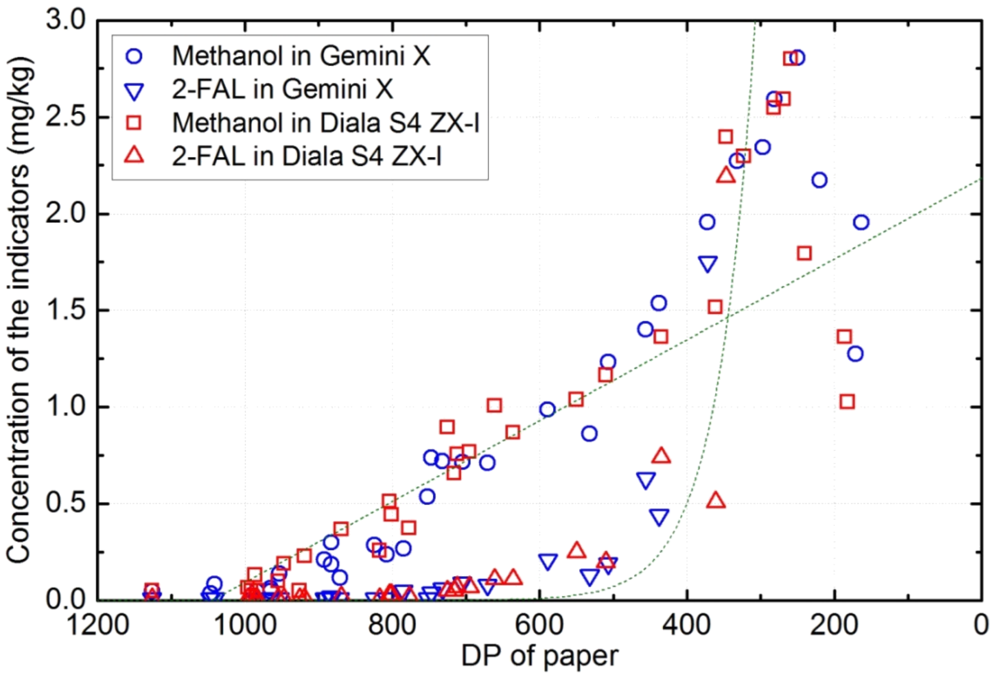
Methanol-CH3OH

2-Furfural (2-FAL) - C4H3OCHO

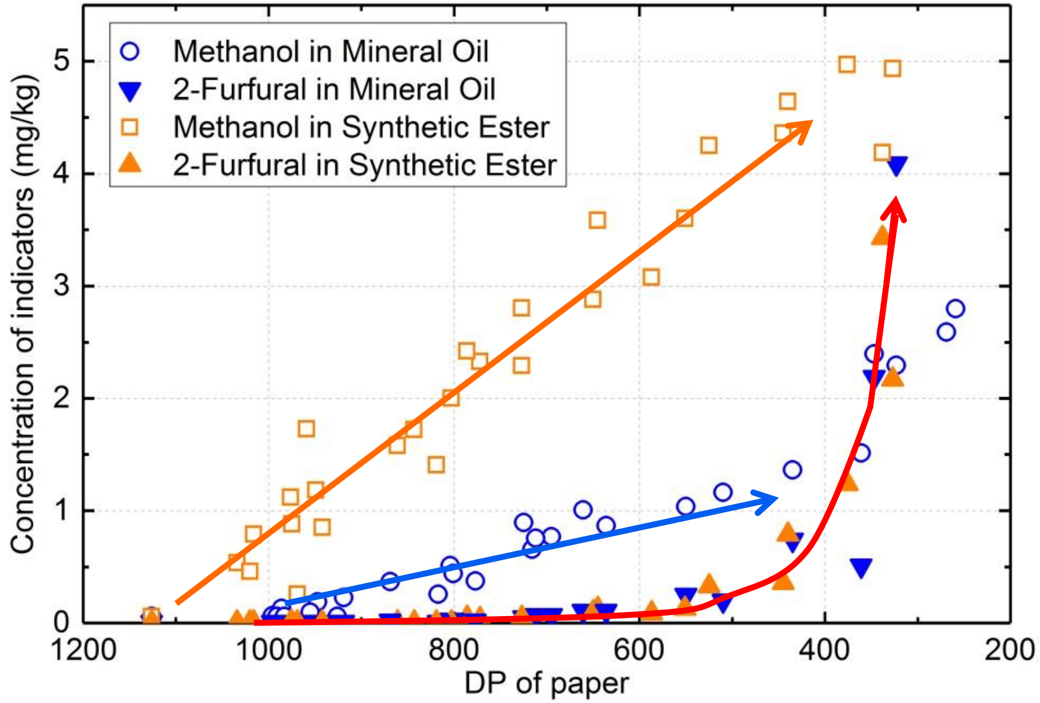




- Methanol and 2-FAL in oil are commonly used paper ageing indicators.
- Laboratory studies have shown a good correlation between the ageing of paper insulation and the chemical marker content in oil
- However, there are many challenges moving from laboratory to in-service measurement



Variation of methanol and 2-FAL against the paper ageing at 80, 100 and 120 ˚C (*UoM Results-mineral oil and GTL*)



Variation of methanol and 2-FAL against the paper ageing at 80, 100 and 120 ˚C (*UoM Results- mineral oil and synthetic ester*)

Partitioning of Chemical Markers

- S. Y. Matharage, Q. Liu, Z.D. Wang, G. Wilson, and C. Krause, "Aging assessment of synthetic ester impregnated thermally non-upgraded kraft paper through chemical markers in oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 2, pp. 507-515, 2018.
- W. Sun, and Y. Zhang, "Effects of temperature and aging on furfural partitioning in the oil-paper system of power transformers," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, no. 3, pp. 1393-1401, 2016.
- J. Hao, D. Feng, R. Liao, L. Yang, and Y. Lin, "Effect of temperature on the production and diffusion behaviour of furfural in oil–paper insulation systems," IET Generation, Transmission & Distribution, vol. 12, no. 13, pp. 3124-3129, 2018.
- Y. Lin, R. Liao, Y. Liu, H. Zhao, J. Li, and Z. Zhao, "Effects of moisture on furfural distribution and aging estimation of transformer cellulose insulation," in 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), pp. 447-450, 2018.
- J. Jalbert, M. C. Lessard, and M. Ryadi, "Cellulose chemical markers in transformer oil insulation Part 1: Temperature correction factors," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 20, no. 6, pp. 2287-2291, 2013.
- J. Jalbert, C. Rajotte, M. C. Lessard, and M. Rodriguez-Celis, "Methanol in oil interpretation model based on transformer post-mortem paper analysis," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 2, pp. 568-573, 2018.

Small Scale Partitioning Studies by External Addition of Markers

- Samples were prepared by mixing paper and new oil samples with ~5 ppm of methanol and ethanol
- Experiments at room temperature were conducted with headspace vials
- Experiments at high temperature were conducted using gas-tight syringes

