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Deliverable Report

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This report presents a review of Asset Health implications of the deployment of the CELSIUS techniques, including the use of the Celsius Daily Rating. This report primarily considers 11/0.4kV distribution transformers. A second report will be issued in due course for cable assets, once more site data becomes available.

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Executive Summary

The CELSIUS project seeks to identify means by which additional capacity can be released in the LV network. In order to achieve this, the project is investigating the thermal conditions seen by LV network assets (in particular cables and transformers). Electricity North West (ENW) have installed thermal monitoring equipment within 520 distribution substations, allowing the conditions seen by these assets to be recorded over time.

This data has been used by Ricardo Energy & Environment, who have developed a number methodologies for:

- Calculating the hot spot temperature of a transformer using its external tank temperatures, and local ambient conditions.
- Identifying "Thermal Factors" (for example, substation building design) which will affect the temperature of a given asset.
- Use this information to determine the potential up-rating that might be available for a given transformer asset, installed in a certain location.

University of Southampton has been contracted to review the implications of utilising the above methods for the Asset Health of a transformer. This report presents our initial findings, split into four primary components.

- Part 1 reviews the context to the work, including identification of relevant information from within ENW specifications.
- Part 2 presents a review of the main temperature related factors that can lead to degradation of a transformer, focusing on the winding insulation and the condition of the insulating oil. Evidence from the technical literature is used to explain the degradation pathways that may occur, and how they might be affected by changing temperatures and loads as a result of the CELSIUS methodology being deployed onto a transformer.
- Part 3 conducts a brief modelling study to illustrate how the remaining life of a transformer may be affected by the deployment of the CELSIUS methodology. Thermal models are solved in conjunction with loss-of-life models in order to demonstrate the degradation which might be seen by the transformer under the four primary loading regimes identified by Ricardo. The predicted change in loss of life, compared to the design assumptions, is identified.
- Part 4 provides recommendations which might be considered by ENW in order to ensure that the benefits of the CELSIUS methodology can be realised without significant adverse impact on asset health, or asset life expectancies.

Version History

A version history for this report is included below.

Date	Document Version	Comments
29/10/2018	V0	Initial issue of draft report
31/10/2018	V1	First formal issue after client comments

Contents

1.0 Introduction

1.1 CELSIUS Project

Celsius is funded via Ofgem's Network Innovation Competition (NIC) funding mechanism. The project was authorised to commence in December 2015 and is expected to be complete by March 2020. It explores innovative, cost-effective approaches to managing potentially excessive temperatures at distribution substations, which could otherwise constrain the connection of low carbon technologies (LCTs).

A two-step structured approach used to gather data that will increase Electricity North Wests (ENW) understanding of thermal behaviour within their LV asset base, and potentially release additional capacity to customers. With greater knowledge of the behaviour of these assets, ENW can support the connection of increasing numbers of low carbon technologies more quickly and at lower cost.

In the first phase of the project, load and temperature monitoring has been deployed to 520 distribution substations, allowing data to be gathered across a range of environmental, load and seasonal factors. The substation portfolio selected is intended to be representative of 80% of the substation population in Great Britain. The output from this work will be a simple 'Thermal Ratings Tool' (developed and delivered by Celsius project partner Ricardo) which will accurately indicate an asset's internal operating temperature using low cost external retrofit sensors. This knowledge will enable ENW and other network operators to release the maximum capacity from existing assets without degrading their health and reliability.

1.2 Scope of Works (Asset Health study)

University of Southampton have been engaged in the CELSIUS project to provide internal technical review of a number of components, including the Hot Spot Temperature calculations undertaken by Ricardo. This specific deliverable consists of an Asset Health Study related to transformers. The contracted scope of work includes:

- A review of published knowledge and service experience concerning the effect of operating temperature on high voltage assets.
- Identification of possible asset health implications of deploying the hot spot temperature calculation approach.
- Review of the potential asset health implications of deploying the range of Asset Cooling solutions identified during the CELSIUS project, including both passive and active options.

For the purposes of this initial report, our focus is on the first two bullet points above. The scope of the report is limited to transformers; a second report will be issued in due course for underground cables, once additional site measurement data becomes available, with a review undertaken later in the project on the effectiveness of the cooling techniques (which have been installed during summer and autumn of 2018).

1.3 ENW Transformer Rating Policy

Prior to considering the performance of the CELSIUS methodology, it is important to consider the context in which it must operate. As a retrofit solution, it will not lead (at least in the short term) to fundamental changes to transformer ratings used on the distribution network, but is intended to complement the policies and procedures already in place within ENW.

Transformer ratings within ENW are calculated according to CP382 "Transformer Ratings"

Issue 3, July 2009 [1]. This document outlines the transformer rating methodology used by ENW across the full range of voltages in the distribution network, including 132kV assets. A brief summary of the existing practice is given here, to allow subsequent comparison with the CELSIUS methodology.

1.3.1 Rating Definitions

The ratings contained within the document have been determined using IEC354:1991. Although this was superseded by IEC 60076-7 "Loading Guide for Oil-immersed transformers" [2], ENW concluded that the revision to the standard did not lead to any significant change in rating values. A range of ratings are defined, with the specification of "continuous", "normal cyclic" and "long term emergency" being the most relevant to this work. For reference, the definitions of these terms are reproduced below:

- **Continuous:** a loading that can be applied continuously to the transformer that ensures negligible loss of insulation life within the transformer at a specified ambient temperature condition.
- **Normal Cyclic:** A loading with cyclic variations (the duration of the cycle usually being one day) that is regarded in terms of the average amount of ageing that occurs during the cycle. A higher loading than the continuous loading is applied during part of the cycle, but from the point of view of thermal ageing, this loading is equivalent to the continuous loading at normal ambient temperature. This is achieved by taking advantage of low ambient temperature or low load currents during the rest of the load cycle. The load cycle adopted in this CP is one with 8 hours at the peak value of the load cycle with a previous 16 hour period at no more than 75% of the peak load.
- **Long Term Emergency:** An increased cyclic loading (8 hours at the peak load, previous 16 hour period at no more than 75% of the peak load) which will allow an acceptable loss of insulation life over an extended time to cover operational problems, for example, the replacement time of a failed transformer of a group. The Long-Time emergency ratings given in this document can be used for a continuous period not exceeding 6 months.

A large percentage of the CELSIUS transformer installations are single transformer sites, where CP382 states that the planned load shall not exceed the Normal Cyclic rating under naturally cooled conditions. Paired transformer sites are planned such that the substation may be loaded up to the Long Time Emergency rating of one transformer without any additional safeguards.

The Normal Cyclic ratings are only applicable to a given site if the daily load factor is less than 0.833, and the total duration of the peak load is less than 12 hours in 24 hours (including multiple peak load profiles).

1.3.2 Standard Distribution Transformer Ratings

Section 5.5 of CP382, Table 9, provides a summary of the ratings of distribution transformers. These ratings are based on ONAN operation, and ***it is explicitly noted that the ratings do not allow for factors such as phase unbalance, restricted ventilation or solar gain***.

These ratings are calculated using the following assumptions:

- Standard IEC 60076 Distribution Transformer thermal parameters
- Hot spot temperature for continuous rating operation of 98°C (assuming a 20°C ambient). For Normal Cyclic, a value of 105°C is permitted. For Long Term Emergency, the winding hot spot may be 115°C.
- The top oil temperature is required to be not more than 85°C for Continuous operation, and 90°C for Normal Cyclic.

Table 1 - Ratings for Distribution transformers as per CP382

Load Type	Ratings (% of ONAN rating)			
	30°C	20°C	15°C	0°C
Continuous	90	100	105	120
Normal Cyclic	100	105	110	125
Long-Time Emergency Cyclic	105	115	120	135
3 day Emergency Cyclic	115	125	130	140
3 hour Emergency	120	130	135	150
30 minute Emergency	130	135	140	150
3 minute auto switching	150	150	150	150

1.3.3 ES322 Transformer Specification

ES322 “Ground Mounted Distribution Transformers – Issue 8” [3] describes the fundamental specification of three phase distribution transformers rated from 50kVA to 1000kVA for use on the ENW network. The following features of this specification are relevant to this work:

- Unless otherwise specified in ES322, products shall conform with IEC 60076 (Section 3).
- The minimum life expectancy should be 40 years (Section 5.6).
- Transformer Rated Power is to comply with ratings specified in Appendix B, Table B1 of ES322. Cyclic and overload capabilities shall comply with the IEC60076-7 requirements, unless otherwise stated (Section 7.1).
- Losses from the transformer shall comply with the European Union Commission Regulation for Transformers No 548/2014. This specifies maximum Iron and Copper losses for given transformer ratings. (Section 7.7.2).
- Oil within (new) transformers should be napthenic in nature and comply with the requirements of IEC 60296, along with a number of ENW mandated additions (Section 9).

In addition, reference is made within ES322 to BS EN 50180 (Specification for Bushings above 1kV up to 36kV and from 250A to 3.15kA for liquid filled transformers). For ease of reference, Table B1 (which specifies standard ratings) is reproduced below.

Table 2 - Reference Transformer kVA Ratings from ES322 Appendix B

Voltage Ratio	kVA Rating	Impedance	Sound Power Level (dB(A))
6600/433-250V	25	4.75%	45
	50	4.75%	45
	100	4.75%	48
	200	4.75%	52
	315	4.75%	54
	500	4.75%	56
	800	4.75%	58
	1000	4.75%	59
11000/433-250V	25	4.75%	45
	50	4.75%	45
	100	4.75%	48
	200	4.75%	52
	315	4.75%	54
	500	4.75%	56
	800	4.75%	58
	1000	4.75%	59

TABLE B1 –TRANSFORMER RATINGS

1.4 ENW CBRM Policy

ENW operates a Condition Based Risk Management Methodology according to CP151, Issue 2, August 2017. This document identifies the general principles by which asset health is reported to Ofgem, including the assessment of Health Index (HI) and Consequence of Failiure (CoF, or Criticality).

