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Paper Lifetime Mathematical Modelling based on Multi Pre-Exponential Factors for Oil-Immersed Transformer

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ABSTRACT

This work examines the impact of multi pre-exponential factors on the lifetime modelling of the paper in oil-immersed transformers. First, the corresponding pre-exponential factor was determined based on the concentrations of the three parameters known as oxygen, moisture and acid. Next, the pre-exponential factor for each of the parameters at different concentrations was combined based on the summative approach to obtain the overall impact on the lifetime of the paper. It is found that the expected life of the paper for overall multi pre-exponential factors is higher than either single or double pre-exponential factors. For a single pre-exponential factor, the expected life of the paper decreases by a factor of 59.8 as the oxygen concentration increases from 15,000 ppm to 210,000 ppm. Moisture can decrease the expected life of the paper by a factor of 34 as it increases from 0.5% to 5%. Low molecular weight acid (LMA) has a higher impact than high molecular weight acid (HMA), whereby its impact is further enhanced through multi pre-exponential factor effect whereby the expected life of the paper decreases by a factor of 7.9 as the moisture content increases from 0.5% to 5% and oxygen increases from 300 ppm to 20,000 ppm.

Keywords: Arrhenius equation, cellulose ageing, life estimation, paper ageing, pre-exponential factor

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INTRODUCTION

The reliability of a transformer ultimately depends on its insulation system, which consists of paper and oil. Paper insulation is quite important since it cannot be replaced or repaired, similar to oil, once subjected to ageing or advanced degradation. Therefore, the life of a transformer is normally dependent on the condition state of the paper (Susa et al., 2011).

Paper degradation or ageing is commonly evaluated through the degree of polymerization (DP). Normally, the DP of a new paper starts at around 1,000, and it will reach its end of life once it reaches 200, whereby the paper becomes brittle and loses its mechanical strength (Lelekakis et al., 2012b). The degradation of the paper can be accelerated in the presence of oxygen, moisture and acid. Several studies have been carried out to examine the ageing of paper under different conditions and configurations (Ese et al., 2010; Lelekakis et al., 2012b; Lelekakis et al., 2012c; Lundgaard et al., 2005; Lundgaard et al., 2008; Lundgaard et al., 2004; Martin et al., 2013; Martin et al., 2015; Teymouri & Vahidi, 2019).

Currently, there are several models that have been proposed to represent the degradation of a paper (Emsley et al., 2000a; Emsley et al., 2000b; Gasser et al., 1999; Heywood et al., 2000; Hill et al., 1995; Kim et al., 2010; Mirzaie et al., 2007; Verma et al., 2005). Ekenstam kinetic model is among the common method used to represent the paper ageing whereby the degradation can be affected by the temperature, pre-exponential factor, A and activation energy, E_a (Emsley et al., 2000c; Emsley & Stevens, 1994a; Lelekakis et al., 2012b; Lelekakis et al., 2012c; Martin et al., 2015; Teymouri & Vahidi, 2019). The presence of ageing accelerators such as moisture, oxygen and acid can influence the pre-exponential factor, which subsequently affects the expected life of a paper. Previous studies mainly focus on the effect of single pre-exponential factor on the expected life of a paper (CIGRE Brochure, 2009; Emsley et al., 2000c; Emsley & Stevens, 1994b; Lelekakis et al., 2012a; Lelekakis et al., 2012b; Lundgaard et al., 2004; Martin et al., 2013; Martin et al., 2015; Teymouri & Vahidi, 2019). There are also other studies that focus on double pre-exponential factors effect on the paper (CIGRE Brochure, 2009; Emsley et al., 2000c; Emsley & Stevens, 1994b; Lelekakis et al., 2012c; Lundgaard et al., 2004; Martin et al., 2013; Martin et al., 2015; Teymouri & Vahidi, 2019). Previous studies focus on experimental works where the pre-exponential factors and activation energies are determined based on accelerated ageing conditions. Since the moisture, oxygen, and acid could co-exist in an oil-immersed transformer, it is essential to determine the multi pre-exponential factors effect of the acceleration of paper ageing to improve the lifetime modelling and asset management practice.

The effect of a multi pre-exponential factor is examined to determine the lifetime of paper based on a mathematical approach by utilizing the information from the previous experimental works. First, the pre-exponential factors for different concentrations of moisture, oxygen and acid are determined. Next, these pre-exponential factors are combined based on a summative approach. Finally, the expected life of the paper is determined based on the different concentrations of moisture, oxygen and acid.

METHODS

Insulation Paper Ageing

Insulation paper ageing can be subjected to different ageing mechanisms such as oxidation, hydrolysis and pyrolysis. The ageing of paper in oil-immersed transformers starts with oxidation, and it can be further accelerated in the presence of oxygen (CIGRE Brochure, 2009). The by-products of the oxidation process will generate moisture, acid and carbon dioxide (Feng, 2013). Oxidation is an auto-inhibitory process that will be suppressed under an acidic environment whereby hydrolysis will subsequently dominate (Feng, 2013). Moisture and acid can accelerate the hydrolysis process, which can lead to the advanced degradation of a paper (Lelekakis et al., 2012c). Generally, there are two types of acids that co-exist as a result of ageing, known as high molecular weight acid (HMA) and low molecular weight acid (LMA) (Lundgaard et al., 2008). The dissociation of acids, especially LMA, through its interaction with moisture can generate H^+ ions which later accelerate the hydrolysis process of the paper. As a result, the long cellulose chain of the paper will break into smaller chains through the acid-catalyzed hydrolysis process. Pyrolysis can be initiated if a paper is subjected to a high temperature, around 150°C (Feng, 2013). The chain scission of cellulose due to pyrolysis can lead to the breakage of the glucose rings with or without the presence of oxygen and moisture. Among the by-products of pyrolysis are moisture, carbon monoxide and carbon dioxide (CIGRE Brochure, 2009).

Previous studies show that ageing mechanisms, especially oxidation and hydrolysis, can affect the activation energy. The activation energy can be obtained from the gradient of the Arrhenius plot, whereby it is reported around 74 kJ/mol for oxidation, while for hydrolysis, it is around 111 kJ/mol (Ese et al., 2010; Emsley & Stevens, 1994b). The ageing rate of paper can be affected by the changes of the pre-exponential factor (Emsley & Stevens, 1994b).