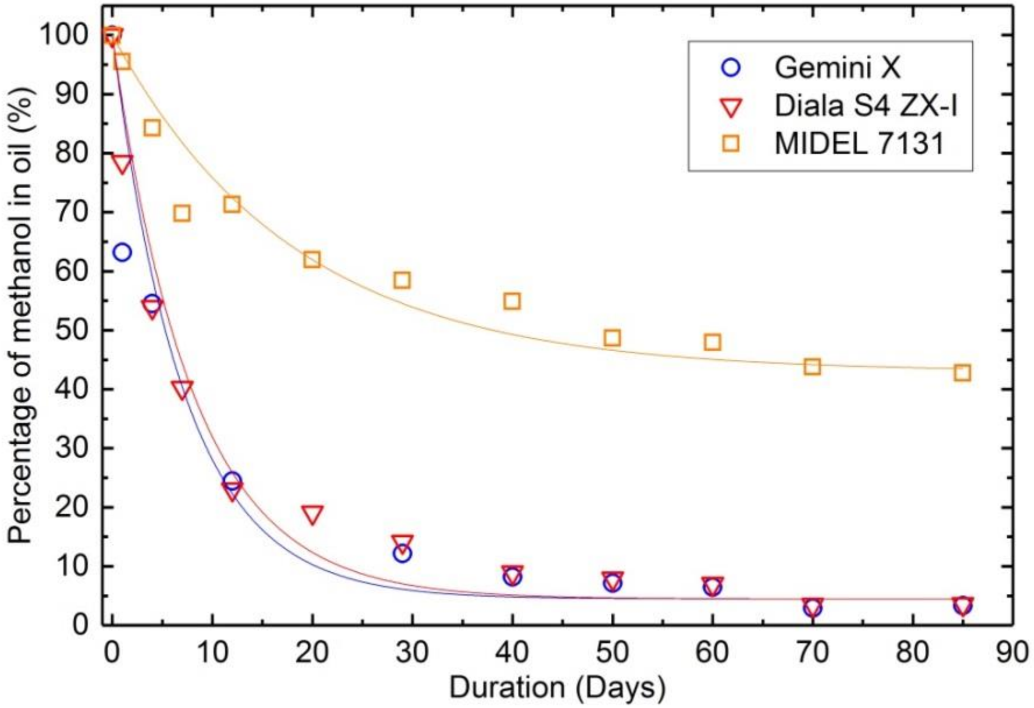
Details of the experiment

Liquid	Mineral oil (Gemini X) , Gas-to-liquid oil (Diala S4 ZX-I), Synthetic ester (MIDEL 7131)
Solid	NTU Kraft paper
Solid : Liquid	1:20
temperature	20 °C and 60 °C
Duration	Up to 90 days

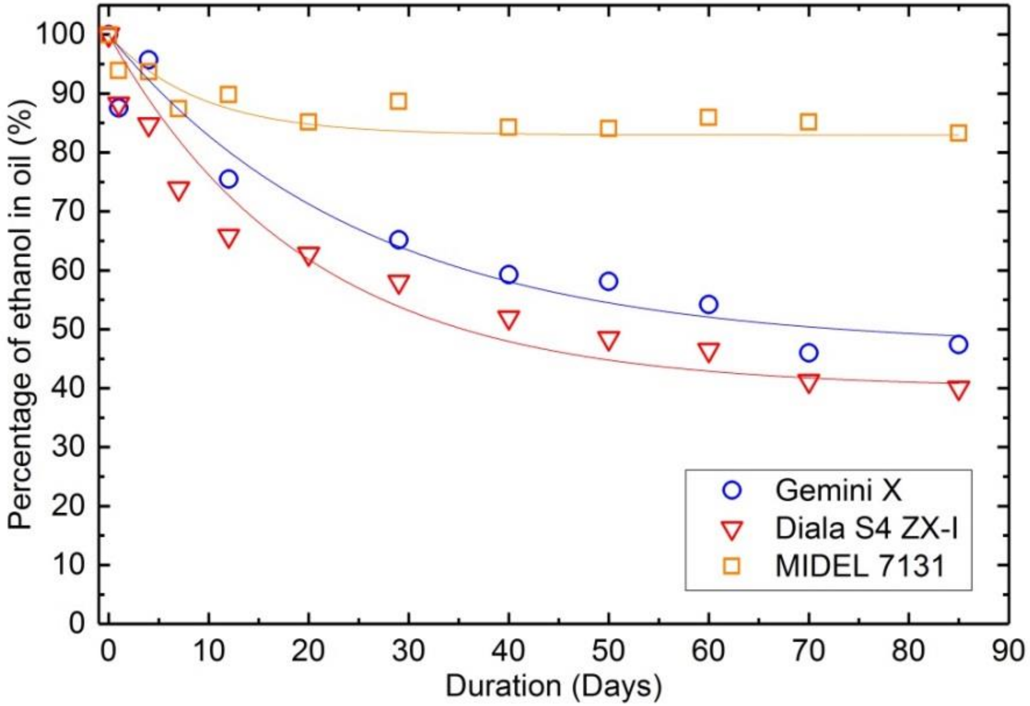
Headspace vials and gas-tight-syringes

Partitioning Experiment at 20 °C

- Synthetic ester has higher affinity for methanol and ethanol than mineral oil and GTL oil