It is understood that for condition related data, since 2004, a scale of 1 to 4 is used, where 1 corresponds to an “as new” condition and 4 is a condition that is unacceptable and indicative of end of life. This system is being replaced in 2018, with a new system intended to reduce the subjectiveness of the previously used scale. We note that for distribution transformers, there is currently no requirement for regular oil sampling (as would be the case for 33kV and above). As such, most of the condition-based information concerning the asset health of these units comes from external visual inspections (for example, to identify oil leaks, areas of corrosion of the tank). Such factors would not allow interpretation of temperature related degradation of the transformer.

2.0 Review of thermal degradation in Transformers

A review is presented of the load-related mechanisms by which a transformer can be expected to degrade. This allows temperature related effects to be identified, and subsequently used to assess the Asset Health impact of deploying the CELSIUS methodologies. The electrical integrity of the transformer is primarily determined by the condition of the paper insulation on the windings, and the oil which surrounds them.

It should be noted that it is not the intention of this study to provide a hugely detailed scientific review of these fields; indeed, significant research is still being undertaken worldwide to provide a thorough understanding of the ageing process of transformers alongside many other electrical assets. Instead, we seek to highlight the key considerations in a manner which is accessible to the reader. A range of supporting references are provided for interested parties who wish to gain a deeper understanding of particular topics.

2.1 Mechanisms of Paper Ageing

This report is limited in scope to conventional kraft paper insulation, as is used on the vast majority of ENWs transformer assets; no consideration is given to thermally upgraded papers, which are typically not used for Distribution transformers. To guide the reader, the report illustrates the key issues through answering a range of functional questions.

2.1.1 What are the functional requirements for (healthy) insulating papers?

Before considering the factors that make an insulating paper "healthy" or otherwise, it is useful to state the functional requirements that exist for transformer winding insulation:

- **Electrical:** electrical breakdown strength must be sufficient high to withstand the turn-to-turn electric fields. Dielectric loss of the papers should be small.
- **Mechanical:** able to withstand increases in tension from the initial lapping process, but also because of thermal expansion of the winding due to increases in load, or movement due to short circuit forces.
- **Thermal:** a sufficiently low thermal resistivity to ensure that the temperature drop across the insulation is low, allowing heat to be readily transferred to the oil.
- **Chemical:** sufficiently chemically stable to avoid degradation during the asset life.

All of these properties must be adequately available throughout the working life of the transformer, which may be in excess of 40 years (we note that ENW depreciate transformer assets over 40 years, but aspire to 60 year service life).

The most common insulating paper used for distribution voltage transformers is Kraft paper.

2.1.2 What is Kraft paper?

Kraft paper comprises approximately 90% cellulose, 6-7% of hemicellulose and 3-4% of lignin [4]. During paper manufacture, wood is chemically treated to reduce the content of lignin and hemicellulose. For transformer insulation, the most common method is the KRAFT process where wood is treated with a mixture of sodium hydroxide (NaOH) and sodium sulphate (Na_2SO_4).

Cellulose is a polysaccharide, these being a class of carbohydrates whose molecular structure consists of linked monosaccharide units. Cellulose consists itself consists of long unbranched chains or glucose units, with the general formula $(C_6H_{10}O_5)_n$. Hemicellulose, also known as pentosanes, are not actually related to cellulose in spite of the name. It is a fact a group of polysaccharides that join to cellulose fibres via hydrogen bonds.

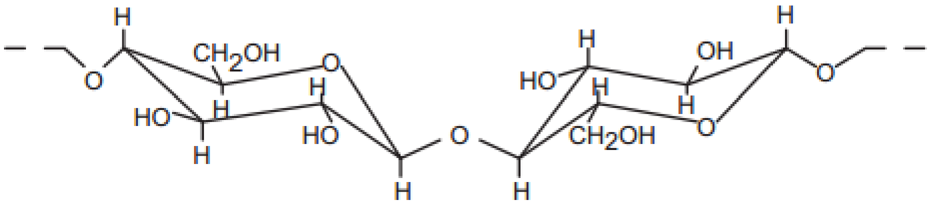

Figure 1 - Chemical structure of cellulose

2.1.3 When is paper at the end of its useful life?

The ability of the paper to meet the functional requirements outlined in Section 2.1.1 depends on a range of physical properties. The direct electrical measurement of the remaining life of a paper insulated, oil-immersed winding is not a straightforward task. Many of the tests that could be undertaken are destructive in nature, meaning that they can't be applied to transformers in the field. Over time, a range of laboratory tests have been conducted which sought to quantify the loss of useful life of such insulation.

At first glance, it might seem that the electrical requirement placed on the paper is actually the most critical, however it is relatively rare to see a paper which has become electrical weak yet retains full mechanical integrity. Conversely, paper which has become brittle is likely to be weak electrically. For this reason, the "loss of life" of transformer insulating papers is normally based on a mechanical property, rather than directly on an electrical one.

It should be noted that excessive mechanical degradation of the paper can also have other undesirable effects; brittle paper which breaks away from the windings can block cooling ducts, further aggravating the temperature increase. Water is produced as a byproduct of the degradation process, and this can build up in the insulation and reduce its resistivity [5].

2.1.4 Why is Degree of Polymerisation (DP) Important?

The electrical integrity of paper insulation systems has been shown to be closely linked to the mechanical integrity of the paper. The cellulose consists of chains of cyclic β-D-glucopyranosyl units, where the number of units per chain is the degree of polymerisation, typically abbreviated to DP. Lundgaard explains that the "chains associate in both crystalline and amorphous regions to form microfibrils, which again form fibrils and finally fibres. Most of the mechanical strength of the paper is due to its content of these fibrils and fibres" [6].

The higher the DP, the higher the tensile strength, as shown by Hill et al in Figure 2 [7]. It is normally assumed that paper is life expired at DP < 200.

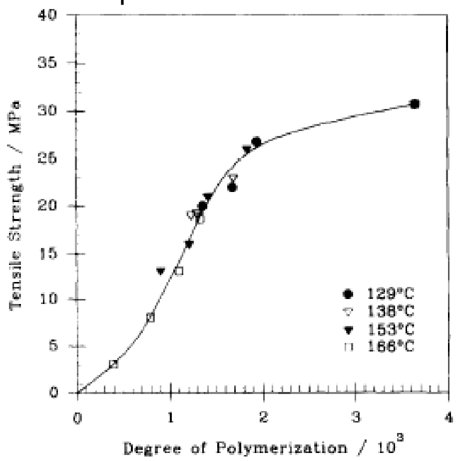

Figure 2 - Relationship between tensile strength and degree of polymerisation for artificially aged paper, reproduced from [7]

2.1.5 What causes DP to reduce?

A wide range of studies have been undertaken which have shown that the DP of papers reduces as the paper ages. For the DP to reduce, this implies that there are less linkages between the polymer chains, which tends to mean that the polymer chains have become shorter. As emphasised by Hill, it is important to note that the DP is a global average, and that in reality the ageing state of the paper will be determined by the distribution of molecular weights present within the paper (noting that shorter cellulose chains will have a lower molecular weight).

It is not the intention of this report to provide a comprehensive review of the processes by which this occurs. A number of factors have been shown to be important. These include:

- Oxidative degradation – Shroff notes that “cellulose is highly suspectible to oxidation, the hydroxyl groups being the weak areas where carbonyl and carboxyl groups are formed and can eventually cause secondary reactions giving chain scission” [8]
- Hydrolytic degradation – resulting in cleavage at the glucosidic linkage.
- Thermal degradation – typically leading to severing of the cellulose chain, temperature also affects the rate of hydrolytic and oxidative degradation processes.

All of the above processes are found to be linked in some way to the load, and hence temperature, of the transformer. DP is typically measured from testing the viscosity of polymer solutions according to techniques such as IEC 60450.

2.1.6 What effect does temperature have on DP loss?

The first thing to note is that the temperature does not just influence “thermal” degradation, but will affect the rate of many other processes, specifically oxidative and hydrolytic processes as noted above. This means that separating out the loss of DP due to temperature alone is not actually straightforward.

Emsley explains in [9] that the degradation process can be expected to obey the Arrhenius law of reaction kinetics, which relates the log of the reaction rate constant to the absolute temperature. Values for the activation energy of degradation of cellulose in oil will vary depending on the specific reaction; oxidative degradation has an activation energy of approximately 85kJ/mole, while the equivalent for the hydrolytic process is ~120kJ/mole. A simple Arrhenius type model would suggest that the reaction rate is constant. Such a process would be described according to:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt = \left(Ae^{-E_A/RT}\right)t \qquad (1)$$

DP_0 is the initial DP, DP_t is the DP at time t, R is the gas constant, T is the absolute temperature, E_A is the activation energy and A is termed the pre-exponential factor. However Emsley and Heywood have shown in [6] that experimental data fitted to an equation where the rate constant decreases with ageing time as follows:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = \frac{k_1}{k_2}\{1 - e^{-k_2 t}\} \qquad (2)$$

Here k_1 and k_2 are constants. They also note that the behaviour of the degradation can change at higher temperatures as different processes begin to take effect. Likewise Hill notes in [7] that above “140-150°C the defects in the polymer chains arising as a result of furan formation may reach a critical size and begin to accelerate significantly the rate of crack propagation, thus accelerating the onset of mechanical failure”.

The maximum winding hotspot temperature limit is selected with reference to the kinetics of the degradation; this explains why Section 1.3 shows a higher limit for emergency loading. As an example of how the temperature can affect the rate of DP loss, Figure 3 shows the correlation between DP and ageing time at different temperatures for paper with 3% moisture (noting that 3% is rather high, and will further accelerate the degradation process).