End of Life Modelling Based on DP

The ageing model of paper can be represented by Equation 1 (Ekenstam, 1936).

$$\frac{1}{DP_t} - \frac{1}{DP_o} = kt \qquad [1]$$

where DP_t and DP_o are the average DP per molecular chain at any time, t and start, respectively. On the other hand, k is the ageing rate, and the ageing rate can be determined based on Equation 2 (Arrhenius, 1889).

$$k = Ae^{-\frac{E_a}{RT}} \quad [2]$$

where k is the reaction rate, A is the pre-exponential factor, E_a is the activation energy in kJ/mol, R is the gas constant in 8.314 J/mol/K and T is the temperature in K. Equation 2 shows that the ageing rate of paper can be affected by temperature, moisture, oxygen and acid. The expected life of a paper can be determined based on Equation 3 through the combination between Equations 1 and 2.

$$Expected\ life, t\ (years) = \frac{\frac{1}{DP_t} - \frac{1}{DP_o}}{A \times 24 \times 365} \times e^{\frac{E_a}{RT}} \quad [3]$$

The pre-determined single pre-exponential factor for oxygen, moisture and HMA/LMA, as well as multi pre-exponential factor, were used to determine the expected life of a paper. In this study, the DP_t and DP_o were set to 200 and 1,000, respectively, while the temperature was varied between 30°C to 98°C. The minimum temperature of 30°C was selected due to the consideration of the maximum daily average ambient temperature (Redline, 2012). The maximum temperature of 98°C was chosen to correspond with the rated relative ageing, *V* for non-thermally upgraded paper (British Standards Institution, 2018). The pre-exponential factor was set according to the concentrations of oxygen, moisture and acid. The activation energy was set according to the ageing mechanisms, namely oxidation and hydrolysis. A comparative study was carried out to compare the effects of oxygen/moisture on the pre-exponential factors based on the previous experimental model to evaluate the performance of summative multi pre-exponential models.

RESULTS

Relationship Between Pre-Exponential Factor and Oxygen

The relationship between pre-exponential factors at different oxygen concentrations and moisture of 0.5% based on Ese et al. (2010) can be seen in Figure 1. The pre-exponential factor was determined based on Equations 1 and 2 according to the previous experimental work with variation of partial pressure for oxygen over the oil with a dry paper moisture content of 0.5% (Ese et al., 2010). The definition of the dry basis for the percentage by weight of moisture in paper is based on the dry, oil-free weight of paper (Redline, 2012). According to Ese et al. (2010), the degradation reaction rate of the paper was not linear with the oxygen concentration increment, and the activation energy of oxidation was lower than hydrolysis. The unit of mbar for oxygen pressure as in Ese et al. (2010), is converted to ppm for the purpose to determine the concentration of oxygen. The conversion of mbar to ppm is shown in Equation 4 (Boyes, 2010).

$$ppm = \frac{VP}{760} \times 7.5006 \times 10^5 \quad [4]$$

where *VP* is vapour pressure in mbar.

Equation 2 was used to obtain the corresponding pre-exponential factor (Ese et al., 2010), whereby the activation energy was set to 74 kJ/mol to represent oxidation since only oxygen is present. A linear fitting was used to represent the relationship as seen in Equation 5 with R^2 of 0.977. It is observed that the increment rate of the pre-exponential factor increases as the oxygen concentration increases.

$$A_1 = 0.1354P - 1582 \quad [5]$$

where A_1 is the pre-exponential factor for oxygen, and P is the oxygen concentration.

The expected life of the paper at different oxygen concentrations and temperatures based on Equations 3 and 5 can be seen in Figure 2. It is apparent that the presence of oxygen at different concentration levels can affect the expected life of the paper, similar as

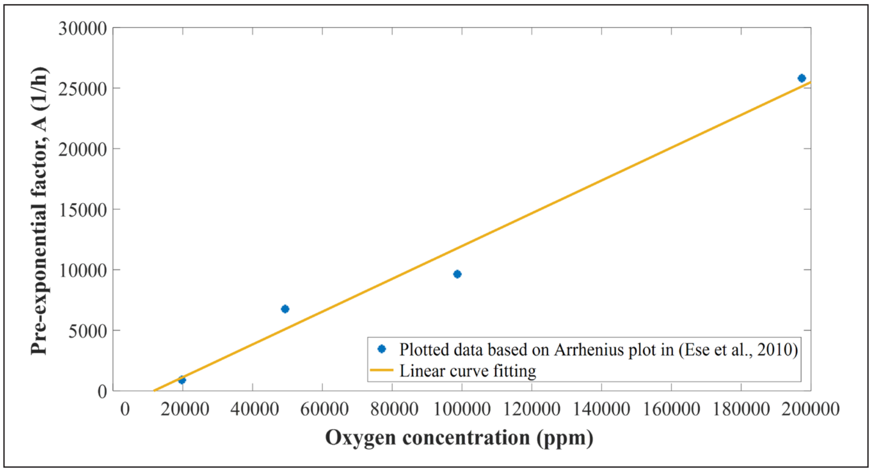


Figure 1. Relationship between pre-exponential factor and oxygen concentration

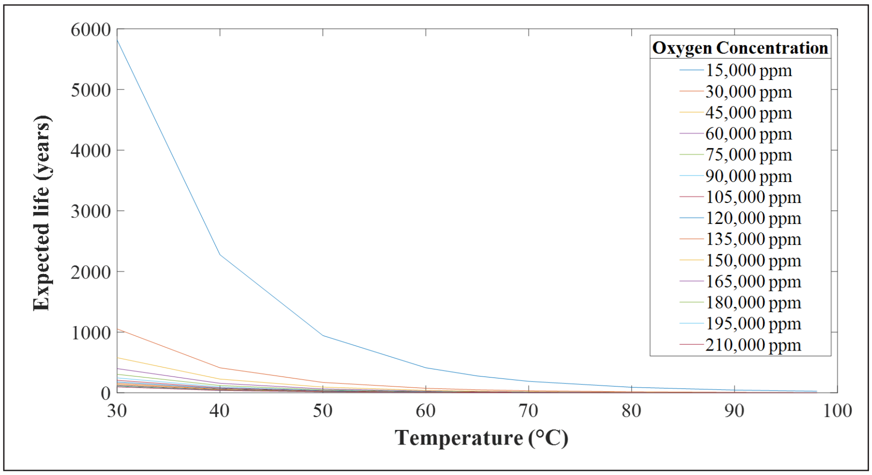


Figure 2. Expected life of paper under different oxygen concentrations

reported in Ese et al. (2010). The expected life of the paper decreases by a factor of 59.8 as the oxygen concentration increases from 15,000 ppm to 210,000 ppm.