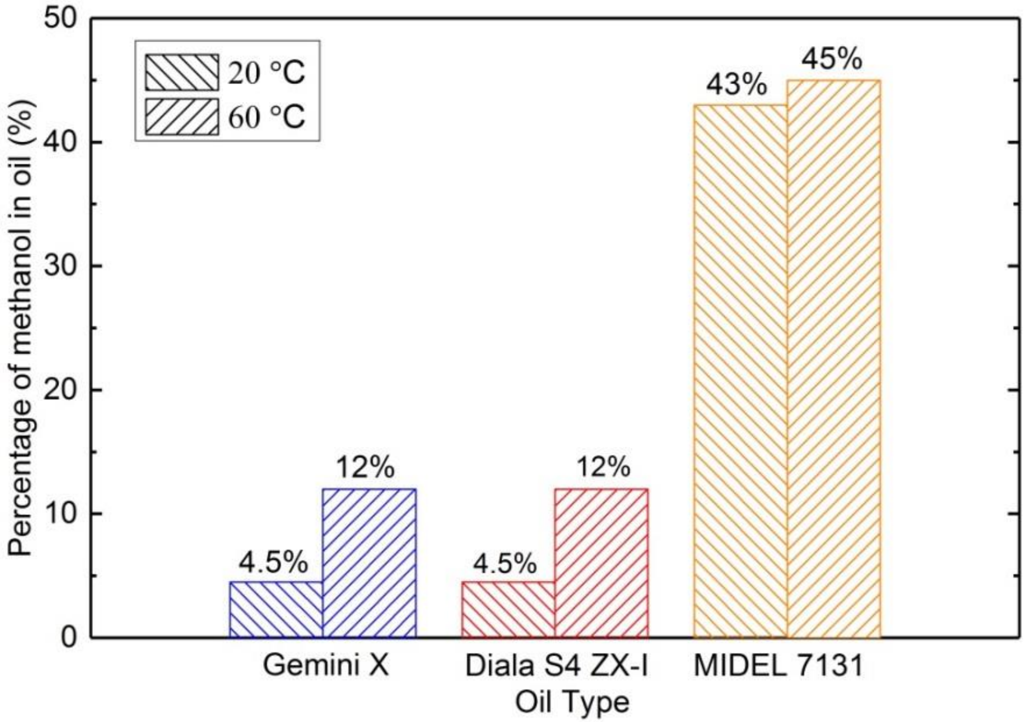
Variation of methanol in oil at 20 °C



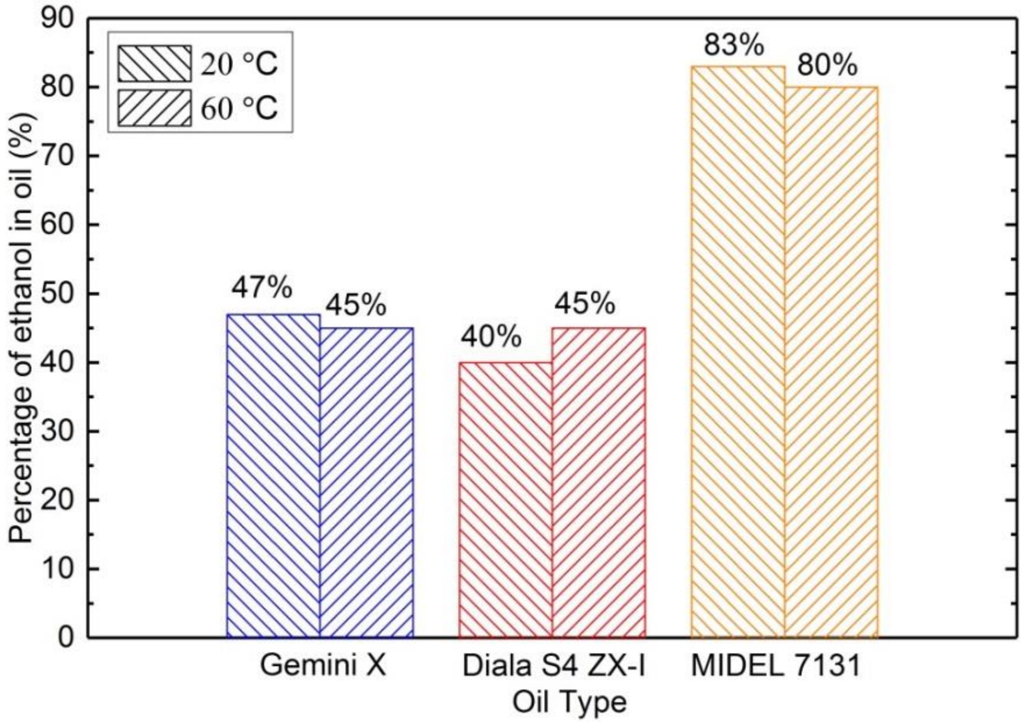
Variation of ethanol in oil at 20 °C

Effect of Temperature on the Partitioning Process

- Temperature affects the partitioning of methanol in insulation systems with mineral oil and GTL oil than with synthetic ester
- Partitioning of ethanol between oil and paper in all the three liquids showed little or no effect by temperature



Effect of temperature on the partitioning of methanol



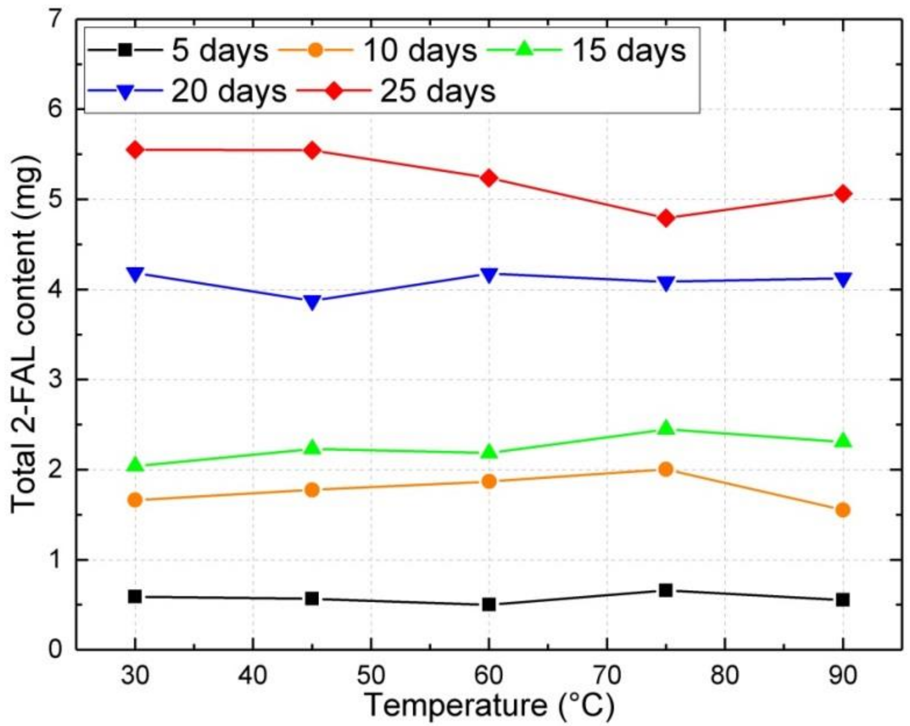
Effect of temperature on the partitioning of ethanol

Small Scale Partitioning Studies by Producing Markers through Ageing

- Oil/paper samples aged at 130 °C for different durations were conditioned at temperatures between 30 °C and 90 °C
- 2-FAL in both **oil and paper** was measured through HPLC
  - 2-FAL in paper was first extracted into methanol using a Soxhlet Extractor

Details of the ageing experiment

Liquid	Naphthenic mineral oil – 1 L
Solid	NTU Kraft paper (0.12 mm) – 87 g
Headspace	Nitrogen
Solid : Liquid	1:10
Ageing temperature	130 °C
Duration	5, 10, 15, 20 and 25 days
Partitioning experiment	30 °C, 45 °C, 60 °C, 75 °C and 90 °C for 30 days



Total 2-FAL content in the samples

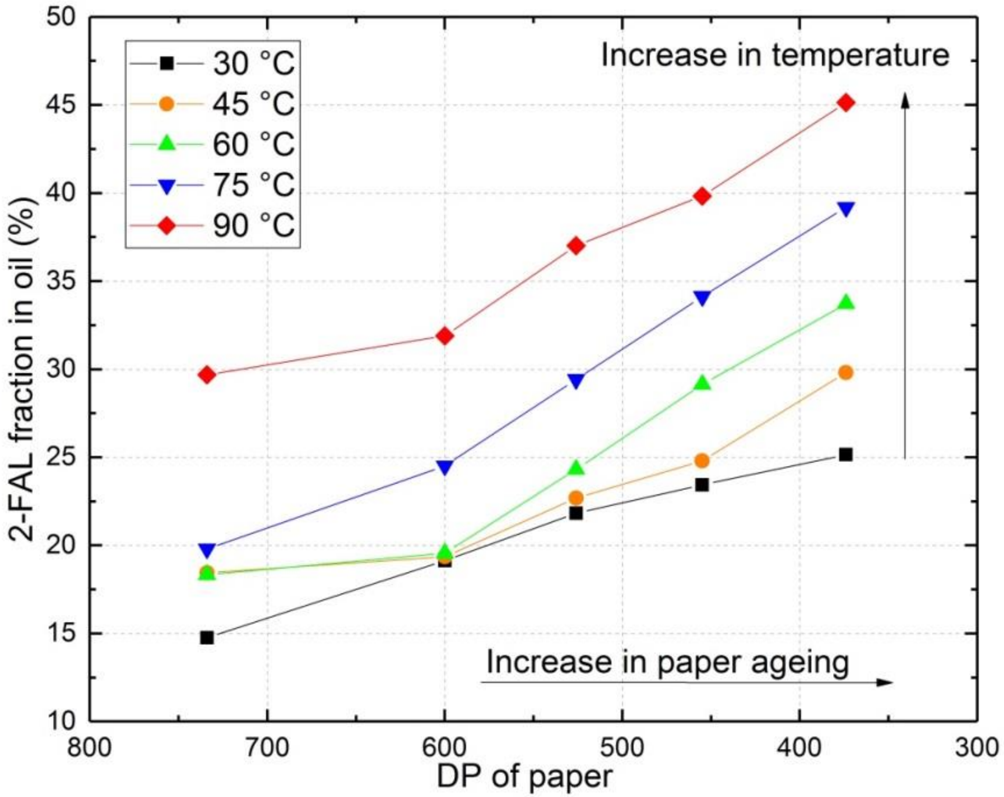
Effect of Temperature on Partitioning of 2-FAL

- Temperature increase from 30 °C to 90 °C resulted in 15% to 20% percent increase in 2-FAL across all the paper ageing levels

- 2-FAL fraction in oil increases by about 10% to 15% with paper ageing

2-FAL fraction in oil

$$\frac{Total\ 2FAL\ content\ in\ oil\ (mg)}{Total\ 2FAL\ content\ in\ oil\ and\ paper\ (mg)} \times 100\%$$