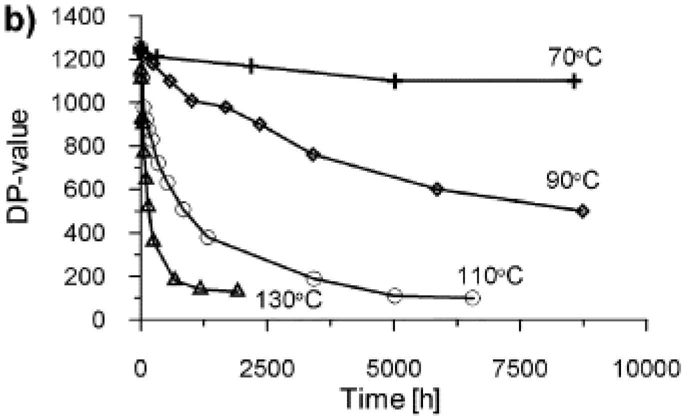

Figure 3 - DP versus ageing time for paper with 3% moisture added [6]

It is evident that operating with sustained, high winding hot spot temperatures leads to much more rapid degradation. In contrast, the change at 70°C can be seen to minimal after almost 1 year. This explains why the DP of many lightly loaded, yet old, transformers can often be found to be quite high.

In the broadest possible terms, this also means that reducing the operating temperature will also increase the life. Shroff quotes an approximation as being that a reduction of operating temperature by 10°C can lead to an increase in the life of the paper by a factor of 3 [8]. This explains why the application of the CELSIUS methodology must be done with considerable care, as operating transformers for prolonged periods with winding hotspot temperatures above 105°C will lead to significant ageing.

2.1.7 What about water?

During manufacturing, the papers used in electrical insulation are carefully dried to remove water. After processing, the papers typically have a DP of around 1000 and a water content of 0.5% by weight. The chemical structure of cellulose is comprised of a large number of polar Carbon-Oxygen (C-O) and Hydrogen-Oxygen (H-O) bonds. These bonds play an important part in the response of insulating papers to water, as they will readily interact with other polar compounds dissolved within the oil. Such compounds are typically water and acidic compounds. For example, water content in oil is typically measured in mg/kg, but water in paper is often given as percentage by weight (note that 1% would equal 10g/kg) [10].

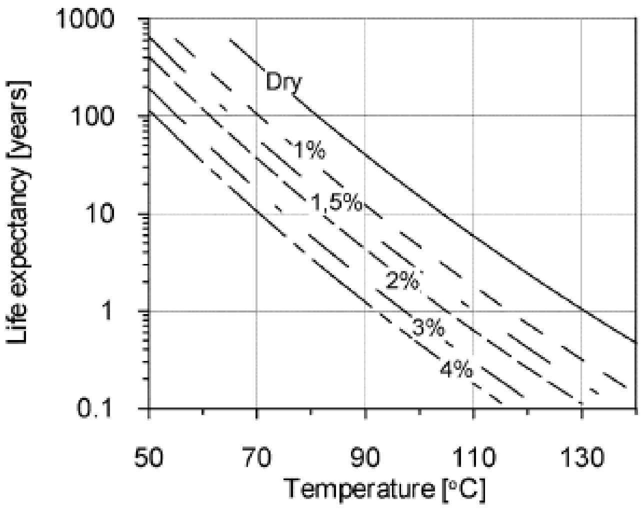

Figure 4 - Expected life for solid insulation and its dependence upon moisture and temperature, as reported by Lundgaard [6]

A further example from laboratory ageing experiments under nitrogen (to limit the rate of oxidative ageing) is shown below in Figure 5.

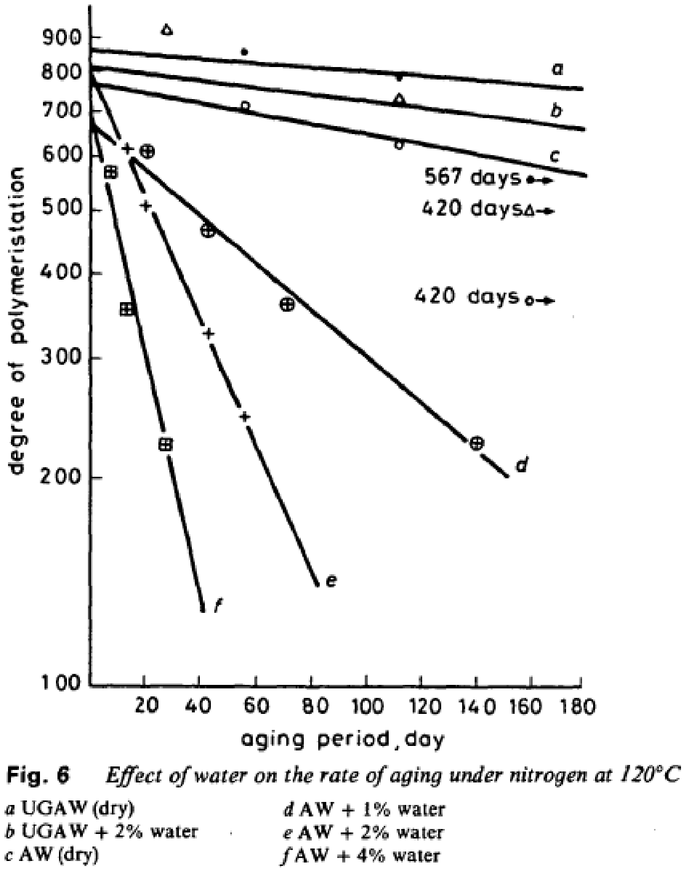

Figure 5 - Effect of water on ageing rate under nitrogen, reproduced from [8]

2.1.8 What about oxygen?

Cellulose can be quite susceptible to oxygen, as a result of the oxidative degradation pathway via chain scission. Figure 6 shows life curves obtained by Lelekakis, as a function of water content. It can be seen that a high oxygen level (16,000-25,000ppm) gave very significant reductions in life expectancy compared to the low oxygen environment (<6,000ppm). For transformers which are free breathing, rather than being sealed units or under a nitrogen blanket, this could have a significant impact on the overall life expectancy of the unit.

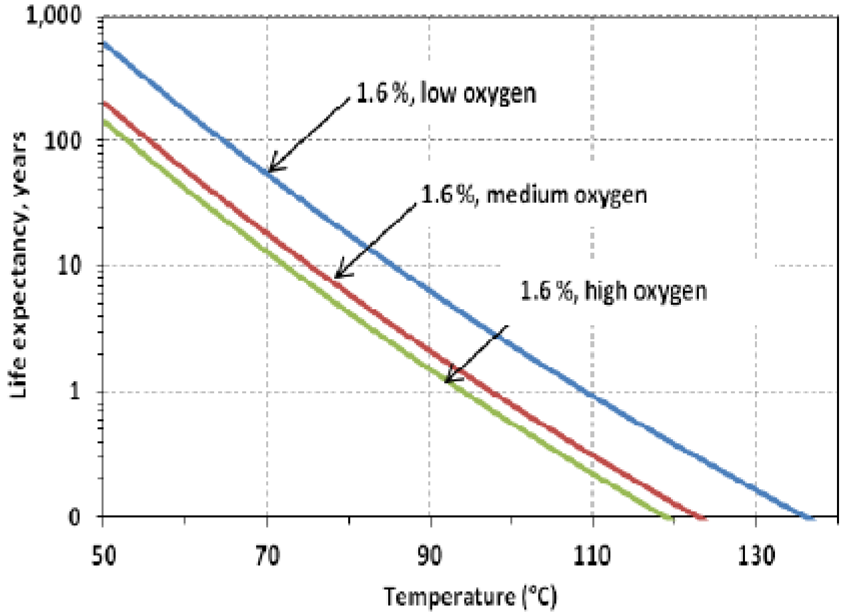

Figure 6 – Life curves for Kraft paper with 1.6% water in different oxygen environments, reproduced from [11]

A systematic study by Emsley et al in [9] also examined the effects of both water and oxygen together. Acting alone, oxygen was shown to be about one-third as efficient at degrading paper as temperature alone, but there was a very clear synergistic effect between temperature and water. The synergistic effects between temperature and oxygen were shown to be weaker. One particularly interesting finding was that water and oxygen actually had an antagonistic effect at lower moisture contents, meaning that the effectiveness of water at ageing the paper was reduced with increasing amounts of oxygen in the oil. Emsley notes that this could explain why the insulation in old transformers which have been scrapped can be found to be in a good condition even if the moisture level is higher than would normally be regarded as acceptable.

2.1.9 What about acids?

The activation energy for hydrolysis is considered to be ~110kJ/mole, higher than the activation energy for oxidation. The rate of 110kJ/mole is equivalent to a doubling of ageing rate for every 7.4 degrees temperature rise [12]. One important fact to note is that the degradation of organic matter, such as cellulose, results in the production of acid and water. This means that hydrolytic degradation can occur, even if there was no acid present in the oil of the transformer initially, as oxidative degradation will lead to the production of the acid.

Work undertaken by Lundgaard has demonstrated that low molecular weight acids accelerate the ageing rate of paper much more significantly than high molecular weight acids, which tend to remain in the transformer oil rather than migrating into the paper [13]. This was noted to be significant, as measured acid content by titration methods commonly used for condition assessment would not distinguish between the different molecular weights.

2.1.10 Life loss estimation methods

Many life loss estimation loss methods rely primarily upon temperature as a factor. The most common transformer rating methodologies are:

- IEC60076-7
- IEEE Transformer Loading Guide C57.91-2011

The IEEE guide in particular notes that improvements in transformer design have led to a reduction in the extent of insulation degradation due to moisture and oxidation, thereby claiming that thermally driven pathways were the only ones that needed to be considered. We should stress at this point that some of the distribution transformers which might need to be up-rated using the CELSIUS methodology may be older units with an imperfect maintenance history, meaning that insulation degradation due to moisture and oxidation should not be ruled out.

The application of the IEEE method leads to simplified life expectancy curves, taking the form of those seen in Figure 7.