Relationship Between Pre-Exponential Factor and Moisture

Previous studies have investigated the impact of both oxygen and moisture on the pre-exponential factor (Lelekakis et al., 2012b; Lelekakis et al., 2012c; Martin et al., 2015; Teymouri & Vahidi, 2019). One of the studies carried out experimental work by maintaining low oxygen concentration with different paper moisture contents of 0.5%, 1.6% and 2.7% (Lelekakis et al., 2012b). Other study had carried out similar work with the introduction of different oxygen concentrations (Teymouri & Vahidi, 2019). Since in this study, an effort was carried out to examine the effect of pre-exponential factors based on summative approach, only the low oxygen concentration was chosen for the computation based on Teymouri and Vahidi (2019). The corresponding pre-exponential factors and activation energies were similarly determined based on Equations 1 and 2. The relationship between pre-exponential factors and moisture at a low oxygen concentration level can be seen in Equation 6. Teymouri and Vahidi (2019) defines low-level oxygen concentration as less than 7,000 ppm. The moisture content of the paper w was increased from 0.5% to 5%.

$$A_2 = 3.07 \times 10^6 w^3 + 1.693 \times 10^8 w^2 + 1.166 \times 10^8 w + 5.327 \times 10^7 \qquad [6]$$

where A_2 is the pre-exponential factor for moisture, and w is the moisture content.

The pre-exponential factor increases with the increment of moisture content of the paper, as shown in Figure 3. The pre-exponential increases by a factor of 9.4 as the moisture content increases from 0.5% to 2.5%. The factor decreases to 3.6 as the moisture content

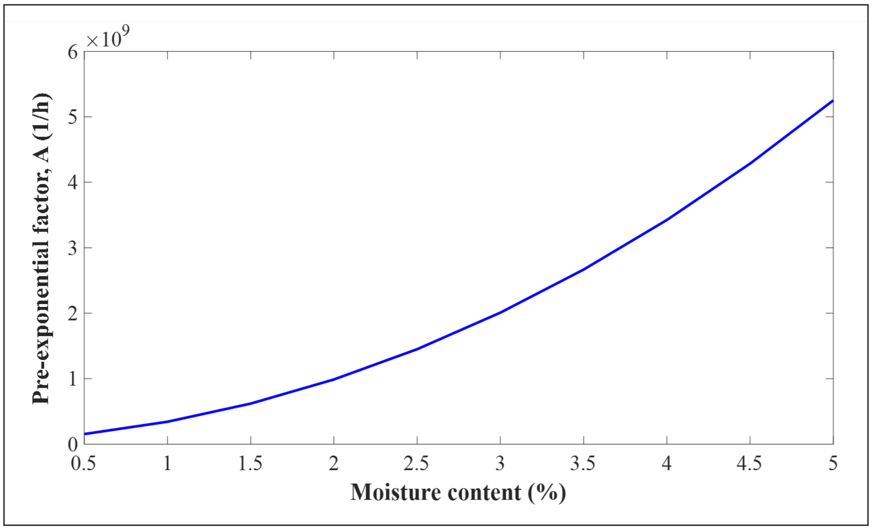


Figure 3. Relationship between pre-exponential factor and moisture content

increases from 2.5% to 5%. In total, the factor increases by 34 as the moisture content increases from 0.5% to 5%.

The expected life of the paper at different moisture contents can be seen in Figure 4. The activation energy was set to 111 kJ/mol. At a moisture content of 0.5% and 5%, the expected life of the paper decreases by a factor of 33.6, respectively, as the temperature increases from 65 °C to 98°C. The expected life of the paper at 65°C are 423 years and 12 years at a moisture content of 0.5% and 5%. The paper experiences a significant reduction of expected life to 13 years and 0.4 years at 0.5% and 5% moisture content once the temperature increases to 98°C.

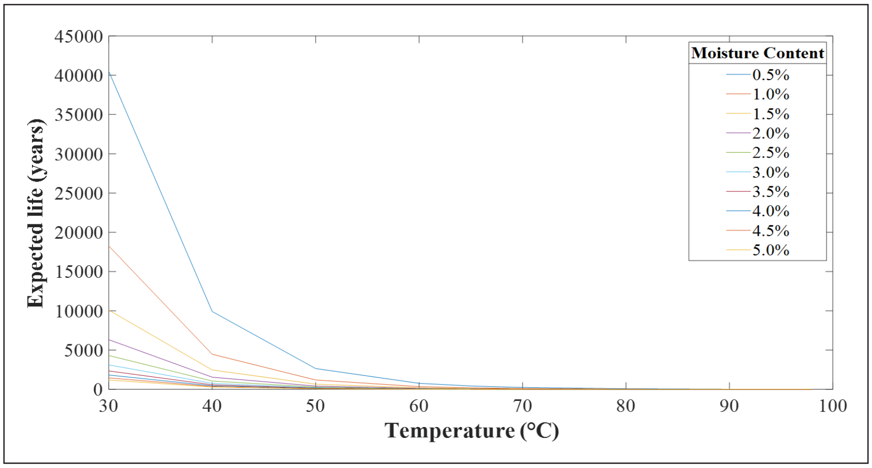


Figure 4. Expected life of paper under different moisture contents

Relationship Between Pre-Exponential Factor and Acids

An updated paper ageing concept based on the acid-catalyzed mechanism of oil-immersed paper was proposed by Lundgaard et al. (2008). The experiment work considered five different carboxylic acids known as LMA and HMA. The types of LMA used were formic, acetic and levulinic acids, while HMA were stearic and naphtenic acids. Similarly, Equations 1 and 2 were used to determine the pre-exponential factors and activation energies for each type of either LMA or HMA. In addition, both dry and wet conditions of papers were considered to examine the effect of moisture on the dissociation of the acids. It was found that LMA was easy to dissociate as compared to HMA, and its detrimental effect could be further enhanced in the presence of moisture through the acid-catalyzed hydrolysis process (Lundgaard et al., 2008). The relationship between the pre-exponential factor and LMA and HMA at different moisture contents can be seen in Figures 5 and 6. The LMA and HMA are formic and naphthenic acids, whereby the concentration is 0.4 mg KOH/g. The corresponding pre-exponential factors for LMA and HMA at different moisture content were obtained based on Equation 2 (Lundgaard et al., 2008). The activation energy was set to 111 kJ/mol. A linear fitting was used to represent the relationship as seen in Equations 7 and 8 with R^2 of 1.