Variation of 2-FAL fraction in oil against DP of paper

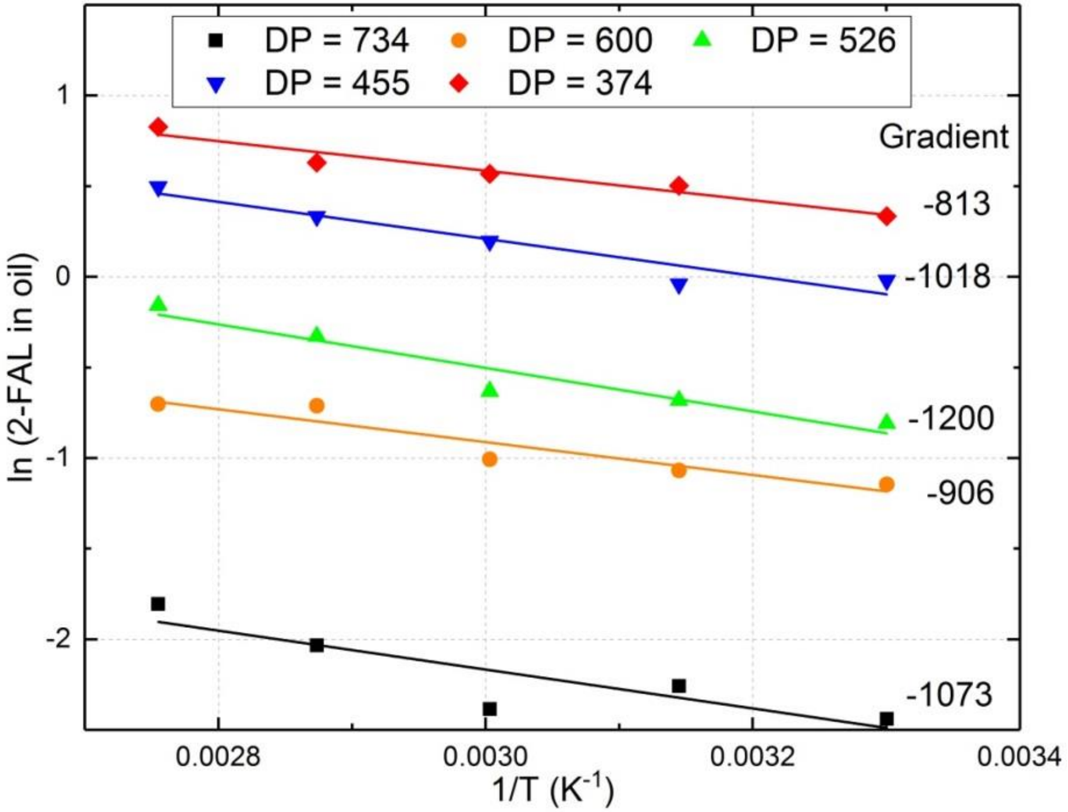
Temperature Correction for 2-FAL

- Van 't Hoff plots were used to understand the effect of temperature on the partitioning of 2-FAL between oil and paper for different paper ageing levels

- Average absolute gradient of **1002** was obtained from the Van 't Hoff plots

Temperature correction for 2-FAL

$$[2FAL]_{80°C} = [FAL]_T e^{1002\left(\frac{1}{T}-0.0028\right)}$$



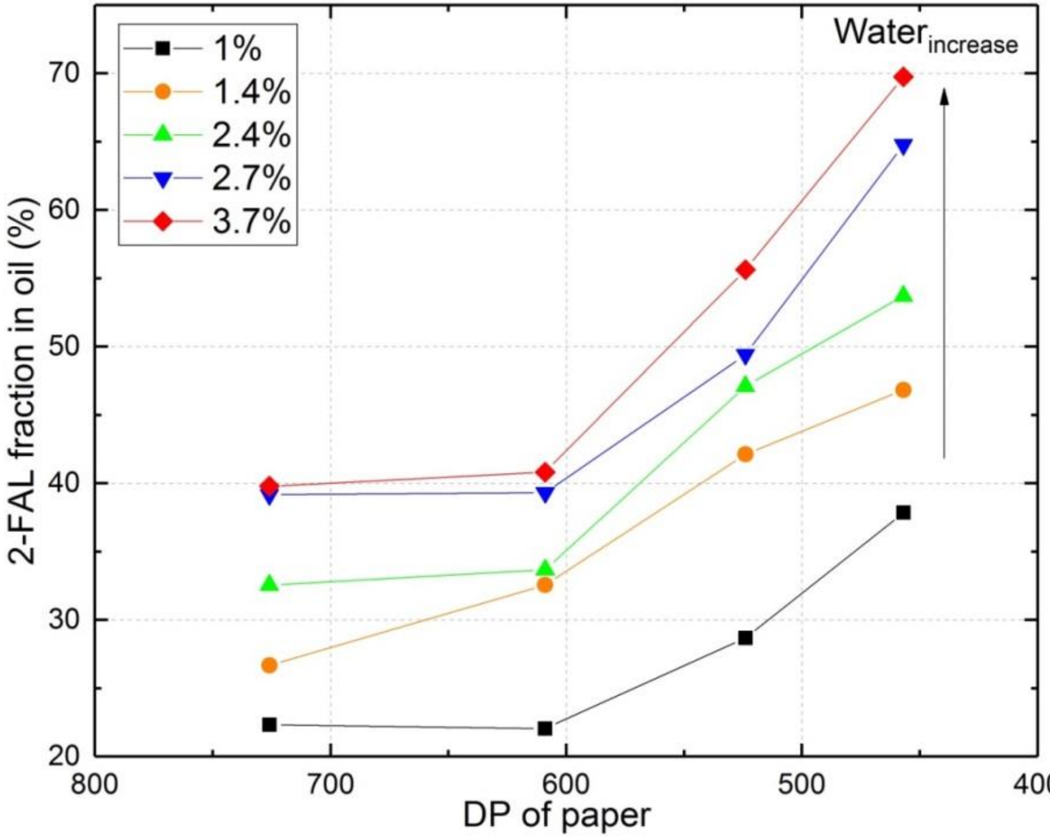
Van 't Hoff plot for 2-FAL in oil

Effect of Water Content on the Partitioning of 2-FAL

- Aged oil/paper samples were conditioned at 60 °C and 60% RH for different durations to obtain samples with different water content
- 2-FAL content in oil increased with increase in water content

Details of the experiment

Liquid	Mineral oil
Solid	NTU Kraft paper (0.12 mm)
Headspace	Nitrogen
Solid : Liquid	1:10
Ageing temperature	130 °C
Duration	5, 10, 15 and 20 days
Moisture conditioning	60 °C and 60% RH for 0, 15, 30, 60 and 90 minutes
Partitioning temperature	60 °C for 30 days