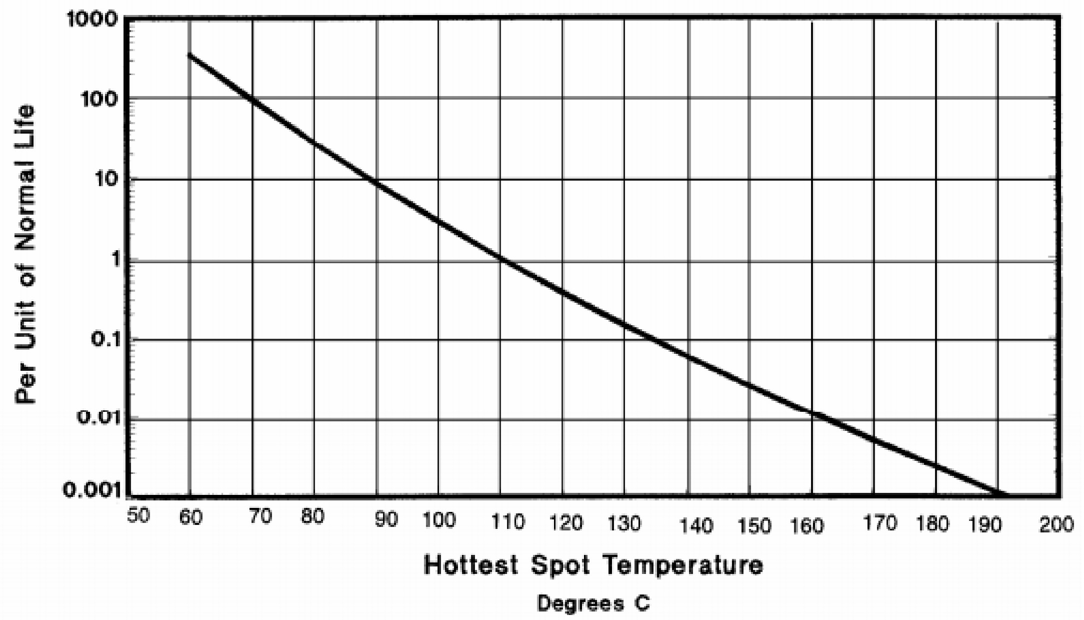

Figure 7 - IEEE C57.91 tranformer insualtion life curve, normalised to 110°C hot spot temperature (noting that this yields 20.5 years life according to IEEE C57.91)

A full description of the equations used by the IEC 60076-7 transformer loading guide is given in Section 3.2, where it is applied directly to results obtained by Ricardo as part of the CELSIUS works.

2.2 Mechanisms of Oil Ageing

Having reviewed the factors which might affect the ageing rate, and hence asset health, of the paper insulation of the winding, this section examines those factors which will affect the transformer oil.

2.2.1 Structure of Transformer Oil

From a chemical perspective, transformer oil is quite complex; a full review of all of the chemical species present is not of interest for this report, however a few key points are noted. Having been refined from crude oil, the typical transformer oil will contain a range of paraffinic and napthenic hydrocarbons. Paraffinic hydrocarbons are considered to have poor low temperature properties as they can crystallise as the oil cools, and have low thermal stability. In contrast, the napthenes tend to have good low temperature behaviour, but are more volatile and the flash point temperature is lower. Most transformer oils used at distribution level will also contain some aromatic hydrocarbons (ES322 requires polycyclic aromatics to be less than 3%).

It should be noted that changes in refining standards will also have led to variation in the content of transformer oils over time, and it can't be assumed that old oils have the same behaviour as those in new transformers.

2.2.2 Requirements for Transformer Oil

The functional requirements of transformer oil, as identified by Cigre in [10], can be summarised as:

- **Viscosity** should be low enough to ensure oil flows well enough to allow convective cooling, which is particularly critical for ONAN distribution transformers. The pour point must be sufficiently low that the oil will behave as needed under low temperature conditions.
- **Density** must be low enough to ensure that ice cannot float on the surface of the oil at low temperatures and lead to internal flashovers.
- **Moisture content** must be low to avoid impairing the electrical strength of the oil, and to minimise the amount of moisture that is absorbed into the paper insulation of the windings.
- **Breakdown voltage** is required to be high enough to prevent breakdown under all operational conditions, including any transient voltage events that might reasonably be expected.
- **Dielectric loss factor (tan delta)** should be low to ensure that the transformer operates efficiently, otherwise significant thermal losses could occur.
- **Contaminants and particles** should be absent, as these are known to reduce the electrical strength.
- **Refining requirements** include a low sulphur content, low furan content (to enable degradation monitoring) and a low acidity.
- **Oxidation stability** should be high to minimise the production of acids and sludge in the oil. The former may accelerate the degradation of the paper, and the latter may reduce the effectiveness of the cooling cycle.

2.2.3 The effect of oxidation

For most oils in use in transformers, oxidation will be the primary degradation pathway. The chemical process by which the oil degrades is complex, but a short summary is given here. Oxygen will react with the hydrocarbons via a free radical process, which leads to the generation of unstable hydroperoxides which then decompose to form ketones and water. The ketones themselves can also be oxidised to form carboxylic acids, or cleaved to produces aldehydes. Eventually the final products of oil oxidation are acids, water and sludge [10]. Some oils will be supplied with, or subsequently treated with, oxidation inhibitors in an attempt to improve their life expectancy. There is some evidence in the technical literature to suggest that increased temperatures will lead to a more rapid depletion of the oxidation inhibitor. This could mean that transformers with older oils will begin to age more rapidly after a period of elevated temperature operation.

It should be noted that some of the acids produced may also attack the paper insulation of the windings, leading to hydrolytic degradation. In addition, the water produced as a by-product of some of the reactions involved in oil oxidation can often be taken up into the paper insulation, further degrading its performance.

2.2.4 The effect of water

The presence of water within the transformer oil will lead to a reduction in the electrical breakdown strength of the oil. Although this is unlikely to lead to an immediate failure under normal working voltages, the risk would be elevated during transient voltage events, for example due to switching. There is also a link between the moisture content of the oil and paper degradation – as degradation of the paper leads to additional moisture in the oil, which reduces its breakdown strength.

It is also necessary to consider the presence of water vapour filled bubbles in the oil, as discussed in the following section.

2.2.5 Thermal evolution of gases

One of the primary oil related issues which may be encountered during elevated temperature operation is the evolution of gases from the oil. There are a range of explanations about why this can occur, and there are some conflicting accounts in the historical literature. The consensus agreed within Appendix A of [14] is that bubbles can be formed by the expansion of a surface cavity at the interface between the oil and paper insulation, which has some initial gas or vapour content. Given that the paper holds a much greater amount of water than oil relative to its weight, it is possible that these cavities contain water vapour and dissolved gases.

As the conductor and the paper covering it heats up, it can be assumed that the cavity would expand, with larger quantities of water vapour leading to a bubble being formed and then eventually released into the oil. The IEEE Guide summarises some experimental evidence, leading to a proposed equation for the temperature at which the bubbles were likely to form:

$$\theta_{bubble} = \left[\frac{6996.7}{22.454 + 1.4495\ln(W_{WP}) - \ln\left(P_{pres}\right)}\right] - \left[\left(e^{(0.473W_{WP})}\right)\left(\frac{V_g^{1.585}}{30}\right)\right] \qquad (3)$$

Where P_{pres} is the total pressure (torr), V_g is the gas content of the oil % by volume, W_{WP} is the weight percentage of moisture in the paper (dry basis – i.e. without weight of oil absorbed). It is reported that the agreement between the equation and physical test validations was sufficient, with the actual temperature of bubble formation being within 4°C of that predicted. It is reported that with a high moisture content, which would typically be found with aged papers (noting that much of the water released into the oil comes from the degradation of paper), θ_{bubble} could reduced to below the normally permissible hot spot temperature limits. This would lead to a weakening of the liquid insulation within the transformer at higher temperatures.

2.3 Other Load Related Risk Factors

Aside from the ageing of the dielectric system, as described in Section 2.1 and 2.2, there are a range of other load related factors which should be considered before a transformer is operated significantly above its name plate level. An excellent summary of these is provided in the IEEE Transformer Loading Guide C57.91-2011 [14]. Removing those factors linked to the dielectric ageing which have been covered in the preceding sections, we note the following factors:

Evolution of Free Gases: although this is primarily an issue for the dielectric strength, it should also be recognised that any transformer fitted with gas monitoring equipment is likely to identify an increase in gas evolution during periods of substantially higher loading.

Mechanical Strength: the conductors and other structural insulation systems (other than the main winding system) may also suffer from decreased mechanical strength under high loads. This is not normally an issue under elevated load itself, but any through fault event (i.e. short circuit on the LV network fed by the transformer) will lead to the sudden application of a large mechanical load to the transformer internal structures, as a result of a large increase in magnetically driven forces. If the structural systems are under greater stress at the time of the through-fault occurring, this increases the chance of significant mechanical damage.

Thermal Expansion Forces: the application of aggressive loading cycling, where the transformer routinely exceeds its nameplate rating, can lead to significant thermal expansion of components within the transformer. This further elevates the risk of mechanical damage within the unit.

Tap Changers: any units which have tap changers, even if they are of the offload variety common to distribution units, may suffer from elevated heating at the tap changer contacts. This can accelerate the decomposition of the oil locally, and lead to issues with gas evolving from the oil. Where the tap changer is housed separately (from an oil perspective), this may dramatically shorten the life of the oil in the tap changer unit.

Auxiliary Equipment: for newer transformers which may have some auxiliary monitoring equipment housed within the transformer, it will be necessary to ensure that the operation of such equipment is not impaired, or its accuracy degraded.

Oil Expansion Capacity: the thermal expansion coefficient of mineral oil is in the range of 6.5×10^{-4} °C^{-1}. This means that an increase in average oil temperature from 20°C to 85°C leads to an increase in the volume of oil of 4.2%. Although this may not seem significant, it is necessary to ensure that the tank, or conservator if present, has adequate capacity to cope with additional expansion. Failure to do so may result in pressure relief valves being triggered, resulting in oil leaks.