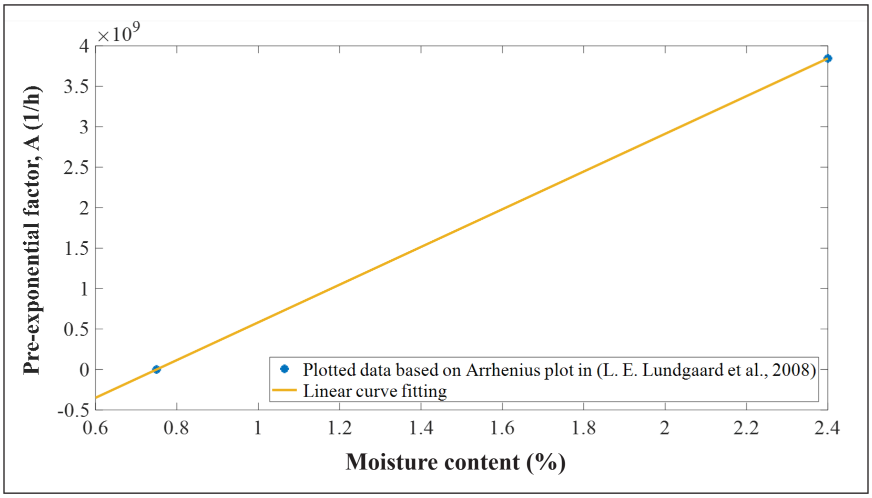


Figure 5. Relationship between pre-exponential factor and LMA/moisture content

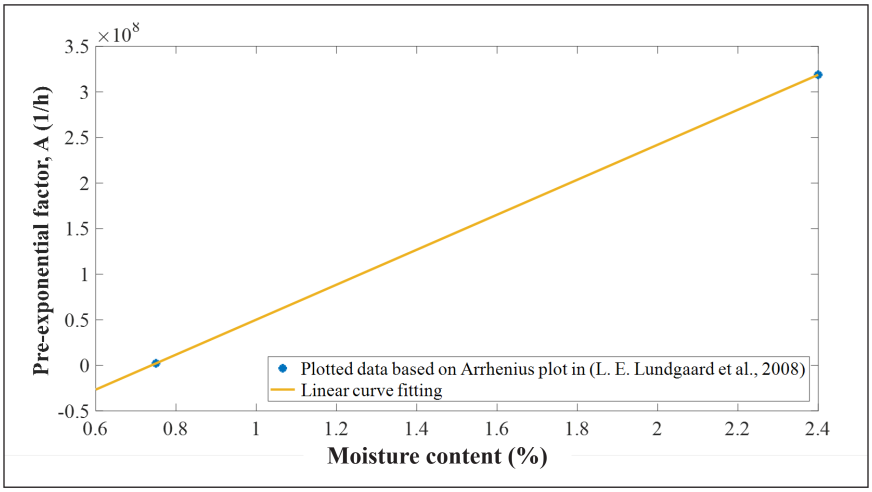


Figure 6. Relationship between pre-exponential factor and HMA/moisture content

LMA and moisture

$$A_3 = 2.330 \times 10^9 w - 1.748 \times 10^9 \quad [7]$$

HMA and moisture

$$A_4 = 1.919 \times 10^8 w - 1.417 \times 10^8 \quad [8]$$

where A_3 and A_4 is the pre-exponential factors for LMA or HMA, respectively.

Based on Equations 7 and 8, the pre-exponential factors at a moisture content of 1% are 5.826×10^8 for LMA and 5.014×10^7 for HMA. The dry moisture content of 1% was considered instead of 0.5% with consideration of the fact that there was not enough moisture to cause significant dissociation of acids and depolymerize the paper (Lundgaard et al., 2004). The pre-exponential factor increases by a factor of 11.6 for LMA relative to the HMA at a moisture content of 1%.

The expected life of the paper with LMA and HMA at 1% of moisture contents can be seen in Figures 7 and 8. At a moisture content of 1%, the expected life of the paper decreases by a factor of 33.6 for LMA and HMA, respectively, as the temperature increases from 65°C to 98°C. The expected life of the paper decreases by a factor of 11.6 for HMA relative to the LMA at both 65°C and 98°C. The presence of LMA leads to the decrement

