The Tony Davies High Voltage Laboratory

University of Southampton

Sustainable Power Transformers for an uncertain future

Thomas Andritsch

28 November 2024

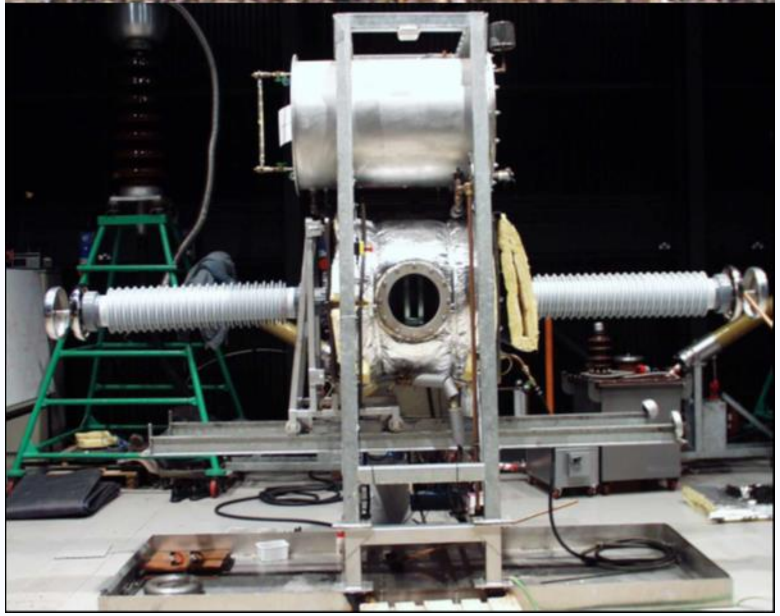
Introduction

- This presentation is a broad summary of a decade of power transformer research undertaken at the Tony Davies High Voltage Laboratory in collaboration with the School of Chemistry.
- All projects funded by the National Grid.
- Primarily our work is centred on understanding certain failure modes and developing tools to assist with condition assessment of NG's transformer fleet.
- Initial projects built on existing TDHVL expertise in partial discharge, condition monitoring and electrical characterisation. Soon realized that we needed to collaborate with colleagues in the School of Chemistry.
- Uncertain future: We know there will be significant growth in demand for electrical energy and that climate change will impact on demand as well as security of supply.

How it all began

ASTI: Ageing Studies of Transformer Insulation

- Experiment to investigate creep stress failure of interphase barrier board of large autotransformers (400 kV:132 kV).
  - Complicated 2 phase field and barrier board design (oil ducts).
  - Experiment designed to replicate interphase conditions, including use of service aged oils and board plus ability to thermally cycle the test chamber.
  - Initial methodology: replicate the failure mode, capture realtime data, develop online CM strategies.
  - However, for this particular failure mode, time from initial detection of PD activity to overcurrent failure is a matter of tens of seconds.

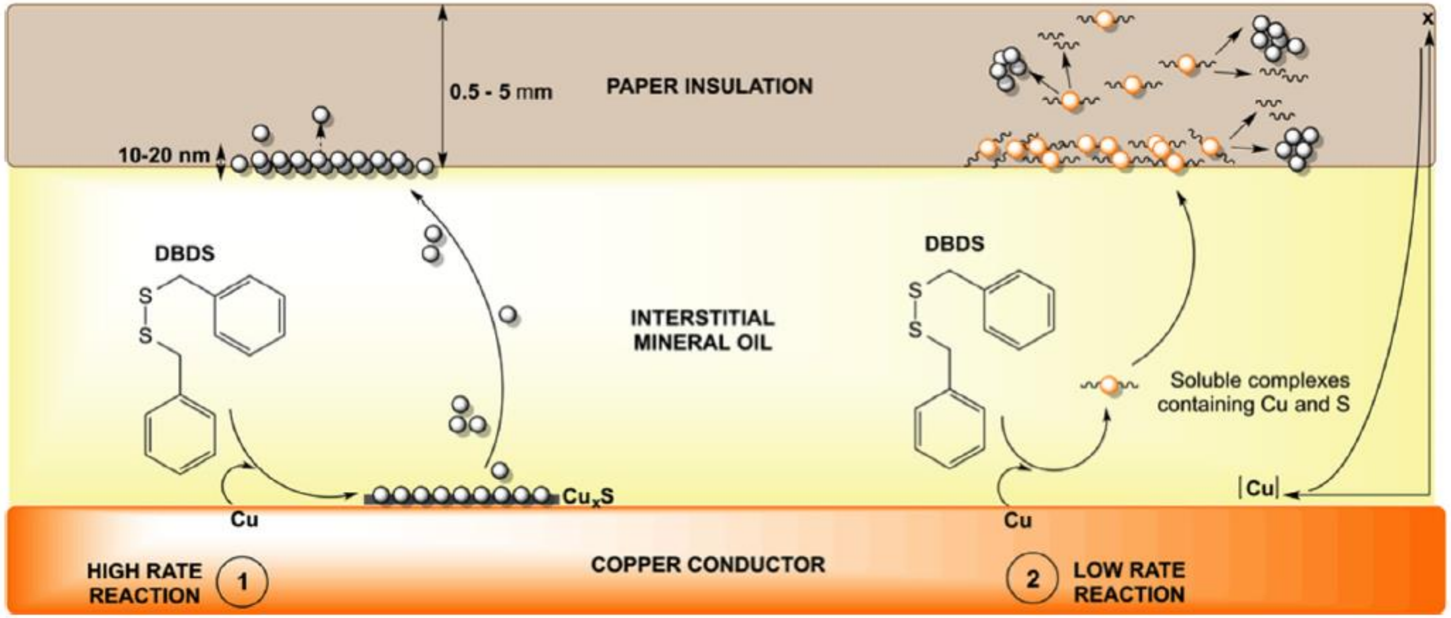


P M Mitchinson, P L Lewin and P Jarman, 'Oil-Gap Discharge in Transformers' IEEE Electrical Insulation Magazine, 29(2), 2013, pp. 50-62.

Corrosive Sulphur and Passivation

TOPICS: Transformer Oil Passivation and the Impact of Corrosive Sulphur

- Determine the mechanism of sulphur corrosion and formation of Copper Sulphide:
  - Seen in oils containing dibenzyl disulphide (DBDS)
  - Rate of reaction increases with increasing temperature
  - Presence of oxygen increases formation of copper sulphide complexes in the paper



TOPICS: Transformer Oil Passivation and the Impact of Corrosive Sulphur

- Understand the **impact of passivation** with respect to reducing copper corrosion:
  - Used X-ray photoelectron spectroscopy and Static-Secondary Ion Mass Spectrometry to investigate presence of passivator on copper surfaces – SSIMS could track passivation and corrosion by-products from samples from a 400/275kV autotransformer.
  - Recommended that passivated units with known thermal issues require closer monitoring of passivator concentration to maintain protection layer.
- Understand and **minimise risks of introducing silver-specific corrosive species** into transformer oils during reclamation.
  - Buffer tank oil should be recycled offsite and only after a negative corrosion test reintroduced to top up transformer oil volume.
  - For transformers deemed at high risk of corrosive sulphur, buffer tank oil should not be reintroduced.

TOPICS: Transformer Oil Passivation and the Impact of Corrosive Sulphur

- X-ray fluorescence spectroscopy can be used as a monitoring tool for the corrosion process but requires a database of historical trends of sulphur content in the oil.
- Copper sulphide deposits were shown to be a source of significant power loss suggesting that hotspots where solid insulation was contaminated would not only lead to local failures but also potentially to thermal runaway.
- Contributed to CIGRE working group A2.40 on Copper Sulphide (CIGRE Brochure 625).