Voltage Regulation: although not a direct health concern for the transformer, from the perspective of the surrounding network it is also necessary to consider the behaviour of the wider network. Increasing the loading of the transformer will naturally lead to a greater voltage drop across the series impedances posed by the windings themselves, hence pushing up the per unit voltage regulation from the input to the output. There may be some natural benefits from reduced voltage at the secondary bus as a result from Conservation Voltage Reduction, as some loads in the distribution system are known to have a voltage sensitivity. This can result in the load decreasing slightly as the voltage decreases thereby offsetting any detrimental effects. However, if a system contains a large number of loads which act as genuine PQ loads (i.e. fixed power consumption regardless of supply voltage), the load current on the secondary side will increase, not decrease.

3.0 Asset Health Implications of CELSIUS Methodology

This section provides a quantitative review of the asset health implications of the CELSIUS methodology from the perspective of the ageing of the transformer insulation. It is important to note that there are many factors which can't be quantitatively assessed by a desktop analysis, and this report does not attempt to provide predictions for any specific transformer. The use of a generic desktop review is not sufficient replacement for a physical inspection and review of specific records and design information for a given transformer. Where it is anticipated that the CELSIUS methodology might be used to drive a significant change in the operation of a specific unit, this should also be considered carefully.

3.1 Summary of Celsius Hot Spot Methodology

For ease of reference, this section briefly summarises the CELSIUS methodology as described in the Ricardo report ED62006- Issue 3. Readers interested in a comprehensive review of the CELSIUS methodology should refer directly to the Ricardo reports. This report is not intended as a review of the accuracy and applicability of the Celsius methodology, which will be published separately.

3.1.1 Hot Spot Calculation Tool

Unlike high voltage power transformers, the vast majority of distribution transformers are not fitted with Winding Temperature Indicators (WTI) or other direct means of measuring winding hot spot temperature (HST). Given that the rating of the transformer is primarily based on the HST, a method is required to calculate it from other external (retrofit) sensors. Ricardo have developed a method with three primary steps to achieve this:

1. Determination of link between hotspot temperature and internal oil temperatures.
2. Determination of link between internal oil temperatures and external surface temperatures.
3. Using step 1 and 2, calculate the HST directly from external tank surface temperatures.

Ricardo claim that the following equation will allow calculation of the hotspot temperature from the internal oil temperature to an accuracy of ±5°C:

$$T_{HS} = (1.397T_I) - (0.272A_T) - 9.35 \qquad (4)$$

Where T_{HS} is the hot spot temperature in °C, T_I is the internal temperature at the top of the tank [presumably in the transformer oil] °C, and A_T is the ambient temperature °C. It should be noted that the equation is derived from fitting to data; from a physical modelling perspective, there does not appear to be a good reason why the ambient temperature component would be necessary.

An equation is then presented for three transformer types by which the internal temperature (presumably of the top oil) can be calculated from the external surface temperatures for the 'T1', 'ESI 35-1 UNIT' and 'ESI35' transformer types respectively.

$$T_I = (1.407S_T) - (0.385A_T) + 0.071 \qquad (5)$$

$$T_I = (1.407S_T) - (0.385A_T) + 5.265 \qquad (6)$$

$$T_I = (1.407S_T) - (0.385A_T) + 1.606 \qquad (7)$$

The Ricardo report shows that for the majority of installations the resulting error are within

±5°C, except those which are lightly loaded for which the errors could be greater. Substituting (4) into (5)-(7) yields the following equations for the HST as a function of Surface (S_T) and Ambient (A_T) temperature.

$$T_I = (1.97S_T) - (0.81A_T) - 9.25 \tag{8}$$

$$T_I = (1.97S_T) - (0.81A_T) - 1.99 \tag{9}$$

$$T_I = (1.97S_T) - (0.81A_T) - 7.11 \tag{10}$$

Ricardo also present in their report some examples that show that the equations give a conservative estimation of temperature compared to the measured performance.

3.1.2 Daily Rating Methodology

Having obtained a means by which a transformer HST can be estimated, Section 3 of the Ricardo report presents a means of calculating the daily rating for transformers at a given site by:

1. Analysing the daily data from each site to determine a statistical relationship between load and HST.
2. Analysing the shape of the load data to determine if the site should be regarded as having a continuous (HST= 98 °C) or normal cyclic rating (HST = 105°C).
3. Estimating the load at which the hot spot temperature would reach the maximum allowable operating temperature.

Some checks were then made by Ricardo to determine if the daily ratings calculated appear to be sensible. Ricardo have provided to the University of Southampton a spreadsheet tool for the estimation of these thermal ratings, which has been used in the study that follows in Section 3.2 of this report.

It is important to note that the Daily Rating Tool for transformers may be modified further during the project, as additional information from the site measurements becomes available. At the time of writing this report, the version of the tool available to us was v1.1. We note that the 95% confidence intervals presented in the present version can be extremely wide, in some cases providing a range of ranges between <100% and >200% of the nameplate rating. This is potentially due to the limited amount of data available from transformers which are genuinely operating at high loads. Our analysis is therefore split into two parts; the first considers that the Hot Spot Calculations are used to determine the rating via the deployment of the CELSIUS temperature monitoring equipment. Comments are also provided on the potential issues associated with the use of the simplified Daily Rating tool.

3.1.3 Temperature Factors Study

The final part of the Ricardo work examines the possible impact of site specific conditions, which may have an affect on the temperature for a given load. This includes factors such as building types, as well as electrical factors such as the harmonic content of the load.

Taken with the estimation of the daily rating, this allows an evaluation of the rating to be made for sites which do not have any sensors fitted to allow the HST to be estimated using the equations 7-9.

3.1.4 Deployment of Cooling Technologies

In addition to the work described above, a separate stream within the CELSIUS project has conducted an investigation into the impact of retrofit cooling technologies on specific assets within the network.

Installation of the cooling technologies has been conducted through 2018; at this stage, there is not sufficient data to make an assessment of any impact on asset health as a result of the retrofit cooling technologies being applied. This will be addressed in subsequent issues of the report.

3.2 Effect on Insulation life of Increasing Transformer Loads

Prior to considering specific changes brought about by the use of the CELSIUS methodology, it is valuable to demonstrate the effect that might be seen from increasing the magnitude of transformer loading more generally, without changing the shape of the load curve itself. The life of the paper insulation is dependent on temperature and other factors like moisture and oxygen content, as discussed above. The water and oxygen levels can be very transformer-specific, so to maintain a general overview here the effects of temperature only are considered.

3.2.1 Methodology

The analysis given in this document adopts the methods in IEC 60076-7 (2005) 'Loading guide for oil-immersed power transformers', using the calculations described in Annex C and adopting suggested parameters for ONAN distribution transformers given in Table E.1.

The differential equation for top oil temperature is:

$$\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) = k_{11}\tau_o \times \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \tag{11}$$

where:

K	is the per-unit load (i.e. the load relative to nameplate rating)
R	is the ratio of copper to iron losses at full rated load
x	is the oil exponent
$\Delta\theta_{or}$	is the top oil rise above ambient temperature at full rated load
k_{11}	is a modelling parameter
τ_o	is the oil time-constant
θ_a	is the ambient temperature
θ_o	is the desired top oil temperature

The winding hotspot temperature is assumed to be greater than the top oil temperature by some variable amount dependent on the load. The equations governing this hotspot temperature rise above top oil are:

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \tag{12}$$

where $\Delta\theta_{h1}$ is governed by:

$$k_{21} \times K^y \times (\Delta\theta_{hr}) = k_{22} \times \tau_w \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \tag{13}$$

and $\Delta\theta_{h2}$ is governed by:

$$(k_{21} - 1) \times K^y \times (\Delta\theta_{hr}) = \frac{\tau_o}{k_{22}} \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \tag{14}$$

The symbols in the above equations are:

K	is the per-unit load (i.e. the load relative to nameplate rating)
y	is the winding exponent

$\Delta\theta_{hr}$ is the hotspot oil rise above top oil at full rated load
k_{21} is a modelling parameter
k_{22} is a modelling parameter
τ_w is the winding time-constant
τ_o is the oil time-constant

The purpose of the intermediate quantities $\Delta\theta_{h1}$and $\Delta\theta_{h2}$is to allow for the fact that the oil has mechanical inertia as well as thermal inertia. Whilst the winding temperature responds quickly (within a few minutes) to changes in load, the oil has to circulate through the cooling system and transformer tank before it becomes fully mixed. Consequently the oil takes a while to 'catch up' to the temperature it should be for the given load. Since the hotspot temperature is being modelled as an offset from the top oil temperature, this effect must be taken into account when calculating the hotspot temperature.

The mechanical inertia effect is greatest for ONAN cooling in large power transformers. However, for distribution transformers it is considered to be negligible. The recommended value for k_{21} in the above equations is 1 in this case, so the equation for $\Delta\theta_{h2}$ that models the mechanical inertia of the oil has no effect.

The actual hotspot temperature is calculated according to:

$$\theta_h = \theta_o + \Delta\theta_h \tag{15}$$

i.e. it is the sum of the top oil temperature and the hotspot temperature rise above the top oil.

Since the rate of paper ageing is temperature dependent, it follows that the highest ageing rate will be at the location of the hotspot temperature. The differential equation for loss of life at the hotspot temperature is:

$$\frac{dL}{dt} = V \tag{16}$$

For insulation paper that has not been thermally upgraded, which is likely to be the case in the majority of units under consideration:

$$V = 2^{(\theta_h - 98)/6} \tag{17}$$

This implies that the rate of ageing doubles for every 6K rise in hotspot temperature above 98^{o}C, but also halves for every 6K decrease below that value. At 98^{o}C exactly, the rate of ageing is unity, or one day per day.

These differential equations can be discretised such that values of the various input quantities can be specified at the beginning of a given time step and the outputs can be calculated from the equations at the end of the time step. These outputs are then used as inputs for the next step. This approach lends itself to straightforward manipulation in a spreadsheet and this has been done for the following calculations.