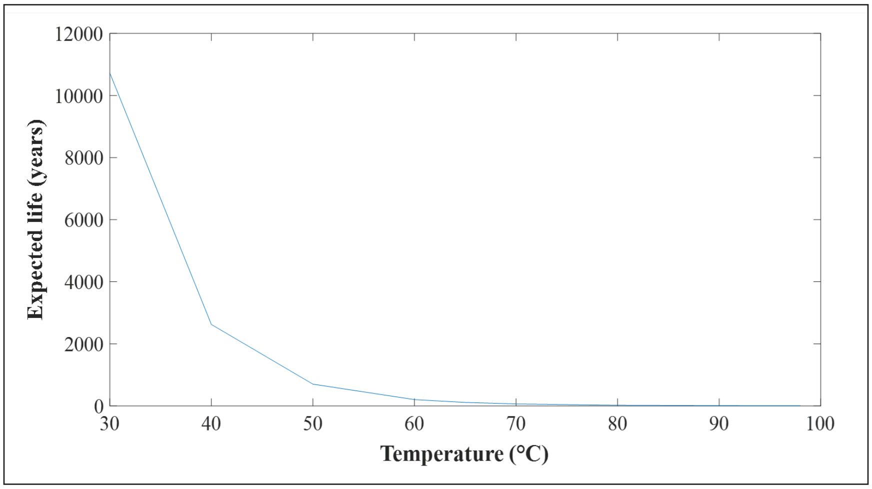


Figure 7. Expected life of paper under 1% of moisture and LMA

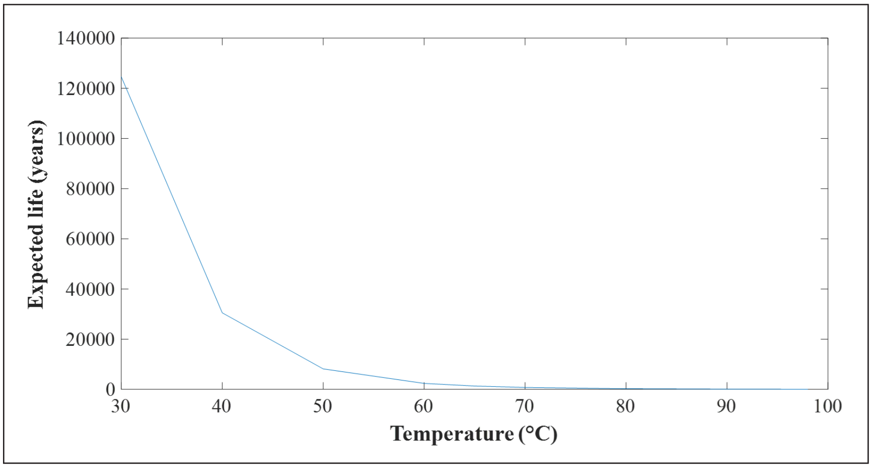


Figure 8. Expected life of paper under 1% of moisture and HMA

of expected life for the paper to 3 years, as compared to 39 years for HMA at 98°C. On the other hand, the expected life of the paper at 65°C is 112 years and 1,300 years for LMA and HMA, respectively.

Relationship between Pre-Exponential Factor and Oxygen / Moisture / Acid

Based on the equation obtained for oxygen, moisture and LMA/HMA, the overall reaction rate was determined based on a summative approach according to Equation 9 (CIGRE Brochure, 2009).

$$k_{overall} = A_1 e^{-\frac{Ea_1}{RT}} + A_2 e^{-\frac{Ea_2}{RT}} + A_{3/4} e^{-\frac{Ea_3}{RT}} \quad [9]$$

where A_1, A_2, $A_{3/4}$ correspond to the pre-exponential factor of oxygen, moisture and LMA/HMA, respectively, while Ea_1, Ea_2, Ea_3 representing the activation energy for oxidation, hydrolysis and acid-catalyzed hydrolysis. In this study, an assumption is carried out whereby $Ea_1 = Ea_2 = Ea_3 = 111$ kJ/mol which leads to Equation 10. The assumption was made since the ageing mechanism of hydrolysis was known to dominate the overall reaction during the presence of oxygen, moisture and acid (CIGRE Brochure, 2009).

$$k_{overall} = \left(A_1 + A_2 + A_{3/4}\right) e^{-\frac{Ea}{RT}} \quad [10]$$

where $k_{overall}$ is the reaction rate for the combination of pre-exponential factors of moisture, oxygen and LMA/HMA. The mathematical model considered the summation of pre-determined pre-exponential factors of oxygen, moisture and LMA/HMA obtained and quantitatively computed from the previous studies.

The relationship of the overall pre-exponential factor based on Equation 10 in the presence of oxygen, moisture, and LMA can be seen in Figure 9. A transformer with new oil has a typical oxygen concentration of 300 ppm and can reach about 30,000 ppm when the oil is fully saturated, but practically most free-breathing transformers in service only have 20,000 ppm of dissolved oxygen in oil (CIGRE Brochure, 2007). In this case, the moisture content and oxygen were varied in the presence of LMA. The differences of pre-exponential factors between the oxygen concentrations are quite small. The pre-exponential factor further increases by a factor of 7.9 as the moisture content increases from 0.5% to 5%. The relationship between the overall pre-exponential factor and moisture/oxygen/HMA can be seen in Figure 10. The absolute level of the pre-exponential for HMA is lower than LMA at different moisture contents. However, the increment rate of pre-exponential for HMA is higher than LMA as the moisture increases from 0.5% to 5% with a factor of 25.9.

The expected life of the paper in the presence of moisture, LMA and different oxygen concentrations can be seen in Figures 11(a) to 11(g). At all moisture contents, the expected life of the paper decreases by a factor of 33.6 as the temperature increases from 65°C to 98°C. The paper expected life decreases by a factor of 1 as the oxygen concentration increases

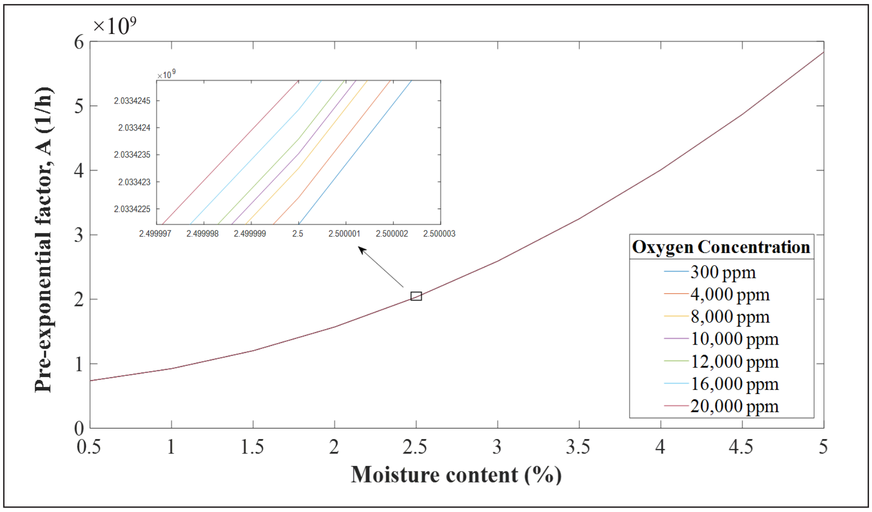


Figure 9. Relationship between pre-exponential factor and moisture content/oxygen/LMA