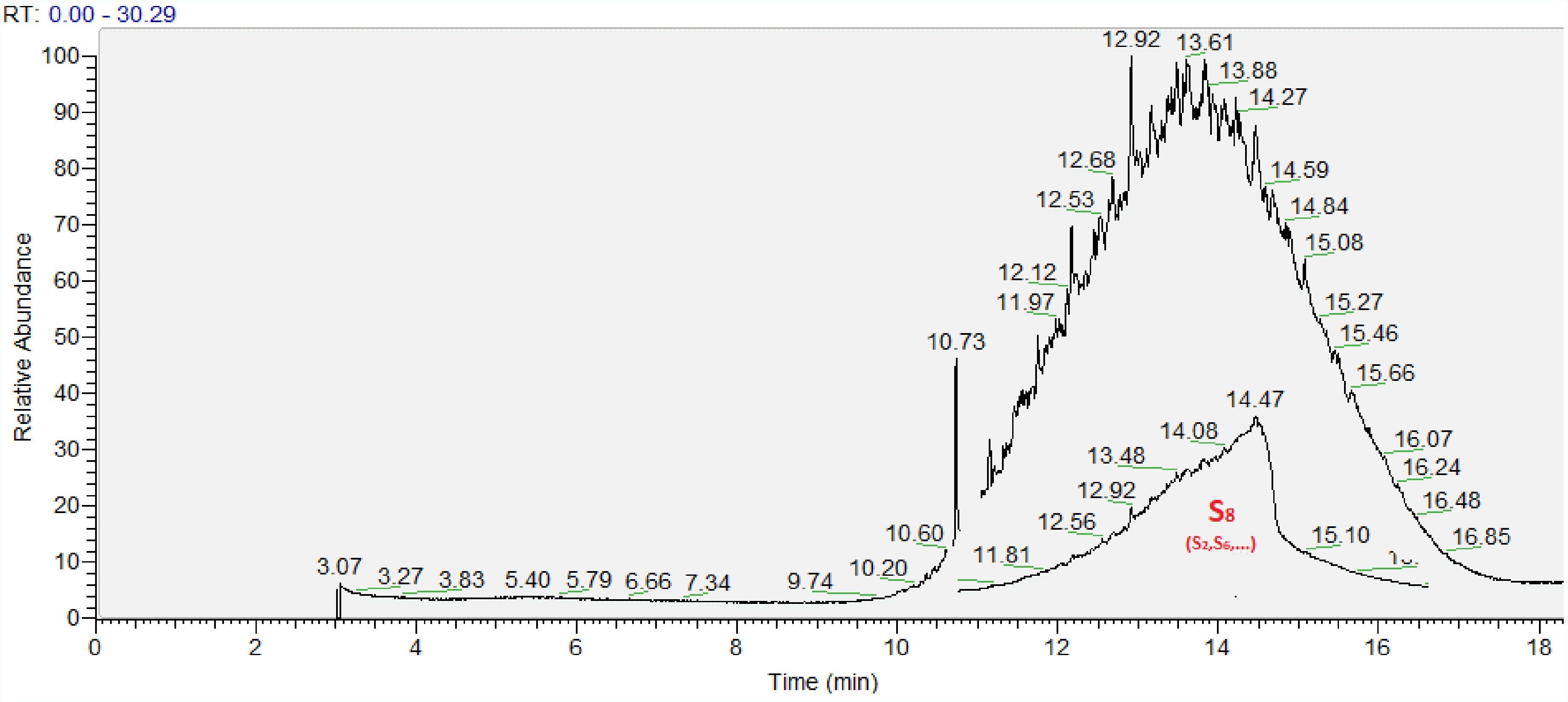
M Facciotti, P S Amaro, A F Holt, R C D Brown, P L Lewin, J A Pilgrim, G Wilson and P N Jarman ‘Contact-based corrosion mechanism leading to copper sulphide deposition on insulating paper used in oil-immersed electrical power equipment’. Corrosion Science, 84, 2014, p172-179, ISSN 0010-938X.

P S Amaro, M Facciotti, A F Holt, J A Pilgrim, P L Lewin, R C D Brown, G Wilson and P Jarman ‘X-Ray Fluorescence as a Condition Monitoring Tool for Copper and Corrosive Sulphur Species in Insulating Oil’. IEEE Transactions on Dielectrics and Electrical Insulation, 22(2), 2015, p701-708, ISSN 1070-9878.

M Facciotti, P S Amaro, R C D Brown, P L Lewin, J A Pilgrim, G Wilson, P N Jarman and I Fletcher ‘Static secondary ion mass spectrometry investigation of corrosion inhibitor Irgamet®39 on copper surfaces treated in power transformer insulating oil’. Corrosion Science, 98, 2015, p450-456, ISSN 0010-938X.

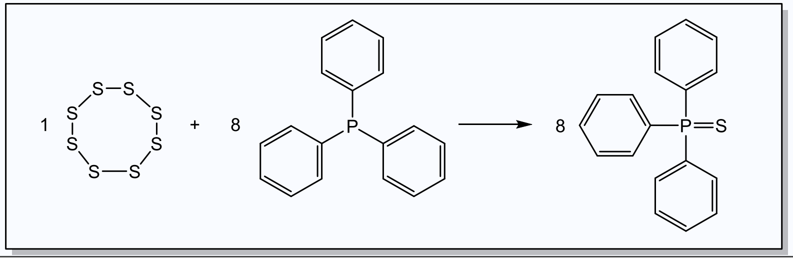
TOPICS 2: Transformer Oil Passivation and the Impact of Corrosive Sulphur

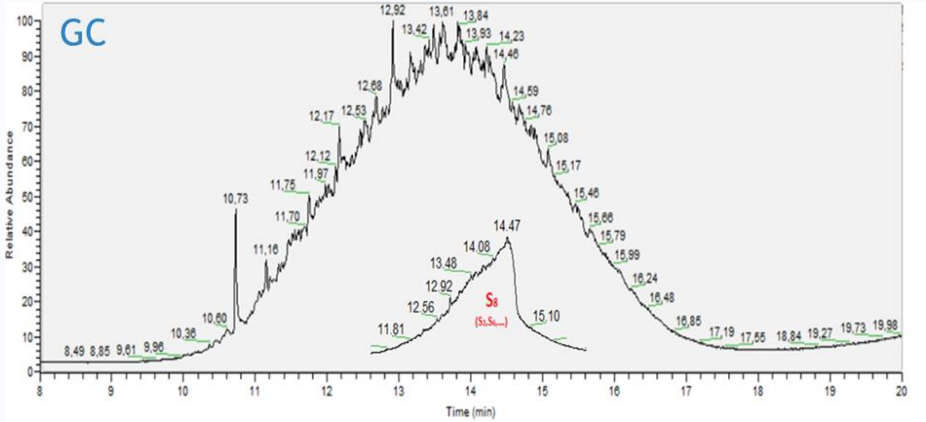
- Develop a methodology to quantify elemental sulphur in transformer oil.
  - The determination of elemental sulphur was firstly tried by GC-MS