3.2.2 Load curve considered

The load curves used for the example ageing calculations are taken from the Temperature Factor Analysis in the Ricardo 'Secondary Network Asset Temperature Behaviour Report'. These four generalised load curves are representations of the typical load profiles found on ENW's distribution transformers. The load profiles are shown below in Figure 8.

The discretised equations give most accurate results if the time steps are small; at most half the size of the winding time-constant. To achieve this, the load curves were interpolated onto a uniform axis of one-minute time steps. They were also adjusted to have the same values at each end, so that they were truly cyclic. This is the reason for the small ‘up-tick’ at the right-hand end of LP3.

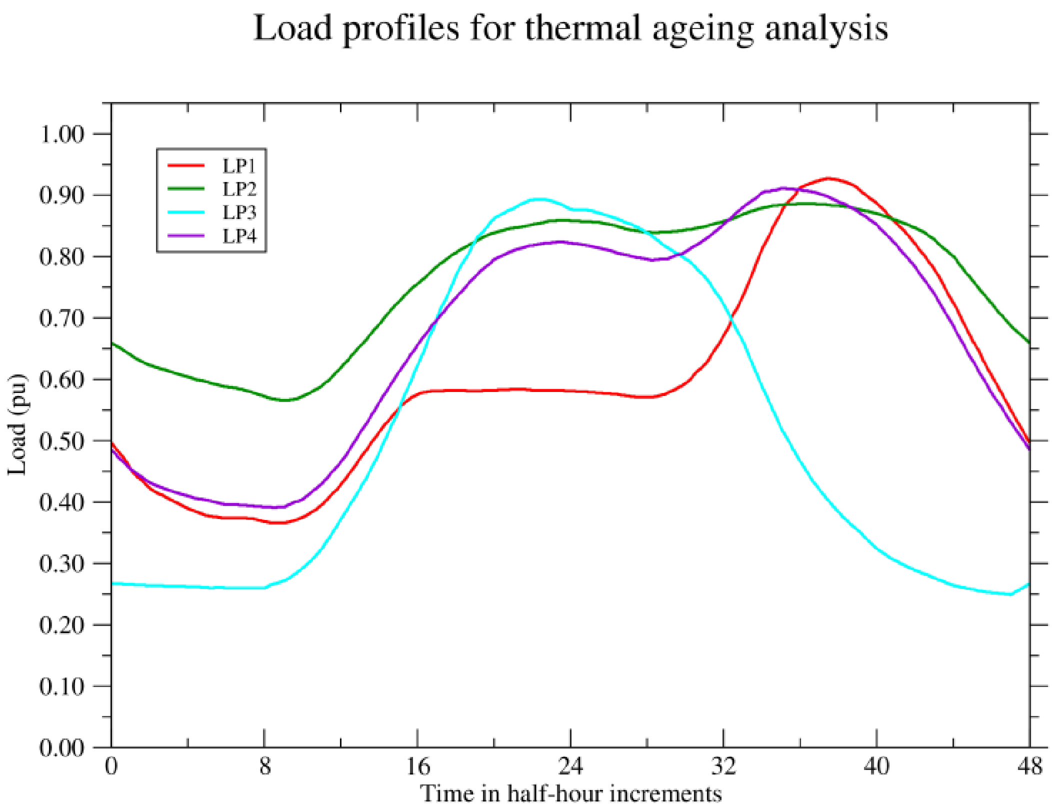

Figure 8 – Load profiles for thermal ageing analysis

The following table lists the transformer parameters that were used for the calculations, taken from Table E.1 of the IEC 60076-7 loading guide.

Table 3 - Parameters from IEC60076-7

Oil exponent (x)	0.8
Winding exponent (y)	1.6
Loss ratio (R)	5
Oil time-constant (τ_o)	180 minutes
Winding time-constant (τ_w)	4 minutes
Hotspot to top oil rise at rated load ($\Delta\theta_{hr}$)	23 K
Top oil temperature rise at rated load ($\Delta\theta$)	55 K
k_{11}	1.0
k_{21}	1.0
k_{22}	2.0

The values for the top oil temperature rise above ambient and the hotspot to top oil rise of 55 K and 23 K respectively are such that the hotspot temperature at 20°C ambient is (20 + 55 + 23) °C, or 98°C, which is the limiting value for an ageing rate of 1 day per day. Any transformer would be expected not to exceed this limit for full rated load at 20°C ambient, so the values in the table are a worst case possibility. Any other combination of top oil rise and hotspot rise that summed to 78 K would also be permissible and such other choices will affect the following calculations to some extent, but the IEC 60076-7 values given above are used here.

3.2.3 Calculation of rate of insulation life loss

The calculations for rate of insulation life loss have been made for three cases:

(a) Average loading of 0.3 pu rated load (i.e. a typically lightly loaded transformer)
(b) Peak loading of 1.0 pu rated load
(c) Load profile scaled to give maximum permissible hotspot temperature

In all cases it is necessary to choose ambient temperatures. Values of 0 °C, 15 °C, 20 °C and 30 °C have been used to correspond to the tables in CP382 'Transformer Ratings', July 2009. These have been taken to be constant throughout the 24-hour (1440 minute) period of each calculation.

<u>Average loading of 0.3 pu rated load</u>

This case is intended to represent typical normal loading. A representative value of 0.3 pu (or 30% average utilisation) was chosen based on the values given in Table 2 of the Ricardo 'Secondary Network Asset Temperature Behaviour Report'. The following figure shows the scaled load curves for this case.

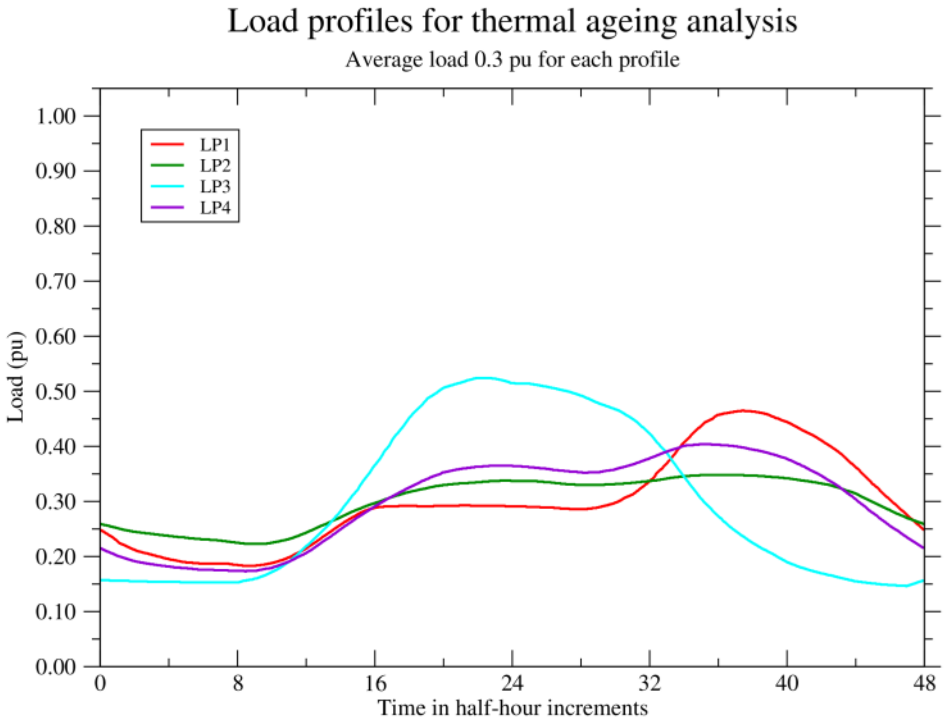

Figure 9 – Load profiles for thermal ageing analysis with each curve scaled to an average utilisation of 30% (0.3 pu)

Graphical results of the temperature and ageing calculation for LP1 are shown in the following two figures.

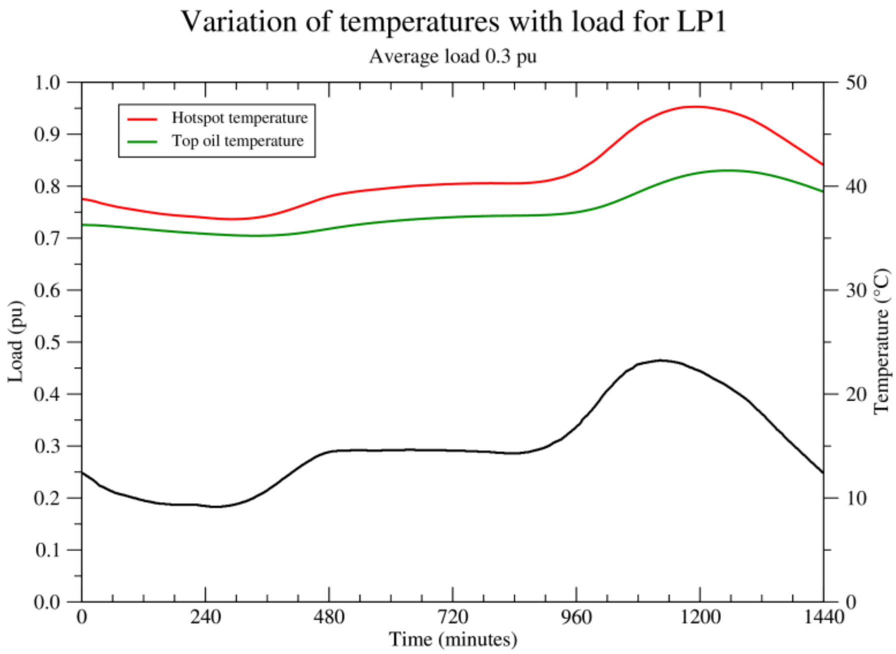

Figure 10 – Variation of hotspot and top oil temperature with load for LP1 with 30% average utilisation at 20ºC ambient

At low loads the degree of heating and overall daily variation in temperatures is typically rather small. An average utilisation of 0.3 pu represents only 9% of the heating effect at full rated load (since the heating effect goes as the square of the current and 0.3 squared is 0.09). Similarly, the degree of paper ageing is so small as to be negligible if the hotspot temperature is the only significant factor. In this case, it can be seen to be only about 2.2 minutes over the entire daily cycle because the hotspot temperature is always very much less than 98ºC.