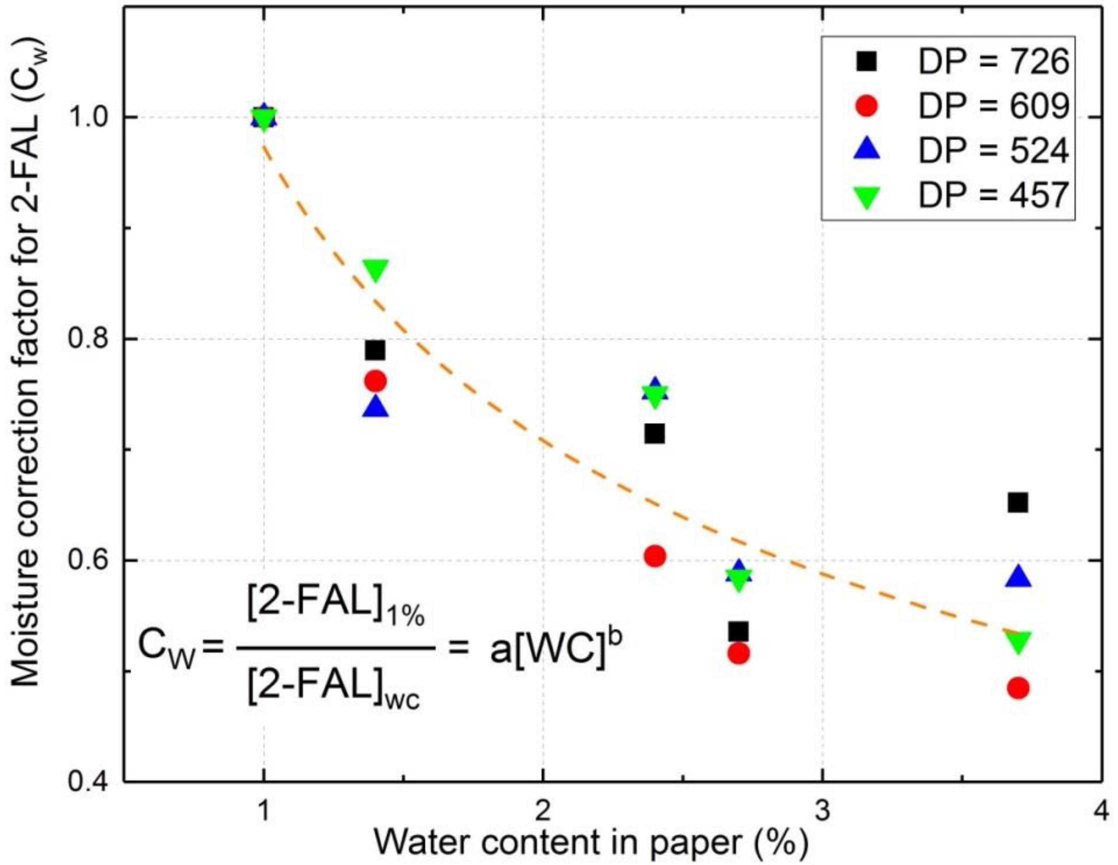


Effect of moisture on the partitioning of 2-FAL

Moisture Correction for 2-FAL

- Graph shows the possibility of obtaining a correction factor for 2-FAL based on the water content in paper

$$[2FAL]_{1\%} = [2FAL]_{WC\%} \times 0.97[WC]^{-0.46}$$

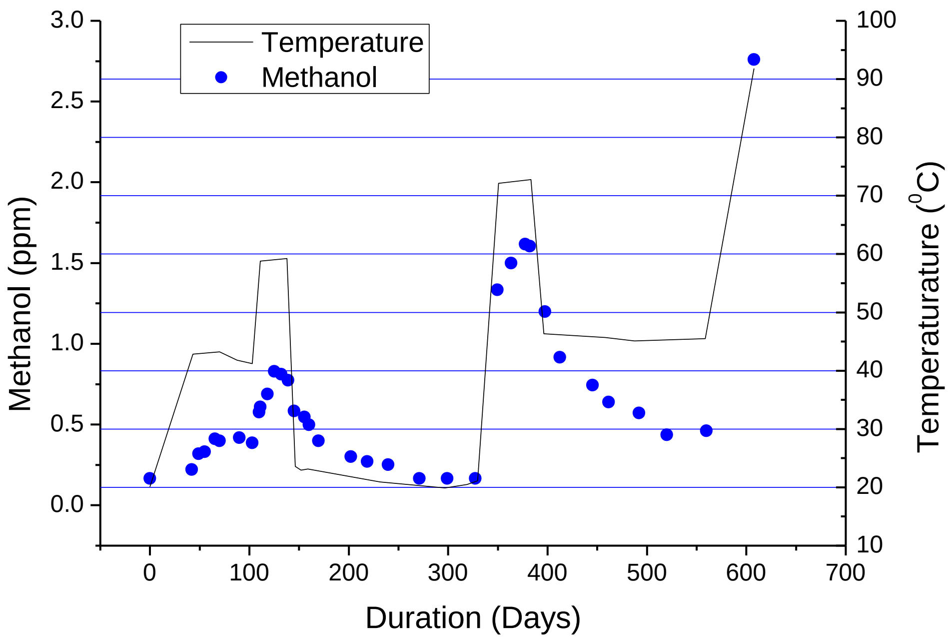


Moisture correction for 2-FAL

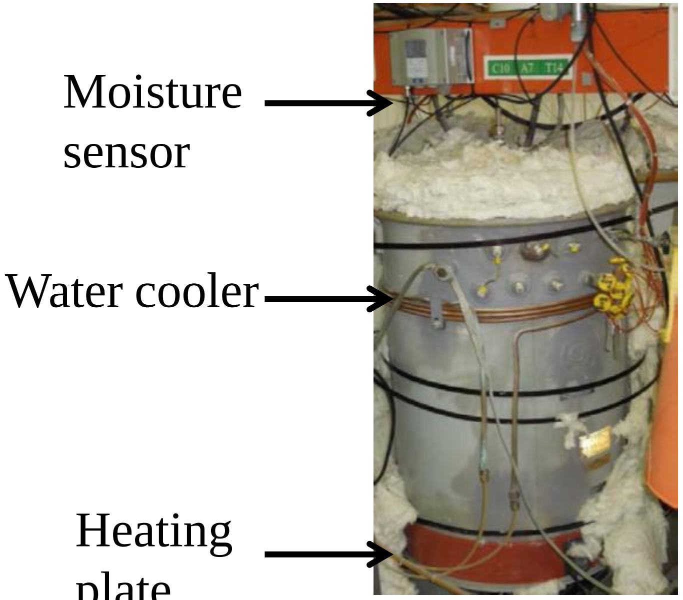
Partitioning Experiment using Model Transformers

- Partitioning tests were conducted with thermally aged model transformers built using 100 kVA distribution transformer tanks filled with mineral oil and NTU Kraft paper

- Temperature of the transformers were varied between 20 ˚C and 90 ˚C up to 700 days



Variation of methanol during the partitioning experiment



Experimental setup

Temperature Correction Factors for Chemical Indicators

- C_f values at any temperature (T_s) were obtained by below equation

$$C_f = \frac{concentration\ @\ 20\ 0C}{concentration\ @\ T_s}$$

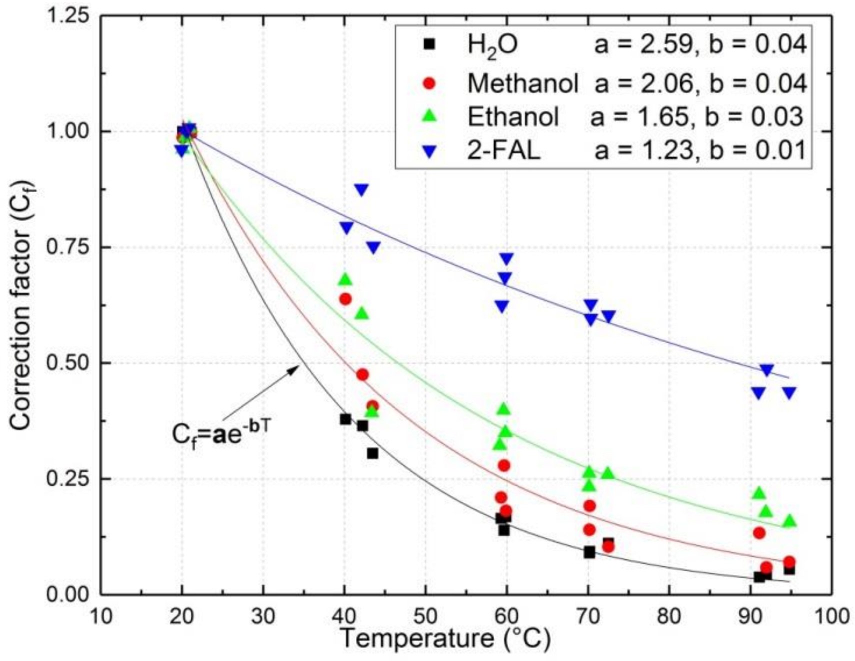
- Exponential curves were obtained using below fitting equation

$$C_f = ae^{-bT_s}$$

- These curves were later used to correct concentrations of chemical indicators at different temperatures into the concentrations at 20 ^{0}C