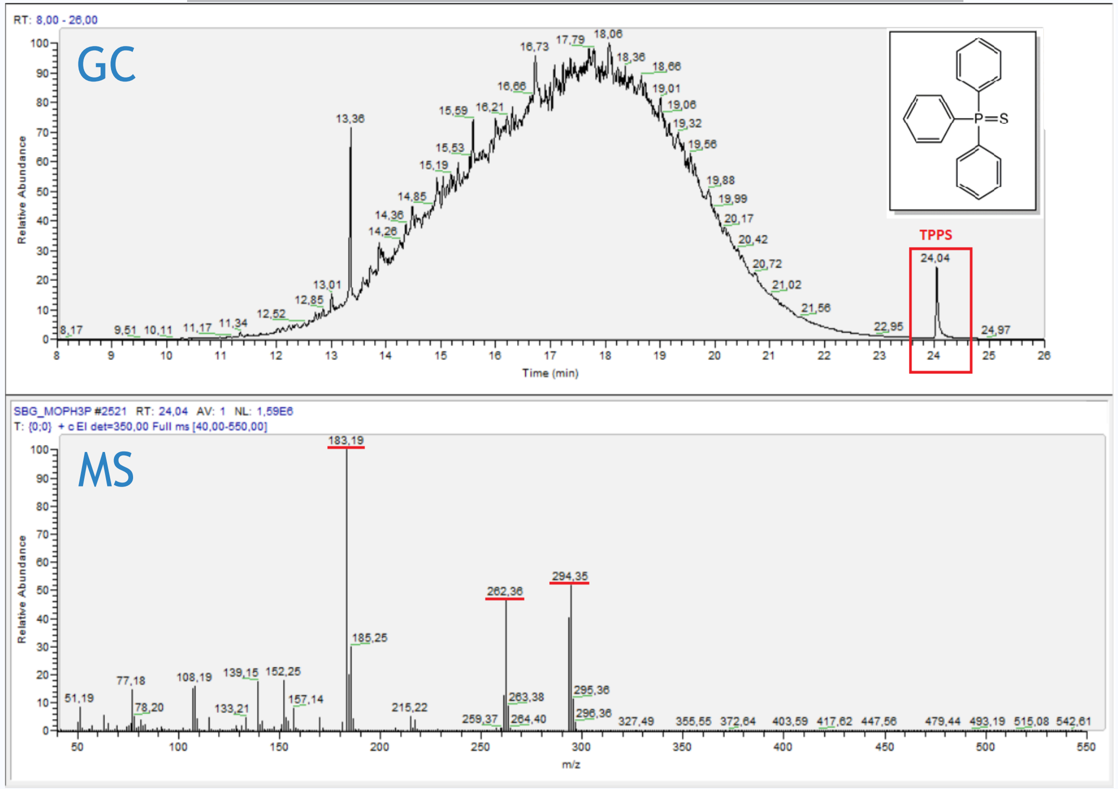


TOPICS 2: Transformer Oil Passivation and the Impact of Corrosive Sulphur

– Derivitization with Triphenilphosphene – reacts with sulphur in the oil sample, has a 9.2 fold increase in mass (i.e 1 ppm elemental sulphur becomes 9.2 ppm of the derivative), derivative has a high boiling point.







S.B.Garcia; R.C.D.Brown; G.J.Langley; P.Birkin; J.Pilgrim; P.L.Lewin; G.Wilson,'Rapid analytical method for elemental sulphur detection in power transformers insulation oil', IEEE 37th Electrical Insulation Conference (EIC), Calgary, June 2019

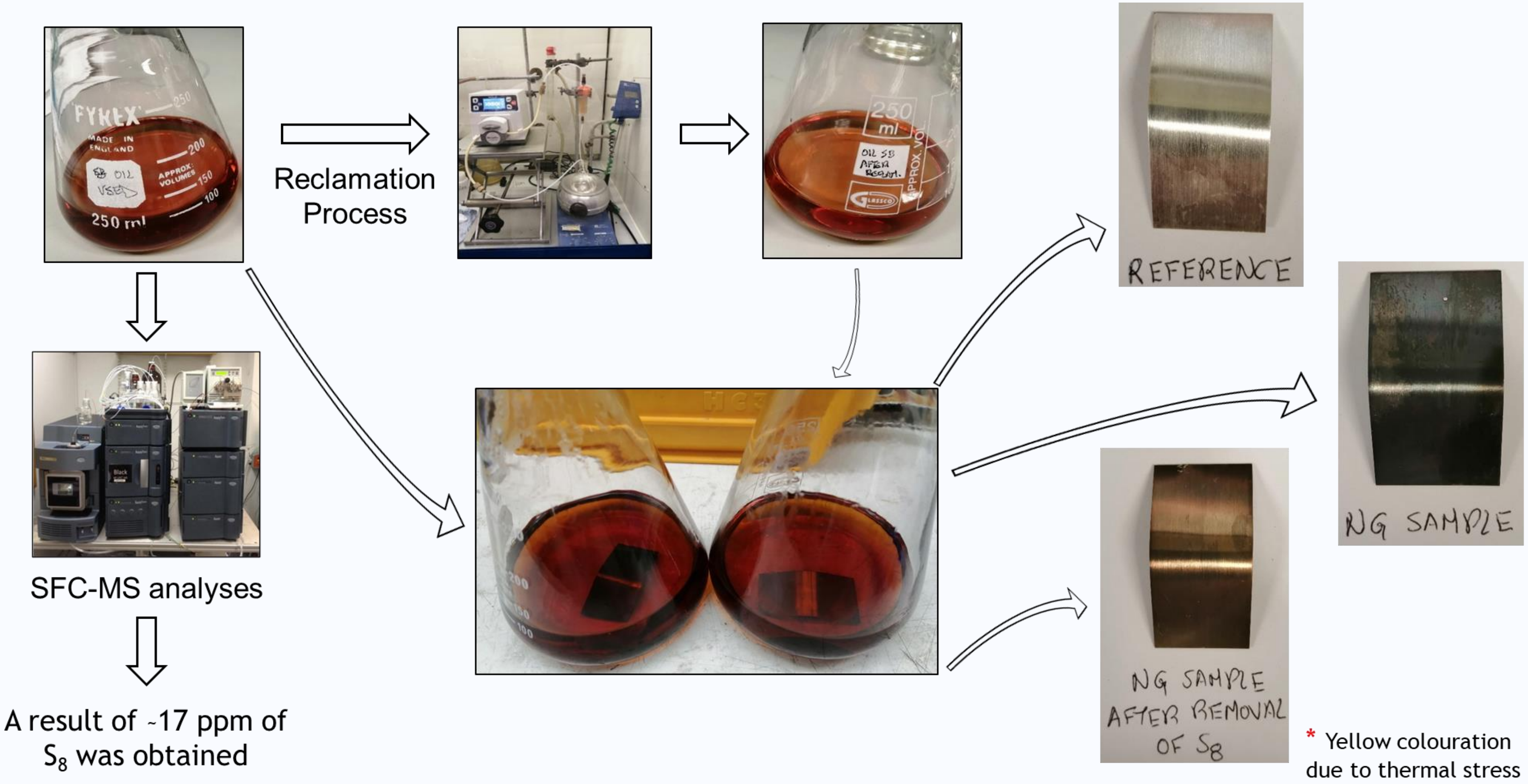
TOPICS 2: Transformer Oil Passivation and the Impact of Corrosive Sulphur

- Utilise the method of quantifying sulphur content to assess potential reclamation strategies to reduce silver corrosion.
  - Experiment: 100mL mineral oil +10mg S_8, heated to 60˚C passed through a polymer-based support at 50mL/min. Support removes S_8 and is recyclable/reusable.
  - Measure sulphur content of mineral oil every hour.