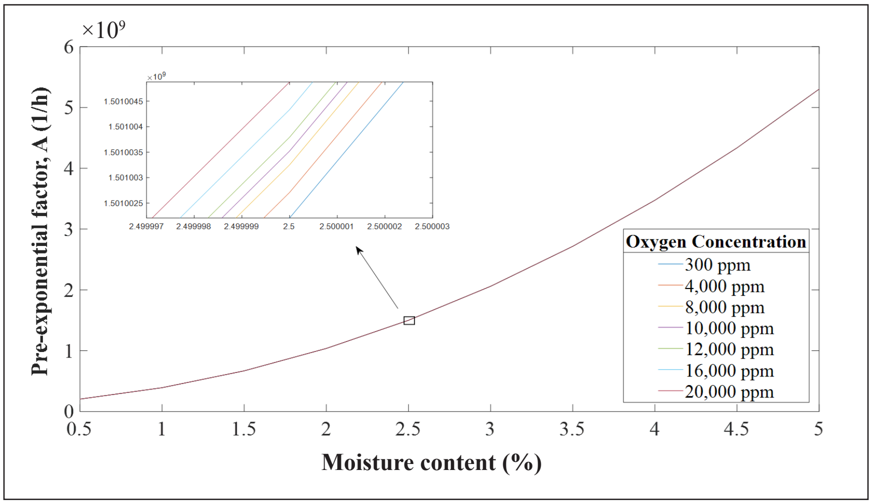
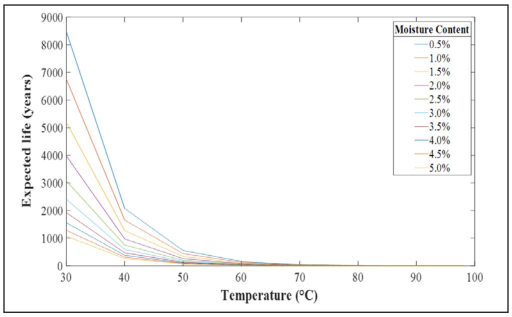
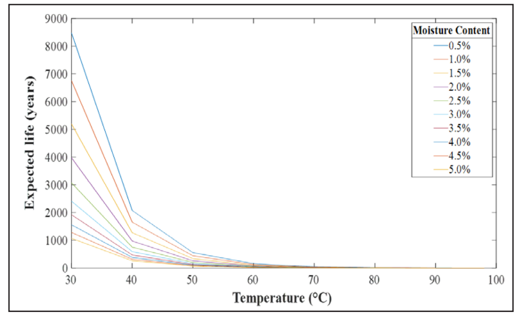


Figure 10. Relationship between pre-exponential factor and moisture content/oxygen/HMA

from 300 ppm to 20,000 ppm at 65°C and 98°C. The expected life of the paper at 65°C for all oxygen concentrations at 0.5% of moisture content is 88 years. It decreases to 32 years as the moisture content increases to 2.5%. Further decrement of the expected life of the paper to 11 years is found as the moisture content reaches 5%. At 0.5% moisture content, the expected life of the paper at 98°C for all oxygen concentrations is three years, and it decreases to 1 year as the moisture content increases to 2.5%. Further decrement of expected life for the paper is found at a moisture content of 5%, whereby it reaches 0.3 years. It is also apparent that the variations of oxygen concentrations have only a small effect on the expected life of the paper, partly due to the large pre-exponential factor contributed by the moisture.



(a)



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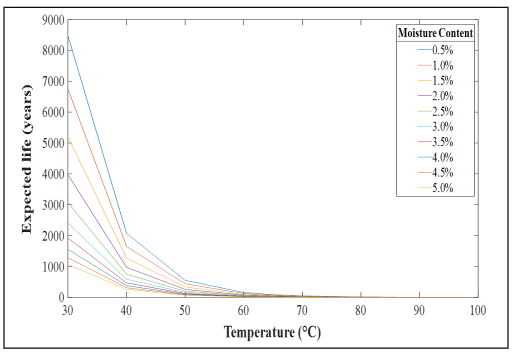

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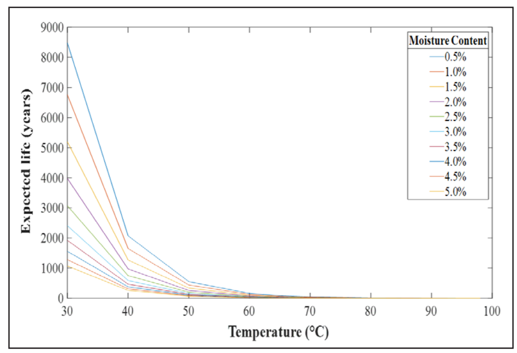

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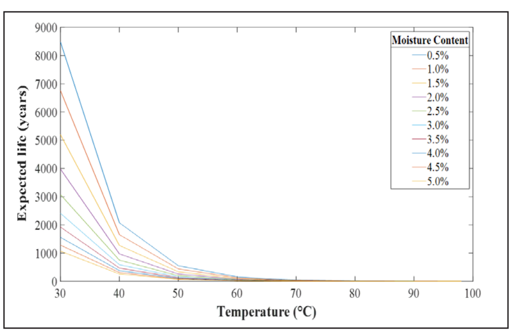
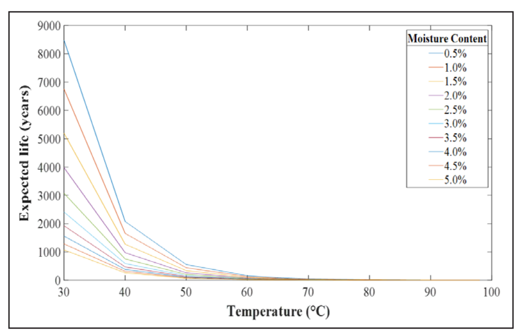
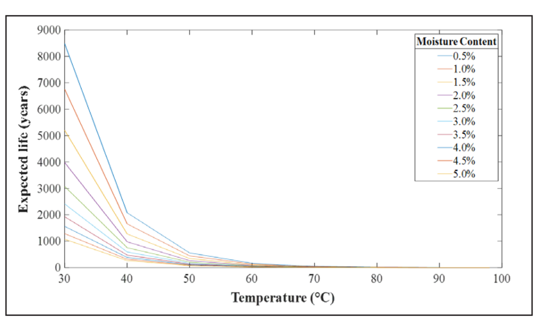


(e)



(f)



(g)

Figure 11. Expected life of paper under moisture contents, LMA and different oxygen concentration of (a) 300 ppm; (b) 4,000 ppm; (c) 8,000 ppm; (d) 10,000 ppm; (e) 12,000 ppm; (f) 16,000 ppm; and (g) 20,000 ppm

Since the pre-exponential for HMA is lower than LMA, the expected life of the paper in the presence of moisture and oxygen is longer, as seen in Figures 12(a) to 12(g). For all moisture contents, the expected life of the paper decreases by a factor of 33.6 as the temperature increases from 65°C to 98°C at the oxygen concentrations of 300 ppm and 20,000 ppm, respectively. At 65°C and 98°C, the paper expected life decreases by a factor of 1 as the oxygen concentration increases from 300 ppm to 20,000 ppm. At 0.5% of moisture content, the expected life at 65°C for all oxygen concentrations are 319 years, and it decreases to 43 years as the moisture content increases to 2.5%. At a moisture content of 5%, the expected life of the paper decreases to 12 years.