Details of the model transformers

No.	DP_v	2-FAL (ppb)	MeOH (ppb)	EtOH (ppb)	H_2O (ppm)	Oil Acidity (mg KOH/g oil)
TX 1	553	1843	814	129	11	0.008
TX 2	682	625	394	57	4	0.004
TX 3	745	247	172	38	2	0.007



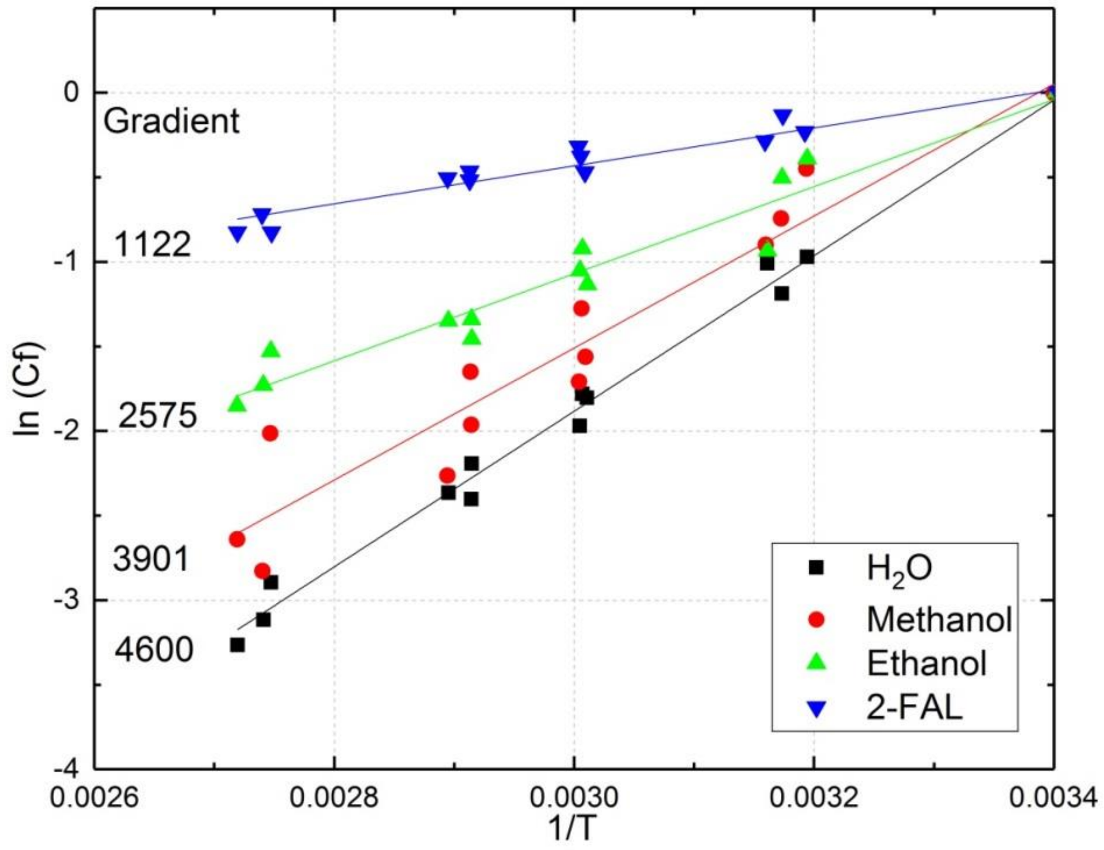
Temperature correction factor for different chemical indicators

Van 't Hoff Plots for the Correction Factors

- The graph shows the Van 't Hoff plots obtained for the chemical indicators using their respective correction factors

Gradient of the Van 't Hoff plots

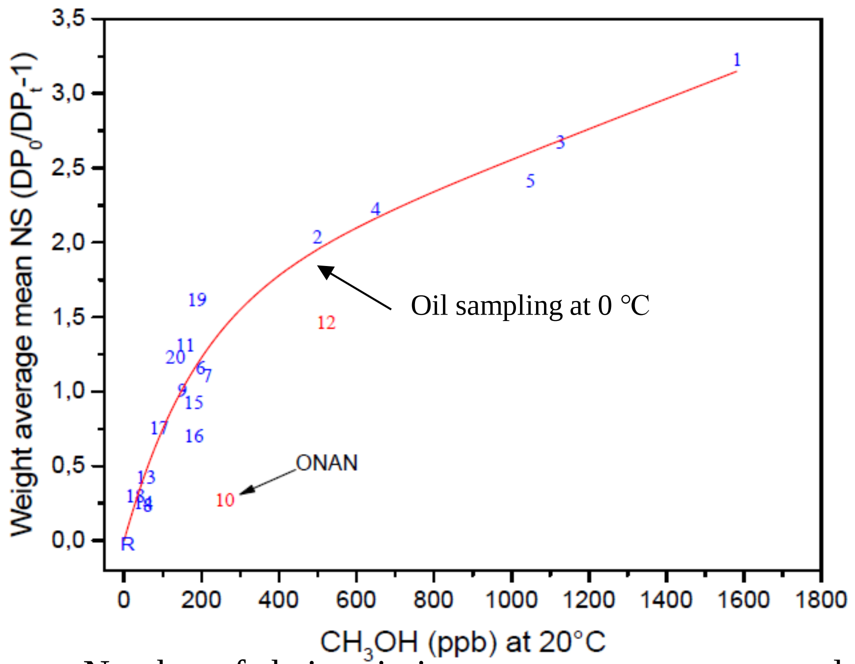
	Absolute gradient
Water	4600
MeOH	3901
EtOH	2575
2-FAL	1122



Van 't Hoff plots for chemical indicators

Application Example of Temperature Correction Factors for Methanol

- DP and methanol concentration from 20 free breathing core type transformers were used to develop a DP estimation model based on methanol concentration in oil
- The group of transformers had similar material ratio when considering paper, pressboard and liquid
- Temperature correction factor was applied to methanol concentration



Number of chain scission vs temperature corrected methanol concentration

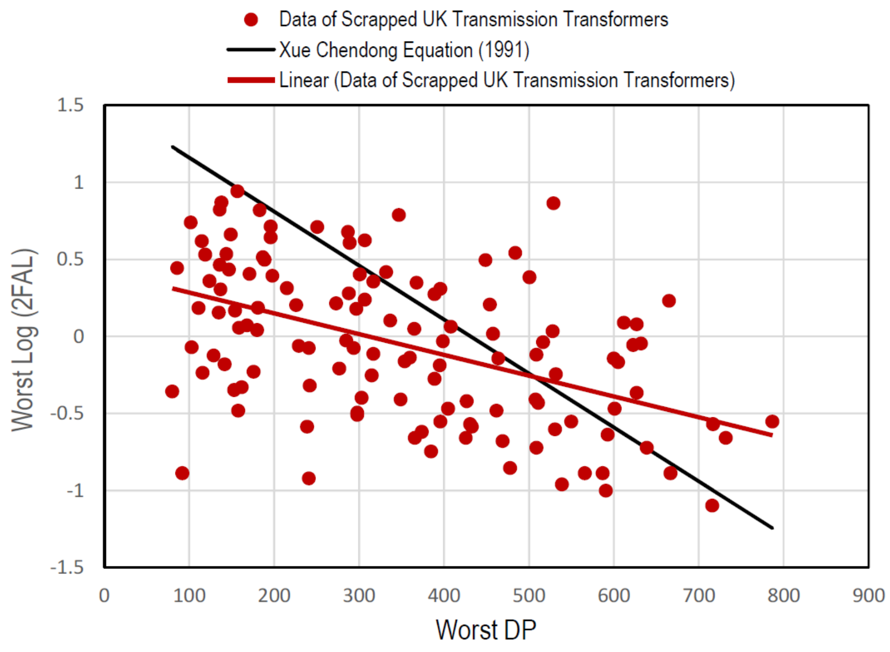
Proposed methanol threshold levels based on temperature corrected methanol concentration