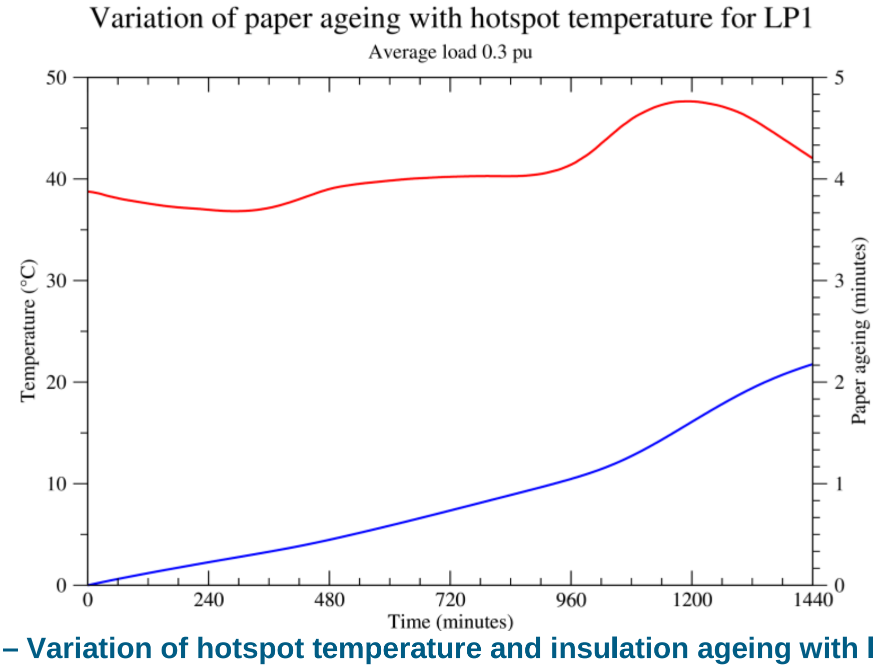

Figure 11 – Variation of hotspot temperature and insulation ageing with load for LP1 with 30% average utilisation at 20ºC ambient

Values for daily ageing for each of the load profiles at the chosen ambient temperatures are given in the table below.

Table 4 - Equivalent daily ageing for 0.3pu load cycle

	Daily ageing (minutes) for given profiles and ambient temperatures for average utilisation of 30% (0.3 pu)			
Ambient (^oC)	30	20	15	0
LP1	6.91	2.18	1.22	0.22
LP2	6.41	2.02	1.13	0.20
LP3	9.14	2.88	1.62	0.29
LP4	6.83	2.15	1.21	0.21

Peak loading of 1.0 pu rated load

This case demonstrates the effect on ageing of scaling each load profile to a maximum value equal to the nameplate rating, i.e. 1.0 pu rated load. The calculated ageing rates are given in the table below and the scaled load profiles are shown in the following figure.

Table 5 - Equivalent daily ageing for 1.0pu load cycle

	Daily ageing (days) for given profiles and ambient temperatures for peak utilisation of 100% (1.0 pu)			
Ambient (^oC)	30	20	15	0
LP1	0.189	0.060	0.033	0.006
LP2	1.011	0.318	0.179	0.032
LP3	0.251	0.079	0.044	0.008
LP4	0.496	0.156	0.088	0.015

Note that these ageing values are in days, whereas they were given in minutes for the previous case. It is evident that even for a peak loading of 1.0 pu, none of these load profiles results in an ageing rate greater than one day per day, except for LP2 which slightly exceeds it for a constant daily ambient of 30 ^oC. The maximum hotspot temperature for LP2 under these conditions is just over 106 ^oC which is slightly greater than the permissible maximum of 105 ^oC for a normal cyclic loading. This could be considered to be within the error margin of the methodology, and is not a substantial concern.

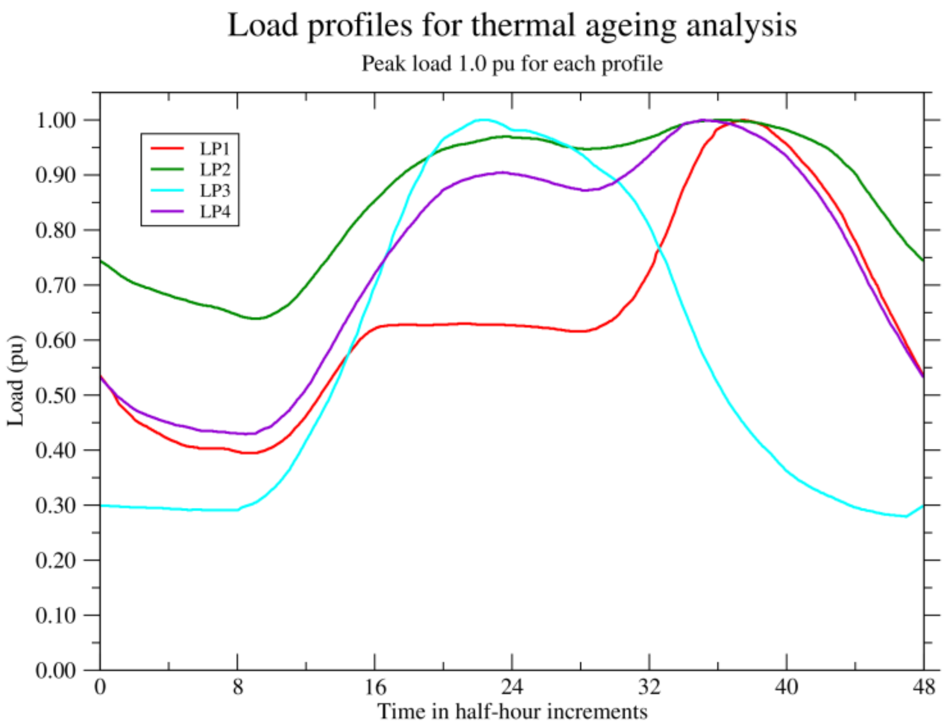

Figure 12 – Load profiles for thermal ageing analysis with each curve scaled to a peak utilisation of 100% (1.0 pu)

Load profile scaled to give maximum permissible hotspot temperature

Each of the four load profiles is scaled until one of the maximum permissible operating temperatures is reached. In fact the hotspot temperature limit is reached in all cases rather than the top oil limit for the modelling parameters used here.

The following tables show the daily ageing rate and the maximum load for the given ambient temperatures. Since the load profiles are for normal cyclic loads, a limiting hotspot temperature of 105 °C was used. The resulting load curves for 20 °C ambient are shown in the next figure.

Table 6 - Daily ageing/peak load for HST of 105 °C

	Daily ageing (days) for given profiles and ambient temperatures for maximum hotspot temperature of 105°C			
Ambient (°C)	30	20	15	0
LP1	0.392	0.356	0.342	0.308
LP2	0.900	0.832	0.803	0.730
LP3	0.470	0.437	0.423	0.389
LP4	0.594	0.538	0.515	0.459

	Peak load (pu) for given profiles and ambient temperatures for maximum hotspot temperature of 105°C			
Ambient (°C)	30	20	15	0
LP1	1.074	1.173	1.221	1.358
LP2	0.990	1.081	1.125	1.251
LP3	1.061	1.159	1.206	1.341
LP4	1.017	1.111	1.156	1.285

For comparison purposes, the following table shows an excerpt from CP382 Table 9 for distribution transformers for normal cyclic loading.

Table 7 - CP382 Table 9 load curves

Load Type	Ratings (pu of full ONAN rating)			
	30ºC	20ºC	15ºC	0ºC
Normal Cyclic	1.000	1.050	1.110	1.250

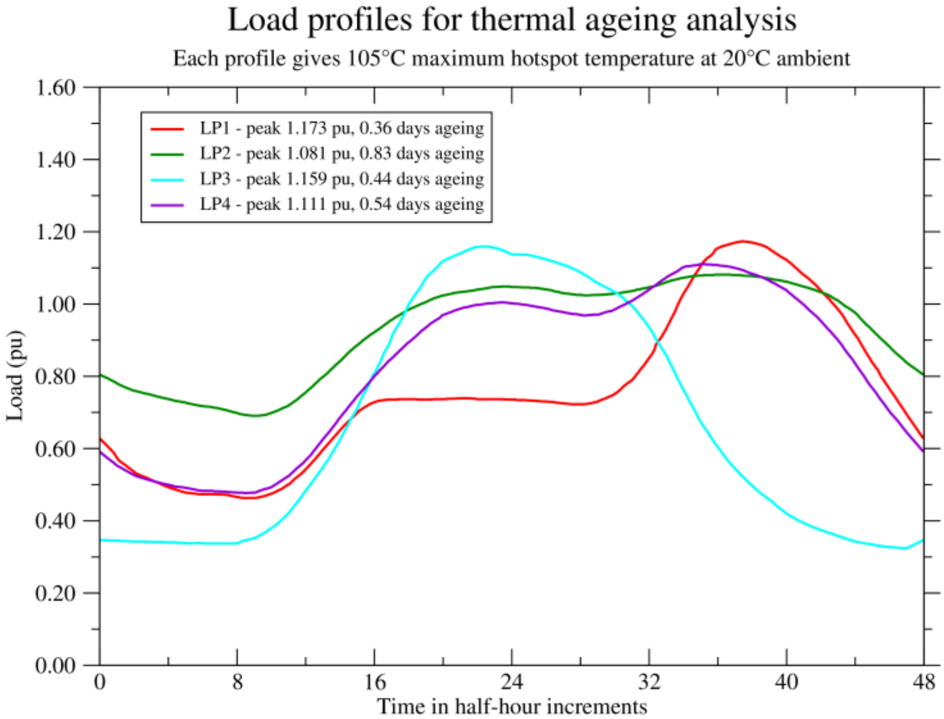

Figure 13 – Load profiles for thermal ageing analysis with each curve scaled to give a maximum hotspot temperature of 105ºC at 20ºC ambient

From the examples above it can be seen that the load profile shape makes an important contribution to the rate of insulation ageing. Generally, a flatter profile is more onerous than a peaky profile if the peak load is used as a determinant of the overall loading. However, if the average utilisation is used as a discriminating factor then a peaky profile can be more onerous than a flatter profile since the rate of ageing at peak load more than compensates for the reduction in ageing at lower loads. The above examples also show that it is actually rather difficult to exceed a rate of insulation ageing of one day per day for typical load shapes and likely loading conditions, even at a constant daily ambient temperature of 30ºC, for the typical transformer parameters given in the IEC 60076-7 loading guide.