Time	7 hours	20 hours	33 hours
S_8 (ppm)	17	0.2	0.04

TOPICS 2: Transformer Oil Passivation and the Impact of Corrosive Sulphur

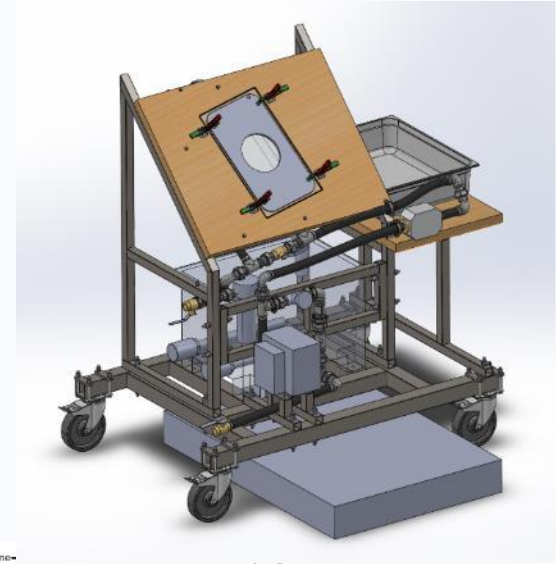
- Reclamation with field samples known to contain corrosive sulphur

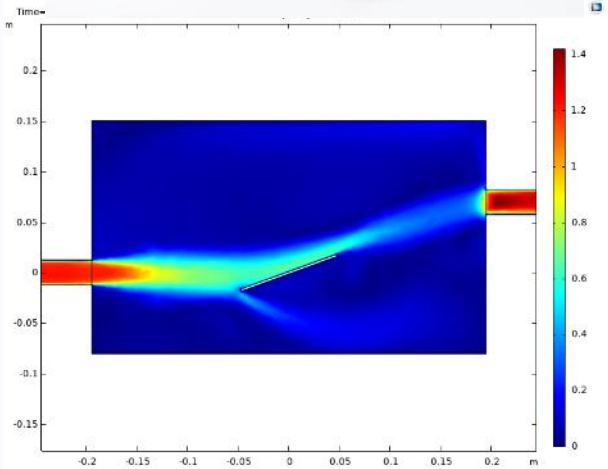


S.B.Garcia, R.C.D.Brown, G.J.Langley, J. Herniman, P.Birkin, J.Pilgrim, P.L.Lewin and G.Wilson, ‘Quantitative UHPSFC-MS analysis of elemental sulfur in mineral oil via derivatization with triphenylphosphine: Application to corrosive sulfur-induced power transformer failure’, Analyst, 2020, DOI:10.1039/D0AN00602E.

TOPICS 2: Transformer Oil Passivation and the Impact of Corrosive Sulphur

- Determine if the reclamation process high oil flow rate causes irreversible mechanical damage to aged (embrittled?) paper.
- Samples placed in an oil flow rig (clean oil and oil with particulates) - level of damage assessed.
  - Whilst the flow is measured at the inlet pipe, it can't be measured at the sample, therefore COMSOL modelling was used to determine the flow pattern (optimise the geometry) and determine the flow rate across the paper
  - No measurable erosion occurs even after long-term temperature/flow cycling in used mineral oil containing a notable particulate content. This indicates that kraft paper is unlikely to be eroded by normal reclamation activities, even in a severely aged asset.





IL Hosier, PL Lewin, G Wilson, 'An Assessment of the Potential for Oil Flow Damage in Kraft Paper Under Normal Operation and Reclamation in a High-Voltage Transformer'. IEEE Transactions on Dielectrics and Electrical Insulation 29(5), 2022, 2050-2057, ISSN 1070-9878

Future environmental impacts

ConCEPT: Condition and Climatic Environment for Power Transformers

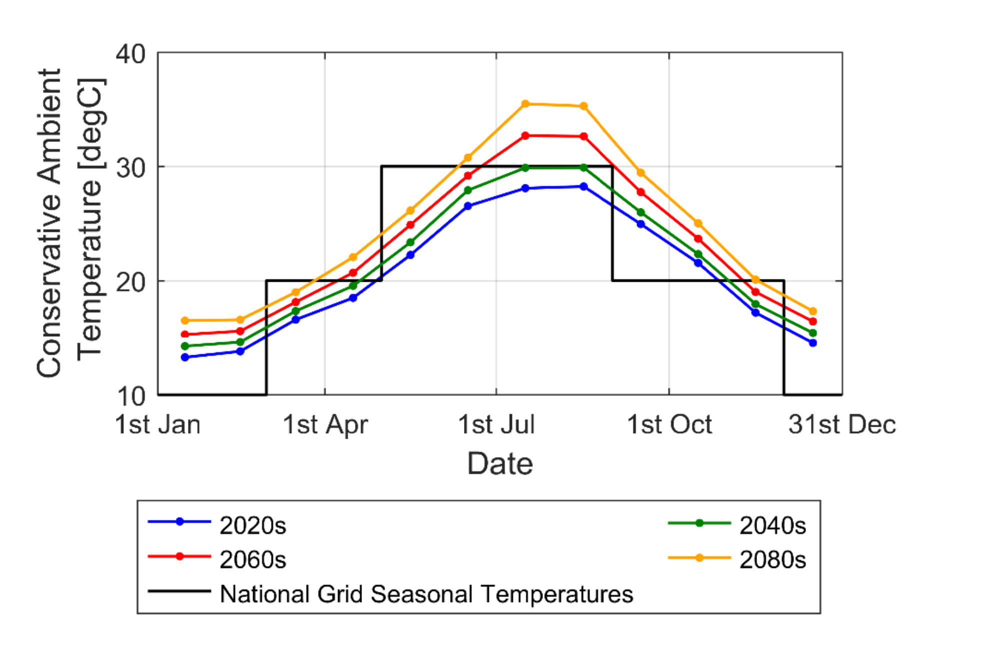
- Quantifying Climate Issues
  - Most operators use conservative ambient temperature assumptions when calculating thermal ratings for power transformers – will this be appropriate in the future?
  - Continuously monitored temperatures at the cooler inlets for 5 transformers around the UK to determine probability of temperatures exceeding NG seasonal assumptions over a three hour period.

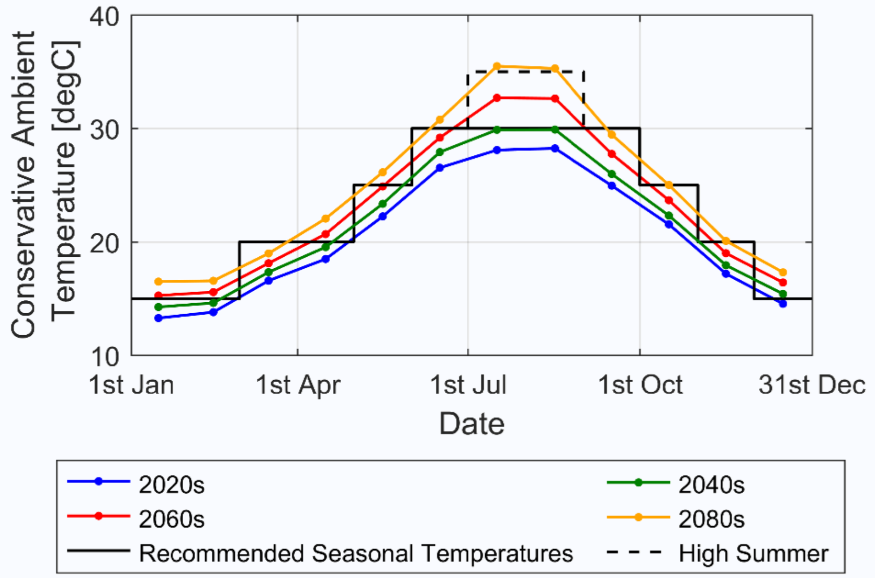
Season	Temperature (°C)
Summer (May – August)	30
Spring/Autumn (March – April / September – November)	20
Winter (December – February)	10