$[CH_3OH]$* (ppb)	Mean Calculated DP_v	Paper condition
0-50	1000-700	Healthy
51-200	700-450	Moderate deterioration
201-1440	450-250	Extensive deterioration
>1440	<250	End of life criteria

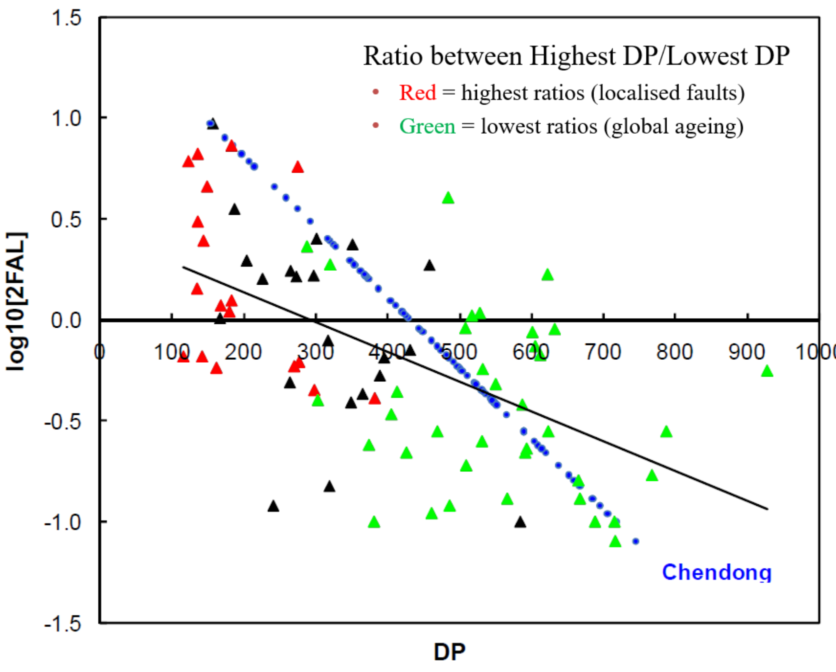
Challenges in Utilising Chemical Markers

Usefulness of ageing marker Data

- Post-mortem data from UK transmission transformers doesn't show a simple relationship
- Will further narrow down into fault types, voltage level, manufacturer , etc. result in revealing new information?



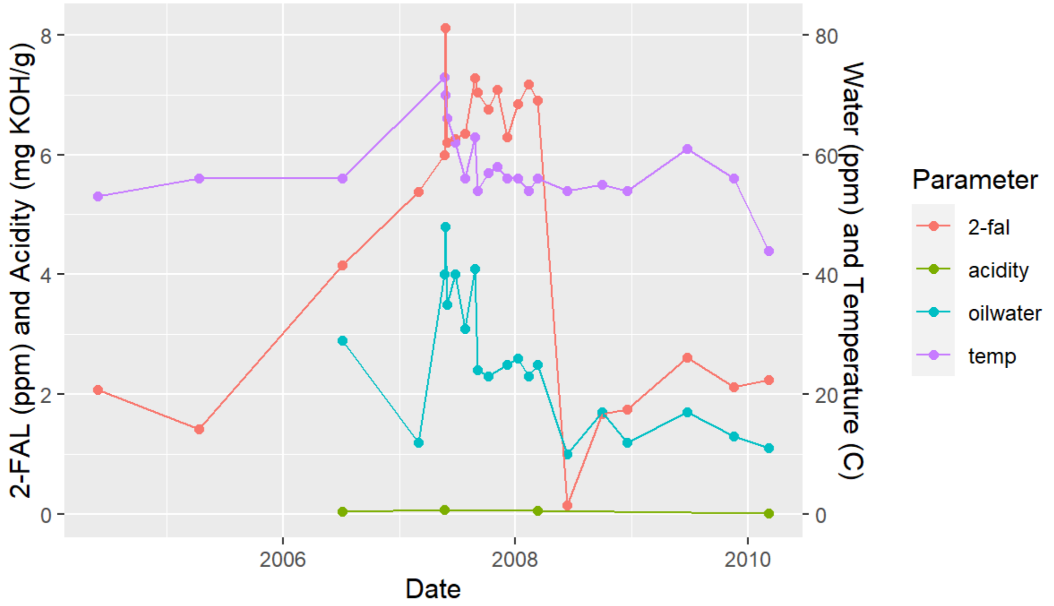
Worst 2-FAL vs worst DP from NG scrapped transformers

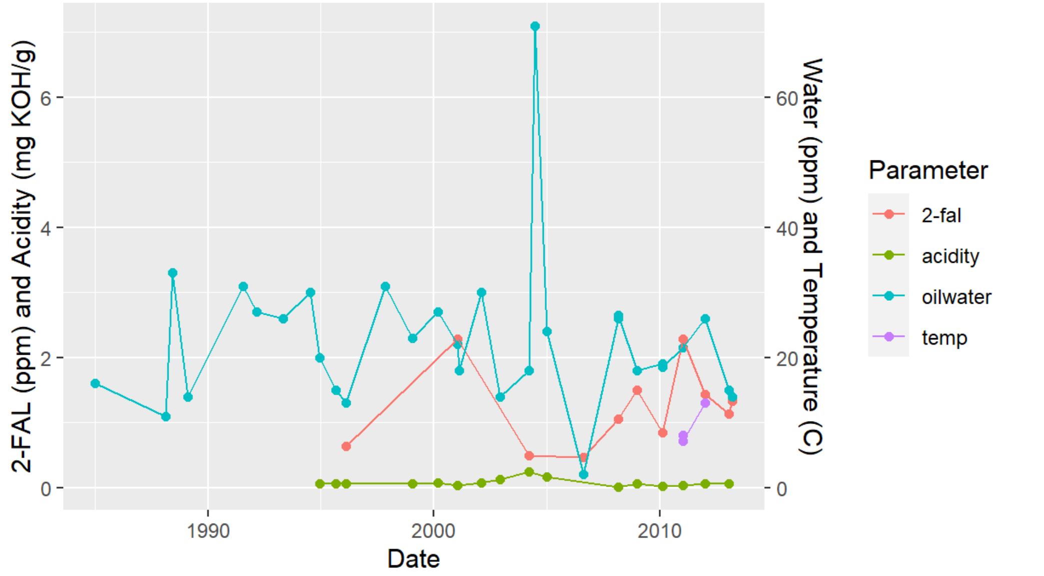


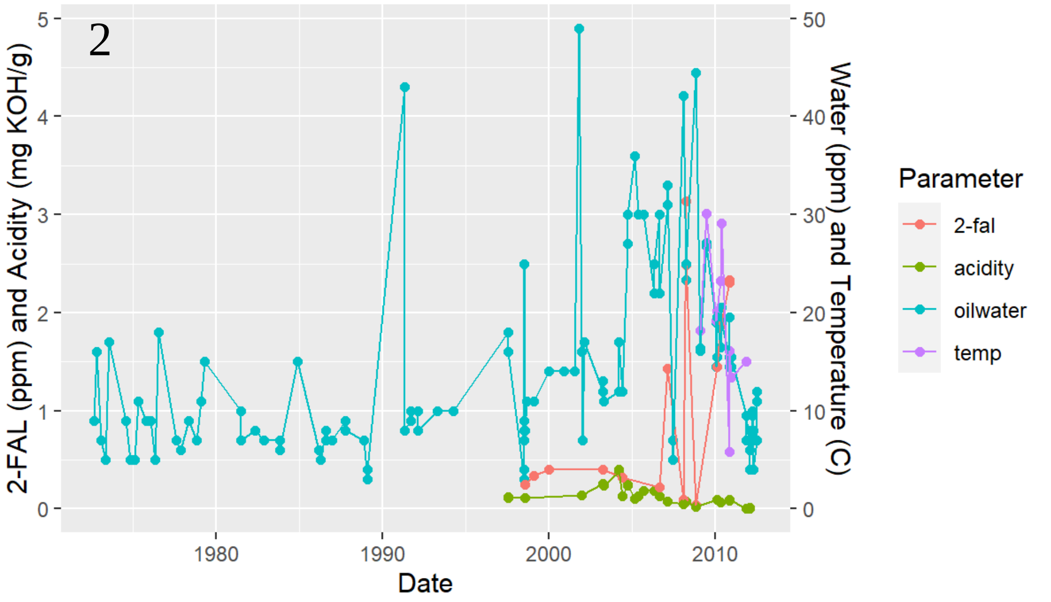
2-FAL vs DP data obtained from 78 scrapped transformers