The expected life of the paper at 98°C for all oxygen concentrations at 0.5% moisture is ten years, whereby it decreases to one year as the moisture content increases to 2.5%. As the moisture content reaches 5%, the expected life of the paper further decreases to 0.4 years. Similarly, the expected life of the paper in the presence of HMA is less affected by variations of oxygen concentrations due to the small contribution by its pre-exponential factor.

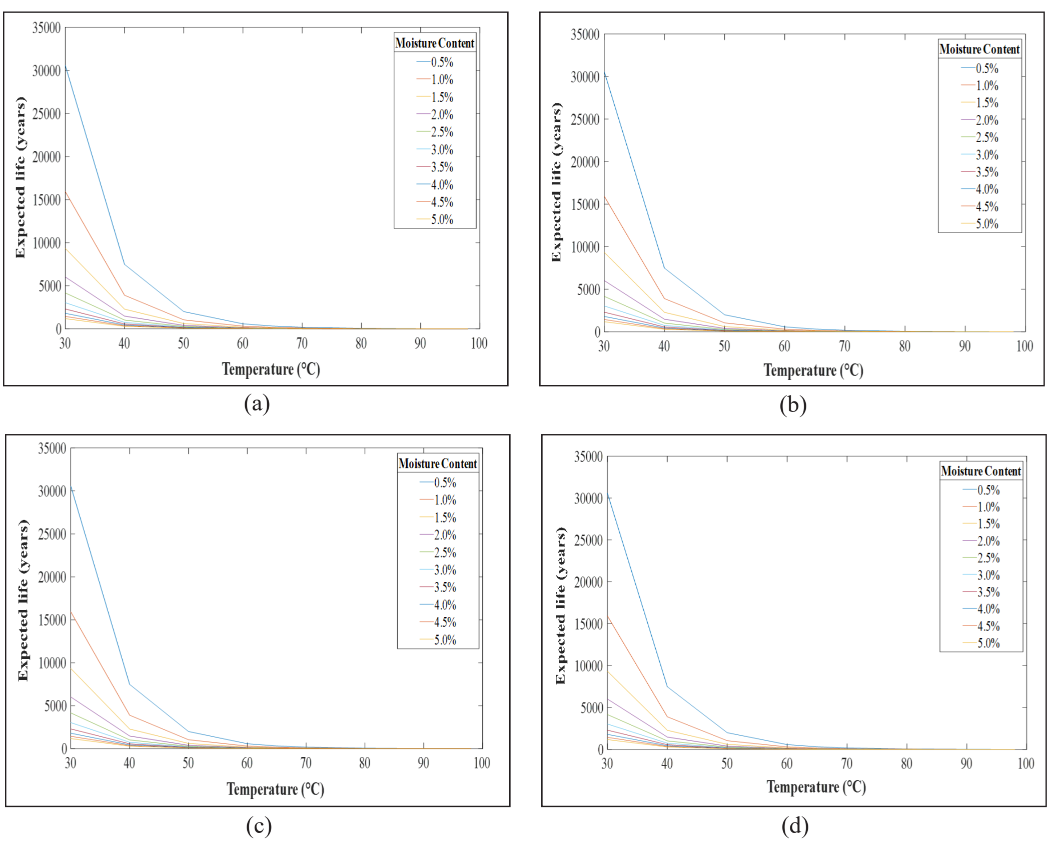


Figure 12. Expected life of paper under moisture contents, HMA and different oxygen concentration of (a) 300 ppm; (b) 4,000 ppm; (c) 8,000 ppm; (d) 10,000 ppm

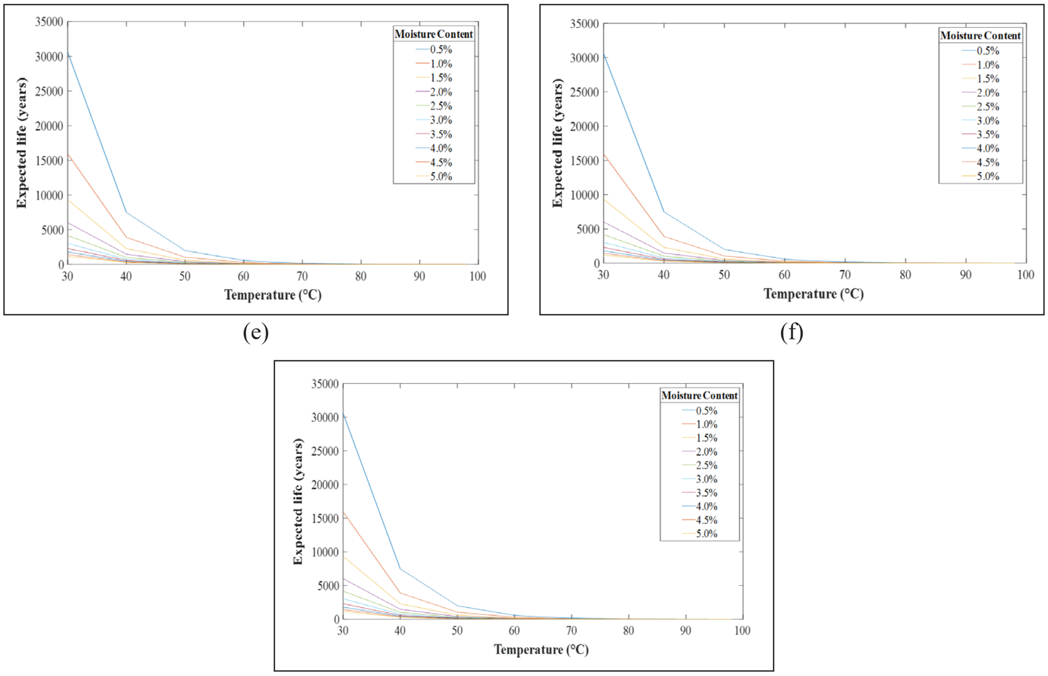


Figure 12. (continue). Expected life of paper under moisture contents, HMA and different oxygen concentration of (e) 12,000 ppm; (f) 16,000 ppm; and (g) 20,000 ppm

At 65°C and 98°C, the paper expected life for HMA relative to the LMA factor in the presence of oxygen concentrations and different moisture contents is shown in Table 1. Regardless of the oxygen concentration, the factor for the expected life of the paper decreases as the moisture content increases. The factor decreases due to the increment of the LMA. The presence of higher LMA results in a higher degradation rate and, in turn, shortens the expected life of a paper.