Transformer	Winter - 10°C		Spring/Autumn - 20°C		Summer - 30°C	
	Cooler	Station	Cooler	Station	Cooler	Station
1			23.0%	10.7%	6.5%	3.3%
2			23.9%	16.8%	6.5%	5.7%
3			23.1%	10.7%	6.5%	0.8%
4	70.0%	45.6%	26.2%	12.3%	6.5%	5.7%
5	72.2%	45.6%	28.7%	12.3%	8.1%	5.7%

ConCEPT: Condition and Climatic Environment for Power Transformers

- Climate projections: Using ambient temperatures only UKCP09 climate projections were used to test validity of current assumptions over the next 60 years

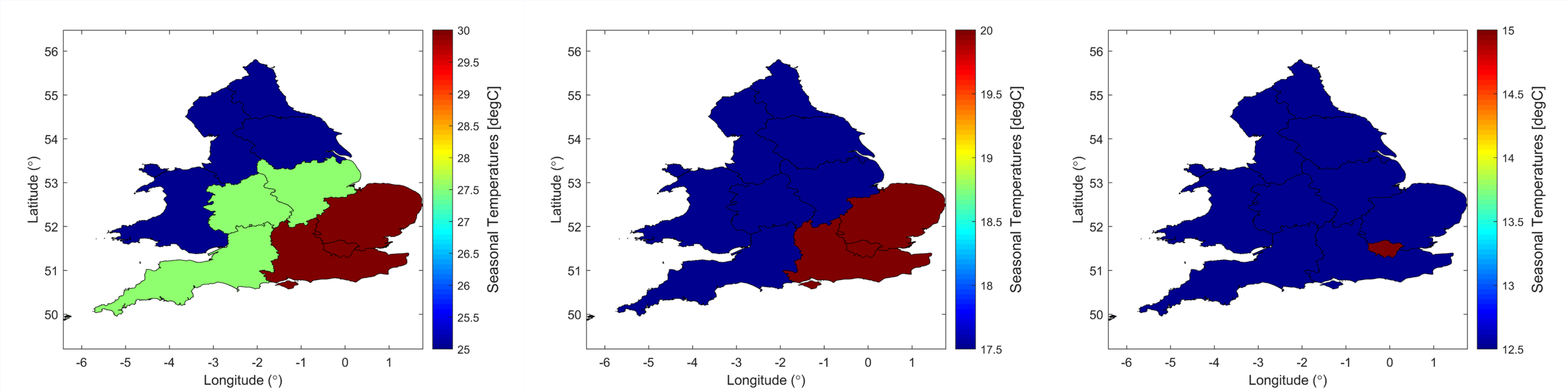




- Add more seasonal steps?

ConCEPT: Condition and Climatic Environment for Power Transformers

- Consider regional ambient temperature ratings (2030’s as an example)



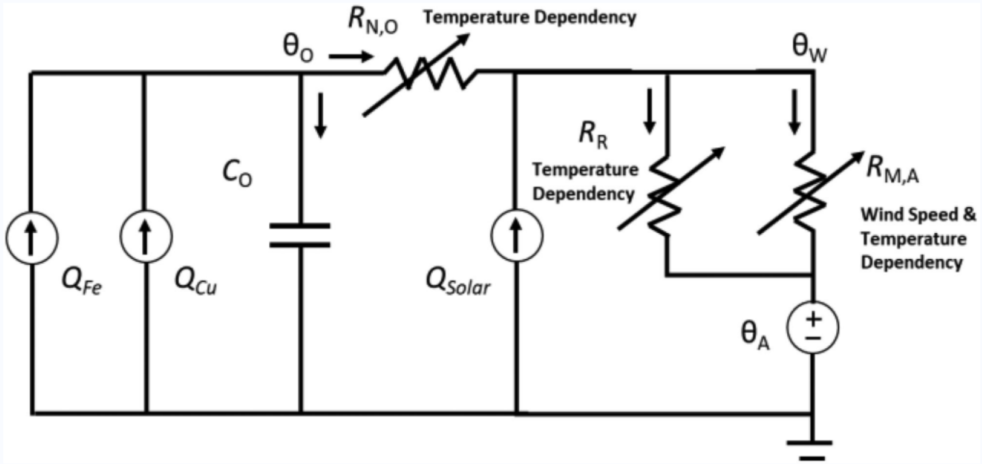
Summer | Spring/Autumn | Winter

ConCEPT: Condition and Climatic Environment for Power Transformers

- Leverage historical data to identify developing thermal issues with individual units (data driven models as opposed to digital twins):
  - Available historical data:
    - Winding Temperature Indicator and Load information: 23 Units c 7 years at hourly resolution
    - DGA data (monthly resolution)
    - Weather data (hourly resolution) from UK Met Office archive for 181 substations from 2011. (Ambient Temp, Wind Speed, Solar Radiation)
  - Additional real time data:
    - 5 units have additional sensors and substation weather stations:
      - Temperature of cooler inlet, cooler outlet, bottom oil pipe, top oil pipe
      - Oil flow rate sensors

ConCEPT: Condition and Climatic Environment for Power Transformers

- Developed data driven models were shown to:
  - Be able to account for weather condition and produce top oil temperature predictions that had far lower RMSE than the IEEE Annex G model.
  - Be an improvement on traditional algorithms for predicting WTI temperatures allowing identification of anomalous thermal behaviour in real time and also assess thermal performance of similar age/design units from the same manufacturer.
  - Example: Unit I has highest operating temperature



Mean Error	Measurement		
Model	**G**	**H**	**I**
G	-0.05 ˚C	-3.67 ˚C	3.95 ˚C
H	3.66 ˚C	-0.01˚C	7.91 ˚C
I	-3.28 ˚C	-7.2 ˚C	0. 37 ˚C

A. Doolgindachbaporn, G. Callender, P.L. Lewin, E.A. Simonson, G. Wilson, 'A Top-Oil Thermal Model for Power Transformers That Considers Weather Factors', IEEE Transactions on Power Delivery, 37(3), 2021, pp 2163-2171, ISSN 0885-8977

A. Doolgindachbaporn, G. Callender, P.L. Lewin, E.A. Simonson, G. Wilson, 'Data driven transformer thermal model for condition monitoring', IEEE Transactions on Power Delivery, 37(4), 2021, 3133-3141, ISSN 0885-8977

Replacements for Mineral Oil

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- Project started September 2022, will conclude December 2024. With aim of developing better understanding of the thermal performance of Mineral Oil alternatives such as synthetic and natural esters. Agreed workstreams:
  - Modelling of thermal conditions for operational transformers filled with ‘alternative’ liquids (CFD+FEA)
  - Understanding the degradation processes of natural ester liquids
  - Development of thermal network models for BAU activities (e.g IEEE Annex G)
  - Performance and degradation of alternative liquids.
- Suppliers of ester-based insulation fluids approached by the project team to take part in the project.
  - 5 Manufacturers supplying 10 different oils
  - 4 synthetic esters, 4 natural esters, 1 bio fluid, 1 mineral oil (for reference)

University of Southampton

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- Sample preparation and ageing

> - Synthetic esters – oils A, F, H, J
> - Natural esters – oils B, E, G, I
> - Bio-based hydrocarbon (biofluid) – oil C
> - Mineral oil – oil D