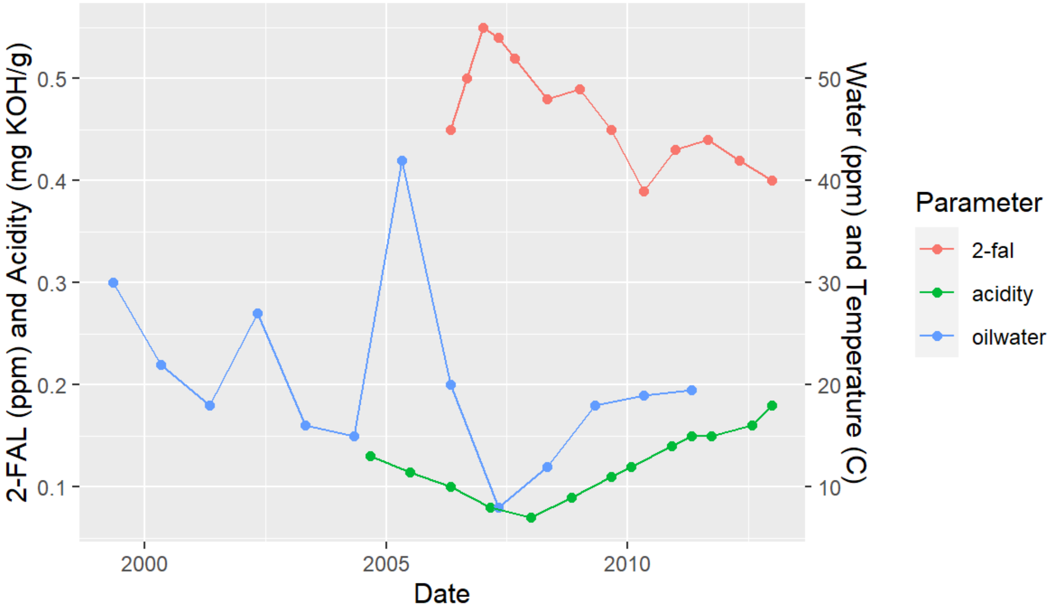
- H. Ding, R. Heywood, J. Lapworth, S. Ryder, and A. Wilson, "Progress in paper degradation assessment in service-aged transformers," in 2017 INSUCON - 13th International Electrical Insulation Conference (INSUCON), 16-18 May 2017 2017, pp. 1-6, doi: 10.23919/INSUCON.2017.8097211
- J. Lapworth, H. Z. Ding, S. Ryder, and P. Jarman, "Progress towards a reliable transformer service life prediction," presented at the 78th Annual International Doble Client Conference, Bostan, MA, USA, 2011.

Fluctuation in Chemical Marker Concentration







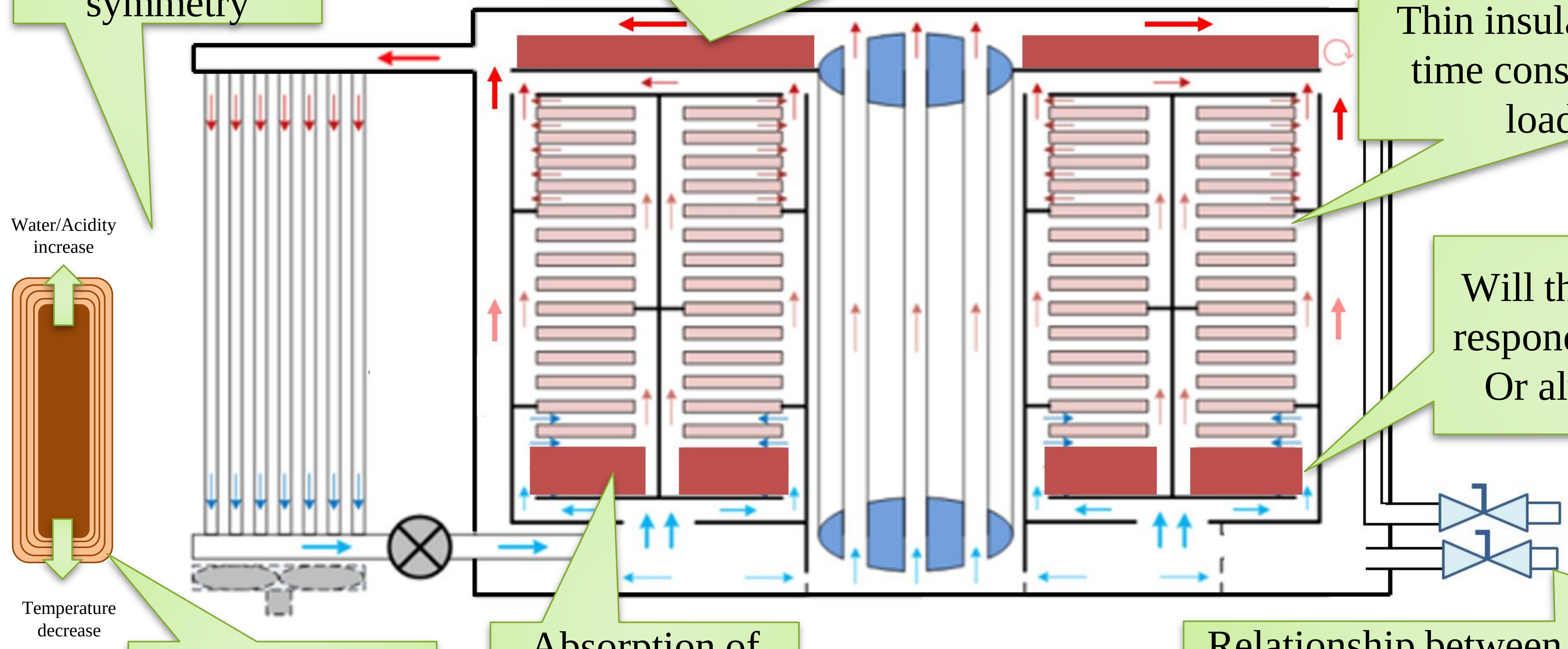


Complexity in chemical marker generation and transport process

Impact of cooler banks and non-symmetry

Quantification of the generation of chemicals from hot thick board or even unprocessed wood?

Thin insulation with small time constant respond to load changes



Will the thick insulation respond to load changes? Or always act a sink?

Impact of conductor insulation layers

Absorption of chemicals by cold thick board

Relationship between concentration at sampling point vs rest of the transformer

Partitioning studies through realistic transformer models

- NGET has observed abnormal chemical marker trends in their transformers which is believed to be due to partitioning process.
- However, detail knowledge of this process including diffusion coefficients, time constants associated different insulation thickness values is unknown.
- A lab-scale model transformer will be used to study the dynamics of chemical marker partitioning process under different operating conditions
- It is aimed to obtain correction factors for the partitioning of chemical markers (Furan, Methanol, Water) considering multiple design and operation aspects.

Lab scale model
(available at the UoM lab)

Oil processing unit
(available at the UoM lab)

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THANK YOU !

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