Table 1
The HMA relative to the LMA paper expected life factor in the presence of oxygen concentration range and different moisture contents

Oxygen concentration (ppm)	Moisture content (%)	Expected life factor
300 – 20,000	0.5	3.6
	2.0	1.5
	3.5	1.2
	5.0	1.1

DISCUSSION

A previous study by Teymouri and Vahidi (2019) proposed to determine the relationship between the pre-exponential factor and oxygen/moisture by using Equations 6, 11, and 12. The oxygen concentration for the low level was set according to Equation 6, and the medium level was set to 7,000 ppm–14,000 ppm, while the high concentration was set to 16,500 ppm – 25,000 ppm.

For medium oxygen (7,000 – 14,000 ppm)

$$A_m = 9.981 \times 10^6 w^3 - 4.839 \times 10^7 w^2 + 1.371 \times 10^9 w - 6.739 \times 10^7 \quad [11]$$

For high oxygen (16,500 – 25,000 ppm)

$$A_h = -5.492 \times 10^5 w^3 + 4.427 \times 10^6 w^2 + 1.705 \times 10^9 w + 1.521 \times 10^8 \quad [12]$$

where A_m and A_h are pre-exponential factors for medium and high oxygen concentration, respectively.

A comparative study was conducted to determine the pre-exponential factor and oxygen/moisture using two approaches. The first approach is based on the summative method according to Equations 5 and 6, while the other approach directly utilizes Equations 6, 11, and 12 in order to determine the relationship between the pre-exponential factor and oxygen concentration. The comparison of the pre-exponential factor for oxygen/moisture using both approaches can be seen, as in Table 2. At all moisture contents, the approach by Teymouri and Vahidi (2019) yields slightly higher pre-exponential factors at medium and high oxygen concentrations. However, both approaches have almost similar pre-exponential factors at low oxygen concentration. The percentage of differences for pre-exponential factors increases as the oxygen concentration increases from 0 ppm to 20,000 ppm, while it decreases as the moisture increases from 0.5% to 5% (Teymouri & Vahidi, 2019). On the other hand, the pre-exponential factors at different oxygen concentrations by the summative approach have only small differences between each of the values. It is because the differences in reaction rates among each of the oxygen pressures are quite small, which leads to almost similar pre-exponential factors at different oxygen concentrations (Ese et al., 2010).

Oxygen has a lower impact on the life of paper as compared to moisture content. According to Emsley et al. (2000c), there is only a weak synergetic effect exist between temperature and oxygen whereby the oxygen accelerates the ageing of a paper only one third as efficient compared to the moisture. It is shown that the combination of oxygen and dry moisture content of 0.5% results in lower pre-exponential factor than the combination of oxygen, moisture and LMA (Emsley & Stevens, 1994b; Lelekakis et al., 2012a; Susa et al., 2011; Teymouri & Vahidi, 2019). Other studies from Lelekakis et al. (2012b) and Teymouri and Vahidi (2019) also show that the combination of different moisture contents with low oxygen concentration leads to a lower pre-exponential factor than the multi pre-exponential factors of oxygen, moisture and LMA. Lundgaard et al. (2004) shows that the combination of acids and water generate lower pre-exponential factor than the oxygen, moisture and acids that exist together. It is apparent, based on the current mathematical expression findings, the overall pre-exponential factor for multi oxygen, moisture and LMA/HMA is higher than either single or double pre-exponential factors.

Table 2
The comparison of the pre-exponential factor for oxygen/moisture based on experimental and mathematical summative approaches

Oxygen concentration (ppm)	Moisture content (%)								
	0.5			2.5			5.0		
	Pre-exponential factor using summative method, A (1/h)	Pre-exponential factor using Equations 6, 11, and 12, A (1/h)	Percentage difference of pre-exponential factor (%)	Pre-exponential factor using summative method, A (1/h)	Pre-exponential factor using Equations 6, 11, and 12, A (1/h)	Percentage difference of pre-exponential factor (%)	Pre-exponential factor using summative method, A (1/h)	Pre-exponential factor using Equations 6, 11, and 12, A (1/h)	Percentage difference of pre-exponential factor (%)
0	$\approx 1.5428 \times 10^8$	1.5428×10^8	≈ 0	$\approx 1.4509 \times 10^9$	1.4509×10^9	≈ 0	$\approx 5.2525 \times 10^9$	5.2525×10^9	≈ 0
6,999	$\approx 1.5428 \times 10^8$		≈ 0	$\approx 1.4509 \times 10^9$		≈ 0	$\approx 5.2525 \times 10^9$		≈ 0
7,000	$\approx 1.5428 \times 10^8$	6.0726×10^8	119	$\approx 1.4509 \times 10^9$	3.2136×10^9	76	$\approx 5.2525 \times 10^9$	6.8255×10^9	26
14,000	$\approx 1.5428 \times 10^8$		119	$\approx 1.4509 \times 10^9$		76	$\approx 5.2525 \times 10^9$		26
16,500	$\approx 1.5428 \times 10^8$	1.0056×10^9	147	$\approx 1.4509 \times 10^9$	4.4337×10^9	101	$\approx 5.2525 \times 10^9$	8.7191×10^9	50
20,000	$\approx 1.5428 \times 10^8$		147	$\approx 1.4509 \times 10^9$		101	$\approx 5.2525 \times 10^9$		50

CONCLUSION

A mathematical model of multi pre-exponential factors has been examined based on the summative approach focusing on the insulation paper of oil-immersed transformer. The model has been evaluated based on the combination of individual pre-exponential factors for oxygen, moisture and LMA/HMA that have been identified based on previous experimental studies. It is apparent with the summative mathematical expression that the multi pre-exponential factors have a significant impact on the expected life of paper. The presence of either LMA or HMA affects the overall multi pre-exponential factor. Based on the current study, the expected life decreases by a factor of 59.8 as the oxygen concentration increases from 15,000 ppm to 210,000 ppm. As the moisture increases from 0.5% to 5%, the expected life decreases by a factor of 34. LMA has a higher impact than HMA by decreasing the expected life by a factor of 33.6. In the presence of LMA, the impact of multi pre-exponential factors is apparent compared to HMA, whereby the expected life decreases by a factor of 7.9 as the moisture content increases from 0.5% and 5% and oxygen increases from 300 ppm to 20,000 ppm. The impact of oxygen on the overall multi pre-exponential factor is quite small compared to moisture and LMA/HMA.

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