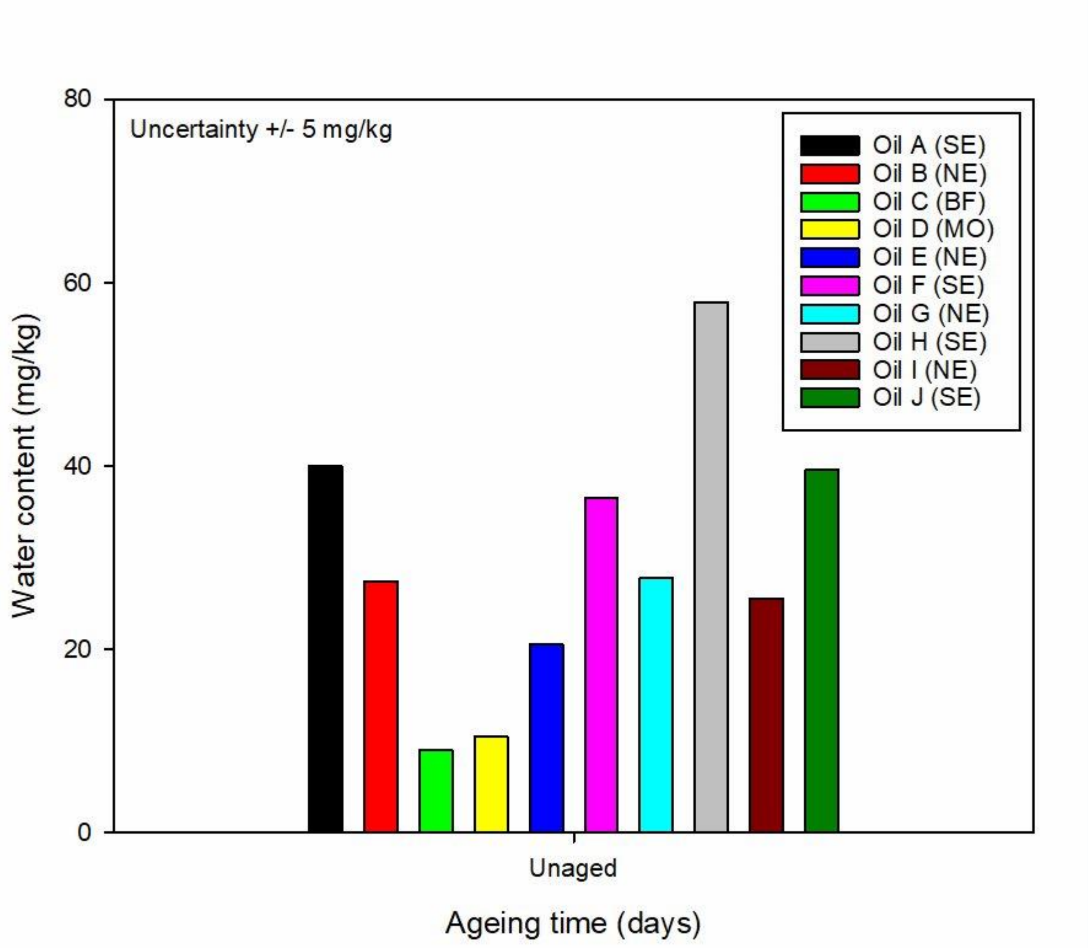
- Oils dried to minimal water content at 60 ˚C (4 hours)
- Kraft paper (0.1 mm thickness) cut into 42 mm disks and dried at 100 ˚C (2 hours)
- Copper sheet polished with fine grade sandpaper and washed with acetone
- Vials = 25 ml of oil, 12 sheets of paper (1.25 g dry weight) and copper (selected samples only) – 12 cm^2 surface area
- Paper was then vacuum impregnated at 60 ˚C
- Aged in fan oven at 130 ˚C for up to 21 days – headspace minimised and vials capped to minimize oxygen ingress during ageing

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- Experimental techniques
  - **Chemical properties**
    - Density measurements – weight of 10 ml samples/suppliers datasheets
    - Degree of polymerisation (DP) - IEC 60450 – viscometric method (paper extracted with acetone)
    - Water content - IEC 60814 - Karl Fischer titration method (oil)
    - Acid number - IEC 62021 - KOH titration method (oil)
    - Infra-red (FTIR) - Thermo-Scientific Summit X/Everest Diamond ATR (oil)
  - **Physical properties**
    - UV/Vis spectroscopy – Perkin Elmer Lambda 35 with 10 mm path length quartz cells (oil)
    - Viscosity – glass capillary tube method at 20 ˚C (ASTM D445) (oil)
  - **Dielectric properties**
    - Dielectric spectroscopy at 20 ˚C – IEC 62631 (paper/oil)
    - AC ramp to breakdown measurements - ASTM D149 (paper/oil) – average of 10 breakdowns
- Some results....

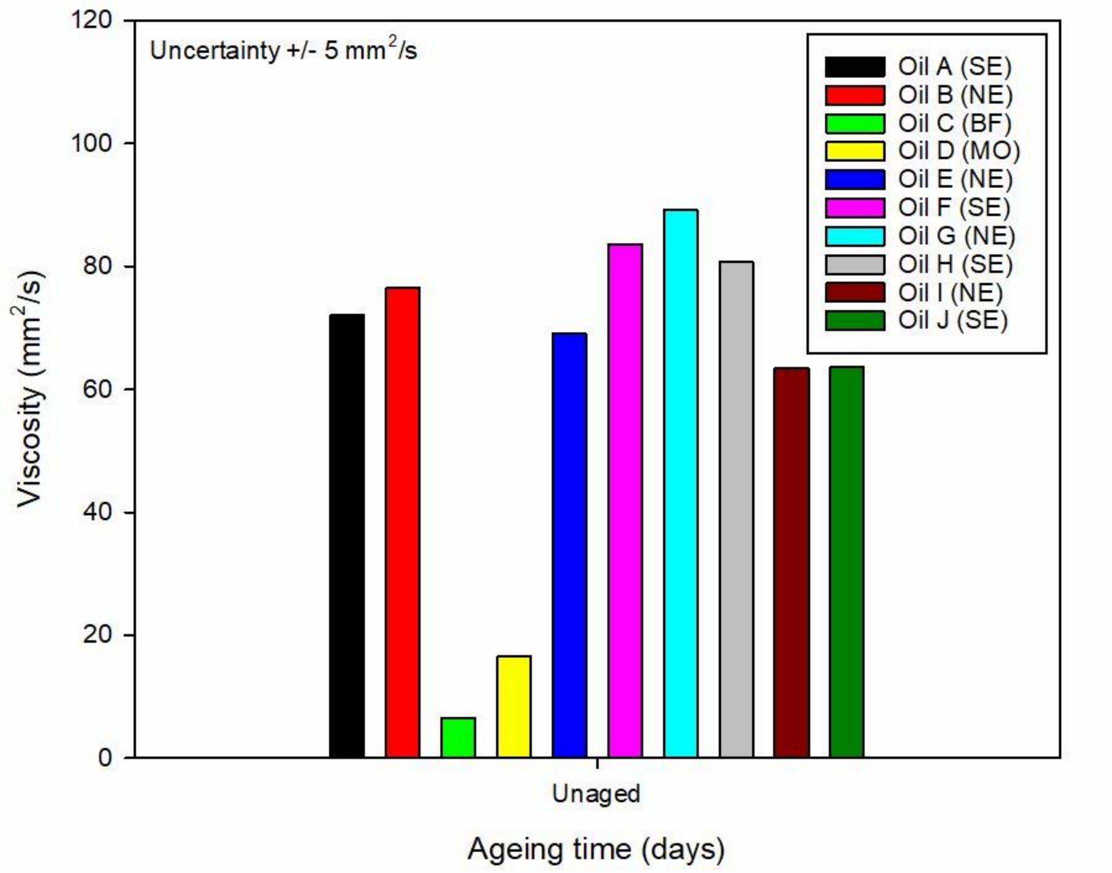
IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- **Unaged Water Content**
- The water content of the synthetic esters is higher than the natural esters, reflecting their higher water saturation value (2200 PPM vs. 1100 PPM)
- Mineral oil and the biofluid have much lower values (saturation 55 PPM)
- Maximum acceptance values for new mineral oil are 30 (IEC 60296) and 200 for ester oils (IEC 61099, IEC 62770) – all oils therefore meet the requirements of the standards