Table 9 for distribution transformers from CP382 'Transformer Ratings' gives good agreement with the values calculated above for normal cyclic loading and a limiting hotspot temperature of 105ºC for the four different load profiles. This suggests that the CP382 ratings are the appropriate quantities to use in the absence of any other information.

3.3 Calculation of rate of insulation life loss using CELSIUS Daily Rating Tool

The CELSIUS Daily Rating Tool was supplied with example data for an ESI 35-1 specified transformer of nominal rating 1000 kVA. From the transformer surface temperature and ambient temperature data it is possible to calculate the expected internal top oil temperatures from the equation:

$$T_1 = (1.407 \times S_T) - (0.385 \times A_T) + 1.606 \quad (18)$$

as given in the Ricardo report. A little experimentation with the IEC 60076-7 model enables a plausible fit to the Ricardo values to be obtained as shown in the following figure. To do this, the Daily Rating values were first interpolated from half-hour steps to one-minute values. The relevant modelling parameters are shown in the next table.

Table 8 - Modelling parameters for Daily Rating example

Oil exponent (x)	0.8
Winding exponent (y)	1.6
Loss ratio (R)	4
Oil time-constant (τ_o)	360 minutes
Top oil temperature rise at rated load ($\Delta\theta_{or}$)	56.5 K
k_{11}	1.0
k_{21}	1.0
k_{22}	2.0

The oil time-constant is perhaps rather too long for a transformer of this size but it seems to give a good fit. Interestingly the top oil temperature rise at rated load is very similar to the IEC 60076-7 example value of 55K. The variation in hotspot temperatures given in the CELSIUS Daily Rating sheet suggest a top-oil to hotspot gradient of 5K or so at most, implying a gradient of about 10K at full rated load (the peak load in the example is around 0.7 pu which gives 0.7 squared (i.e. half) of the heating compared to 1 pu).

If a full rated load hotspot to top oil gradient of 10K is assumed, then using the IEC 60076-7 model and the load and ambient temperature data supplied in the Ricardo Daily Rating tool, a peak load of 1.423 pu (i.e. 1423 kVA) is obtained for a limiting hotspot temperature of 105 ^{o}C. This is very similar to the Ricardo value of 1472 kVA. The estimated daily ageing in this case is 0.59 days, so provided that the estimate of the hotspot temperature is correct, there is no excessive loss of life in using this rating. The greatest possible value for the hotspot to top-oil gradient would be 21.5K (assuming that the transformer was required to meet a hotspot temperature not exceeding 98 ^{o}C at 20 ^{o}C ambient). In this case the Ricardo Daily Rating value of 1472 kVA at peak would give a maximum hotspot temperature of 130 ^{o}C and insulation ageing of 7.9 days per day. Clearly an accurate estimate of the hotspot temperature is very important.

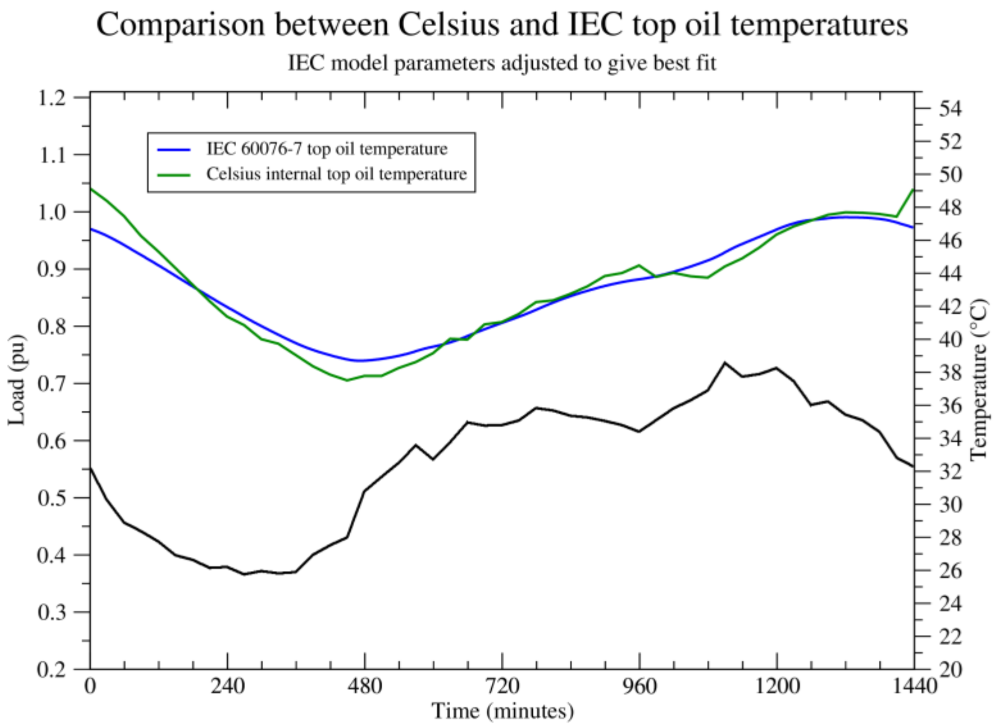

Figure 14 – Top oil temperature calculated from Ricardo equations compared with possible fit from IEC 60076-7 model for example given in Daily Rating tool

3.4 Summary

Estimates of daily ageing have been made for four types of load profiles typically found on ENW's distribution transformers (as derived by Ricardo). Flatter profiles are typically more onerous than peaky profiles, but only one case was found where an ageing rate of greater than one day per day could occur. This was at 30 °C ambient and entailed a hotspot temperature slightly in excess of the permitted maximum of 105 °C for a normal cyclic load. It is likely to be quite unusual to exceed an ageing rate of one day per day under CP382 normal cyclic loading.

The Ricardo Daily Rating tool was examined for one particular case and found to give plausible results, but this does not necessarily imply plausible results in all cases. We particularly note that the performance of the tool seems less realistic for small transformers, given the extremely wide range between the 95% confidence intervals. It is of the utmost importance to estimate the hotspot temperatures as accurately as possible if excessive ageing is to be avoided by using unintentionally high temperatures. But it is often the case that insufficient data are available to determine accurate ratings of older plant and in this situation the asset owner is obliged to accept a certain degree of risk.

4.0 Conclusions and Recommendations

4.1 Conclusions

The following conclusions are drawn with regard to the impact of the CELSIUS methodology being used on distribution transformers within the ENW network:

1. The primary thermal related degradation mechanisms in transformers are the depolymerisation of the paper winding insulation and the evolution of gases from the insulating oil.
2. Given that the oil could be replaced if required, the primary concern from an asset health/life perspective is the irreversible degradation of the paper winding insulation.
3. There are three primary degradation pathways for the winding insulation (oxidative, hydrolytic and pyrolytic). The rate of all three mechanisms is increased at higher temperatures.
4. ENW transformers are purchased according to ES322, with a 40 year notional life if operated at the nameplate rating. This assumes a winding hot spot temperature of no more than 98°C under continuous loading, and 105°C under normal cyclic loading conditions.
5. Although the use of the CELSIUS methodology to deliver up-ratings on specific assets is likely to lead to an increase in the operating temperatures of these assets, remaining within the design thermal limits should ensure that the rate of thermal degradation does not shorten the life of the transformer to less than 40 years.
6. When the CELSIUS methodology is deployed using physical temperature monitoring, ratings will be determined based on the measured thermal parameters at a given site. The performance of the hot spot equations appears to be sufficient that the danger of the design temperature limits being exceeded to an extent which would shorten the operational life of the transformer is small. As such, the asset health impact should also be small.
7. Where the CELSIUS Daily Rating methodology is used to up-rate a transformer without the use of asset specific measurement data, it will be necessary to accept a greater amount of operational risk.
8. It should be noted that changing the loading regime of an aged transformer will always carry some risk, especially if the load becomes more cyclic in nature.

4.2 Recommendations

In order to continue to assess any potential asset health implications arising from the deployment of the CELSIUS methodology, we recommend that ENW consider the following.

Monitoring: in order to continue to build confidence in the methodology, initially up-ratings should only be applied at sites where temperature monitoring equipment can be installed to verify that the transformer is not being subject to excessive temperature rise.

Validation: we note that the 95% confidence limits in the “Full Celsius Rating” are very broad for small transformers. This appears to be due to the form of the equations used, and the limit on the amount of data presently available. We strongly recommend that further validation work is undertaken.

Rating Ceiling: it may initially be prudent to apply a cap to the maximum CELSIUS rating that is actually applied on the network. This could be reassessed as more data becomes available, but would be a simple way of mitigating the risk associated with limited numbers of monitored transformers being subject to high loads. We recommend that the size of any cap is determined with consideration to the condition of the transformer at the time. Although age may be a factor in this, we would also encourage the use of other service experience (such as knowledge of condition of other assets of the same design family).

Site Type: we note that limited data is available at present for some substation types, particularly GRP substations. Upratings to these sites should be applied with caution until additional monitoring data is available.

Asset Health Monitoring: where the CELSIUS methods are to be deployed to enable a transformer to take on additional load, we recommend that ENW consider an enhanced monitoring regime for these units. This would ideally consist of routine oil sampling at intervals (including before the additional load is applied), to verify if there is any significant trend in degradation markers within the oil.

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