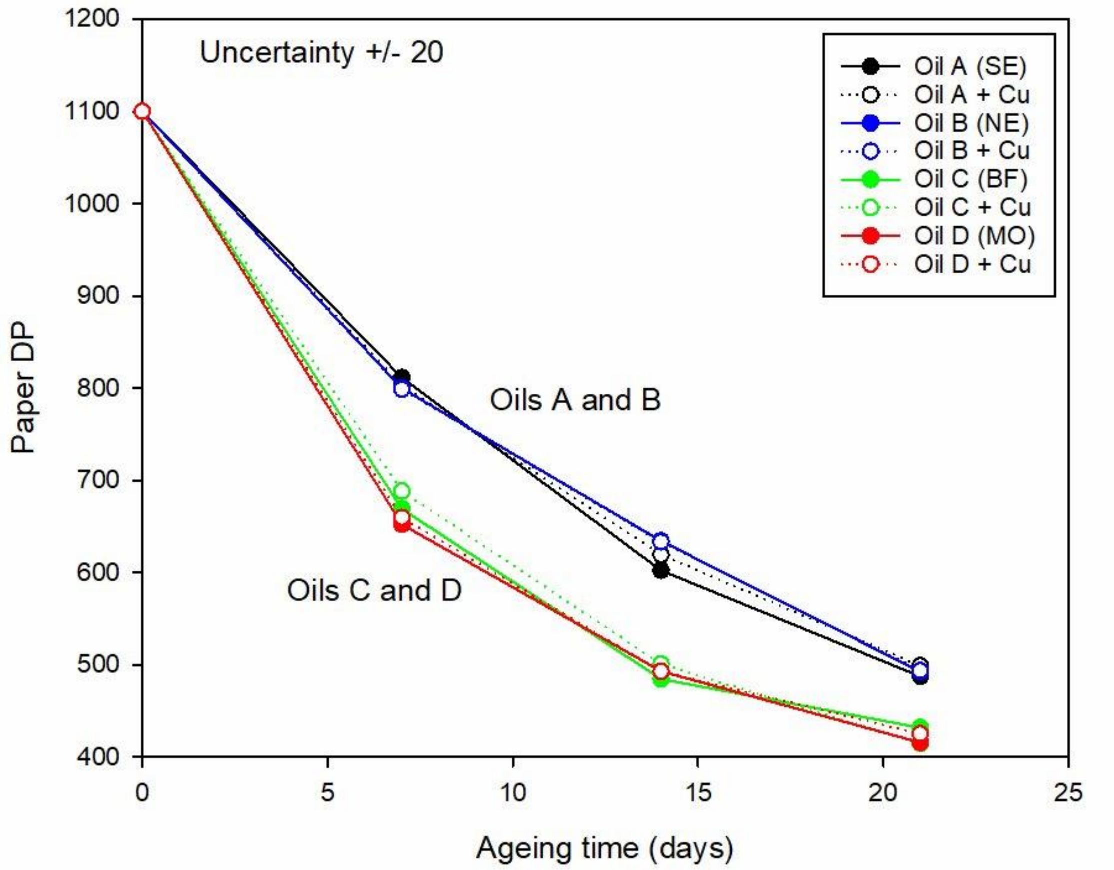
IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- **Unaged Viscosity**
- Viscosity of ester oils is around five times higher than that of mineral oil
- That of the biofluid is lower than mineral oil which could improve cooling efficiency in plant
- Maximum acceptance values at 40 ˚C for new mineral oil are 12 (IEC 60296), 35 for synthetic esters (IEC 61099) and 50 for natural esters (IEC 62770).
- Since the viscosity is a factor of 2.3 higher on moving from 40 to 20 ˚C - all oils meet the recommendations of the standards



IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

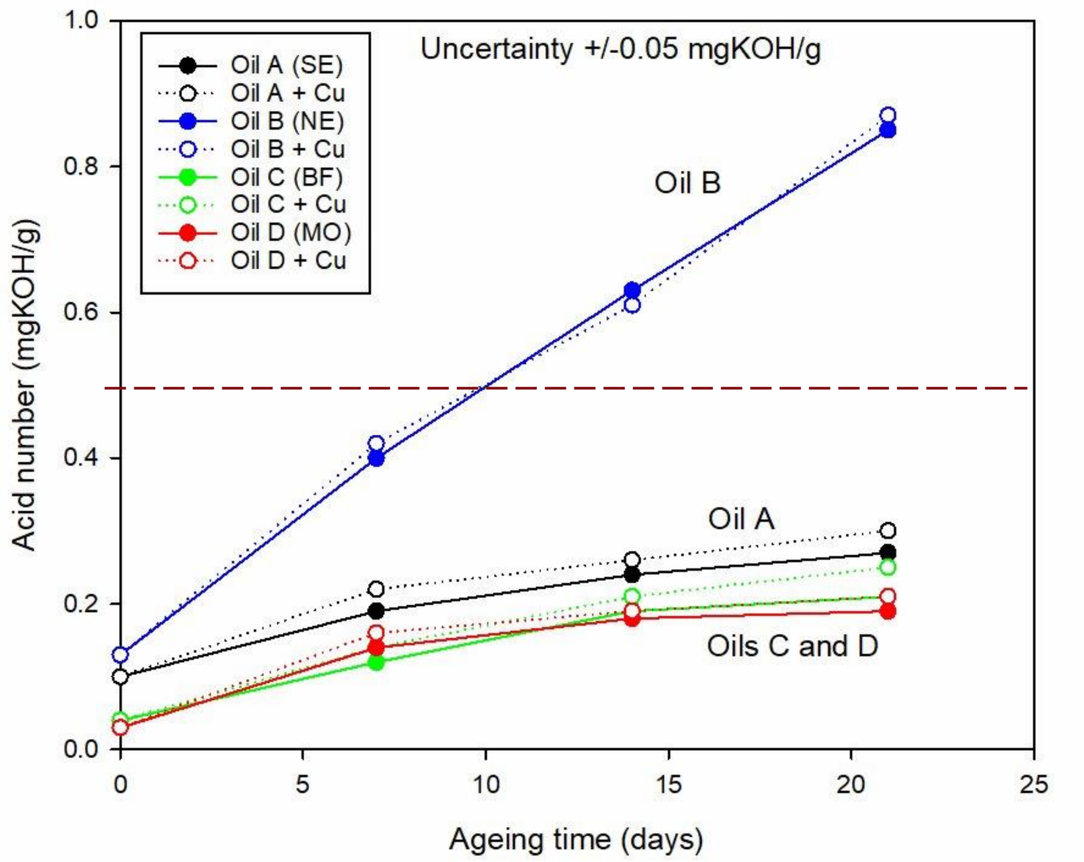
- **Thermal Aging and Paper DP**
- Preserving the DP of the paper is important as transformer lifetime is dependent on the mechanical integrity of the paper
- The ageing was chosen to encompass the lifecycle of paper in a mineral oil filled transformer (DP 1100 to 400)
- Biofluid follows the behaviour of mineral oil
- Ageing under either ester oil results in a higher value of DP;
- The water resides in the oil not in the paper
- Long chain acids are formed on ageing which are not destructive to the paper
- Copper makes no difference



I.L. Hosier, T Andritsch, P.L. Lewin, G. Wilson, 'A Study of Ageing and Gelling in Natural Ester Oils', International Conference on Dielectrics (ICD), Toulouse, France, July 2024

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- **Thermal Aging and Acid Number**
- On ageing, the acid number of the natural ester increases dramatically whilst the remaining oils show a more gradual increase/levelling out
- Acceptance limits for service aged mineral oil are 0.2 (IEC 60422), 2.0 for synthetic esters (IEC 61023) and 0.5 for natural esters (IEC 62975), hence the natural ester only meets the requirement for ageing times < 10 days
- In both esters, long chain acids are formed which are not detrimental to the paper as same DP value in both fluids
- Copper makes little difference



I.L. Hosier, T Andritsch, P.L. Lewin, G. Wilson, ‘A Study of Ageing and Gelling in Natural Ester Oils’, International Conference on Dielectrics (ICD), Toulouse, France, July 2024

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- **Chemical Compatibility 1**

Aims

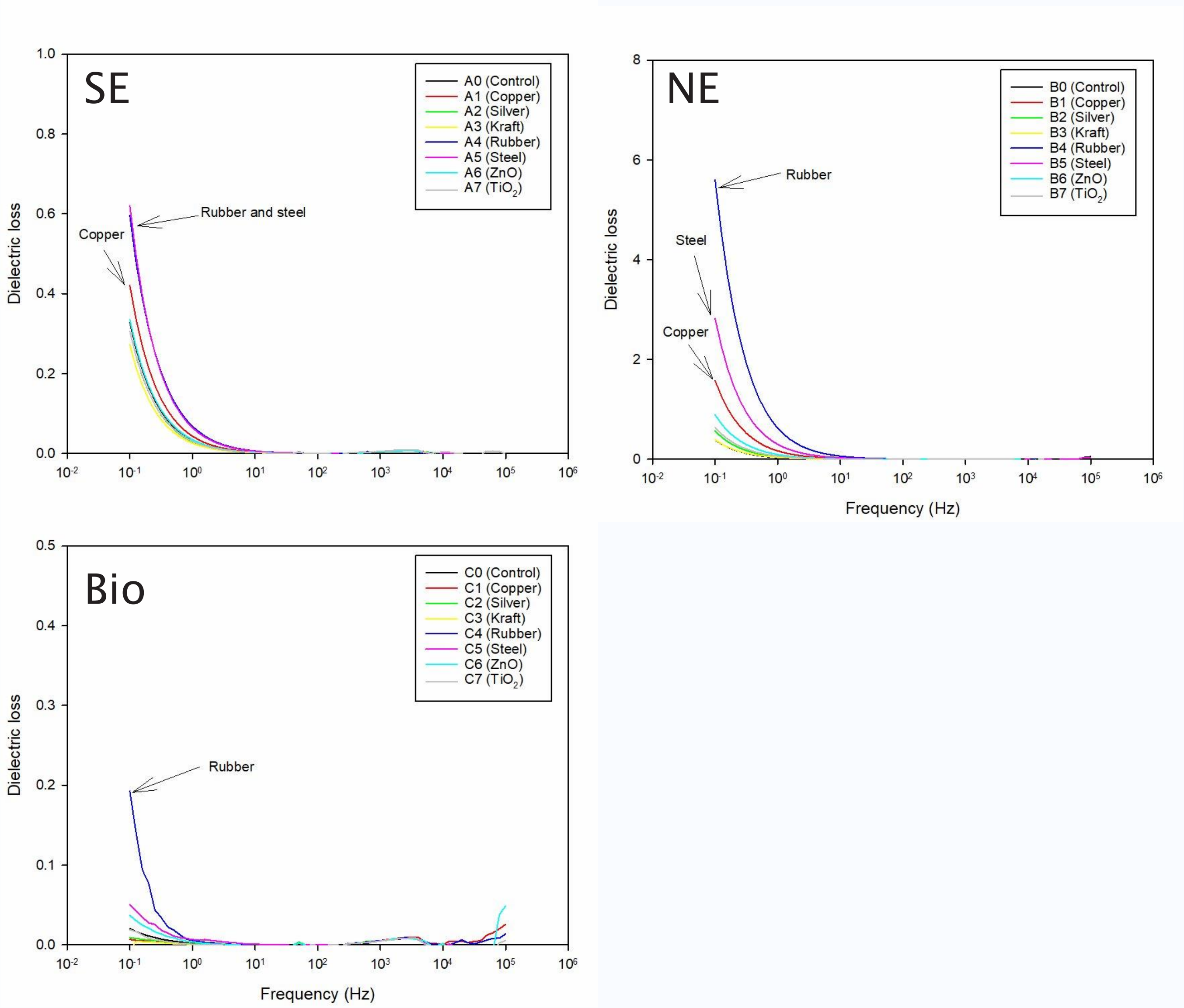
- ASTM D3455-11 test for compatibility of various materials with ester oils
- Involves adding materials to oils in prescribed amounts then moderate thermal ageing
- Testing for changes in chemical, physical and dielectric properties vs. a control sample
- Similar study in literature indicated detrimental effects of rubber but didn't consider metals

Methodology

- Materials are copper, silver, kraft paper, nitrile rubber, steel, ZnO and TiO2
- Separate 25 ml oil samples for each material
- One synthetic ester, one natural ester and the bio fluid have been assessed
- Aged at 100 ˚C for 164 h
- Chemical changes – water content, acid number, Fourier transform infrared (FTIR)
- Physical changes – oil colour (UV/Vis spectroscopy) and viscosity
- Dielectric changes – dielectric spectroscopy (dielectric loss or dissipation factor)

IDEAL: Insulating Dielectrics: Esters and Alternative Liquids

- **Dielectric Loss**
- All show an uplift at low frequencies due to electrical conductivity (water)
- Rubber has the most pronounced effect, followed by steel then copper
- At 50 Hz the loss is increased by rubber, steel and copper
- ASTM standard stipulates a Dielectric Dissipation Factor <0.2 % and only NE with rubber, steel and copper exceeds this limit



Latest work: Improving ageing markers

ADAPT: Ageing Dynamics and Analysis of Power Transformers

- Started December 2023, aim is to investigate if additional paper ageing markers can be identified in transformer oil.
- Workstreams include
  - Identification and quantification of furan markers
  - Identification of other ageing markers
  - Assessing impact of additives on furan concentration
  - Ageing markers in ester oil

Conclusions

Conclusions

- The National Grid/University of Southampton collaboration grew from initial work into the creep stress failure of an interphase barrier board.
- TDHVL working with the School of Chemistry have:
  - Identified the mechanisms for formation of copper sulphide on conductor surface and in the insulating paper.
  - Improved passivation and oil reclamation processes for units with corrosive sulphur issues.
  - Developed a quantitative approach to measure elemental sulphur content in ppb.
  - Considered changes to transformer rating assumptions to mitigate rising ambient temperature over the next century.
  - Demonstrated that historical data for a transformer fleet can be utilised to identify units that have thermal issues.
- Currently we are:
  - Assessing long term performance of esters and other alternative fluids
  - Investigating paper ageing markers and their suitability to mineral oil replacement fluids

Acknowledgements: The team 2014-date

TDHVL

- Pedro Amaro (PhD 2015)
- George Callender
- Sunny Chaudhary
- Atip Doolgindachbaporn (PhD 2021)
- Kevin Goddard
- Alex Holt
- Ian Hosier
- Prof Paul Lewin
- Mark Mitchinson
- James Pilgrim

Chemistry

- Prof Richard Brown
- Marco Facciotti (PhD 2015)
- Sergio Garcia (PhD 2022)
- Prof John Langley
- Prabaharan Thiruvengetam

National Grid

- Ruth Hooton
- Gordon Wilson
- Paul Jarman

The Tony Davies High Voltage Laboratory

University of Southampton