ELECTRICAL, PHYSICAL, AND CHEMICAL PERFORMANCE OF TRANSFORMER'S OIL, PAPER INSULATION, AND GASKET RETROFILLED WITH SYNTHETIC ESTER OIL"

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A report submitted
in partial fulfilment of the requirements for the degree of
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2024

DECLARATION

I declare that this thesis entitled "ELECTRICAL, PHYSICAL, AND CHEMICAL PERFORMANCE OF TRANSFORMER'S OIL, PAPER INSULATION, AND GASKET RETROFILLED WITH SYNTHETIC ESTER OIL" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : MUHAMMED HAIRIE BIN MAT HUSSIN

Date : 11/1/2024

APPROVAL

I hereby declare that I have checked this report entitled "ELECTRICAL, PHYSICAL, AND CHEMICAL PERFORMANCE OF TRANSFORMER'S OIL, PAPER INSULATION, AND GASKET RETROFILLED WITH SYNTHETIC ESTER OIL", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electrical Engineering with Honours

Signature :

Supervisor Name : Ts. Dr. Mohd Shahril Bin Ahmad Khiar

Date : 11/1/2024

DEDICATIONS

To my dearest mother and father, the pillars of my life.

ACKNOWLEDGEMENTS

In order to complete this project, I have researched several projects or projects that have been done through many website and book to improve my understanding in this topic . In particular, I would like to thank my main project supervisor Ts. Dr. Mohd Shahril Bin Ahmad Khiar for his encouragement, guidance and advice.

I would also like to thank my many helpful friends, and for providing various ideas. Their views are greatly appreciated. This project would not have been possible without their support.

ABSTRACT

Retrofilling is a method involving a replacement of aged mineral oil with new insulating oil as the insulating material in transformers. Despite thorough flushing with new oil during the retrofilling process, contamination from the old oil persists. This contamination can lead to the degradation of insulating materials such as insulating paper, pressboard, and gaskets. Over a long period, this degradation can change the properties of the insulating material into a semi-conductor. The transformer's lifespan is assessed based on the performance of the insulation system, including insulating oil and paper insulation oil. Therefore, this research aims to investigate the electrical, physical, and chemical performances of the transformer's oil, paper insulation, and gaskets after the retrofilling process with ester oil. Nynas Nytro Libra (MO), Midel 7131 (synthetic oil) , kraft paper, pressboard, and gaskets made of nitrile rubber (NBR) will be used as insulating materials. The study will be conducted under two conditions: retrofilling with mineral oil (MO) and retrofilling with synthetic oil (SE). A comparison will be made between these two conditions to assess the effectiveness of the retrofilling process using SE. Transformers oil after retrofilled with MO showed better performance compared to after retrofilled with SE where the dissolved decay product (DDP) values after retrofilled with MO was higher compared to after retrofilled with SE. Retrofilled with MO also shows a better effect on kraft paper compared to retrofilled with SE where the tensile strength is slightly higher. However, the shore hardness of the gasket shows a better performance when retrofilling with SE.

ABSTRAK

Pengisian semula ialah kaedah yang melibatkan penggantian minyak mineral lama dengan minyak penebat baharu sebagai bahan penebat dalam pengubah. Walaupun pembilasan menyeluruh dengan minyak baru semasa proses pengisian semula, pencemaran daripada minyak lama akan berterusan. Pencemaran ini boleh menyebabkan kemerosotan bahan penebat seperti kertas penebat, papan tekan dan gasket. Dalam tempoh yang lama, kemerosotan ini boleh mengubah sifat bahan penebat kepada semikonduktor. Jangka hayat pengubah dinilai berdasarkan prestasi sistem penebat, termasuk minyak penebat dan minyak penebat kertas. Oleh itu, penyelidikan ini bertujuan untuk menyiasat prestasi elektrik, fizikal, dan kimia minyak pengubah, penebat kertas, dan gasket selepas proses pengisian semula dengan minyak ester. Nynas Nytro Libra (MO), Midel 7131 (minyak sintetik), kertas kraf, papan tekan, dan gasket yang diperbuat daripada getah nitril (NBR) akan digunakan sebagai bahan penebat. Kajian akan dijalankan di bawah dua keadaan: pengisian semula dengan minyak mineral (MO) dan pengisian semula dengan minyak sintetik (SE). Perbandingan akan dibuat antara dua syarat ini untuk menilai keberkesanan proses pengisian semula menggunakan SE. Minyak transformer selepas diisi semula dengan MO menunjukkan prestasi yang lebih baik berbanding selepas diisi semula dengan SE di mana nilai produk pereputan terlarut (DDP) selepas diisi semula dengan MO adalah lebih tinggi berbanding selepas diisi semula dengan SE. Diisi semula dengan MO juga menunjukkan kesan yang lebih baik pada kertas kraf berbanding diisi semula dengan SE di mana kekuatan tegangannya lebih tinggi sedikit. Walau bagaimanapun, kekerasan pantai gasket menunjukkan prestasi yang lebih baik apabila mengisi semula dengan SE.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

MO	-	Mineral Oil
AC	-	Alternative Current
SE	-	Synthetic Ester
NE	-	Natural Ester
S	-	Sulphur
O	-	Oxygen
N	-	Nitrogen
mL	-	Mililiter
L	-	Liter
NBR	-	Nitrile Butadiene Rubber
Fe	-	Ferum
Cu	-	Copper
Zn	-	Zink
Al	-	Aluminium
M	-	Weight
HA	-	Hardness

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Power transformers are used in generation, distribution, and transmission system [1], [2], [3]. Transformer, which is a static machine, performs the crucial function in electrical power system by either stepping up or stepping down the voltage to ensure the reliability of transmission and distribution networks [1], [4]. There are two types of transformers that are commonly used namely, liquid-filled transformers and dry-type transformers. Liquid-filled transformers use oil as insulation, while dry-type transformers use air or gas.

Using oil as insulation can reduce losses on transformers [5]. Due to this reason, liquid-filled transformers are commonly used in power systems networks as compared to dry-type transformers because liquid in transformers serve as a good cooling medium for coil and core of the transformers. Kraft paper and insulating oil are usually used in liquid-filled transformers to provide an outstanding thermal and dielectric properties in addition to low cost [5], [6], [7], [8].

Insulation paper (kraft paper) serves as an insulator to separates the turn-to-turn conductors (windings) as shown in Figure 1–1. Insulating paper is also used in high-voltage cables and power transformers. It offers high availability, low cost, highly satisfying performance, and excellent mechanical properties at high temperatures compared to synthetic materials [4]. However, when degradation occurs, (during the operation due to heating, environmental impact, and mechanical pressures) insulation system can diminished [2]. The oxidation can cause the degradation of insulating paper due to the loss of mechanical properties, even when exposed to air and temperatures below 100 °C. Insulating material will slowly degrade until it does not function as an insulator when the degradation process takes place over a long period of time [9].

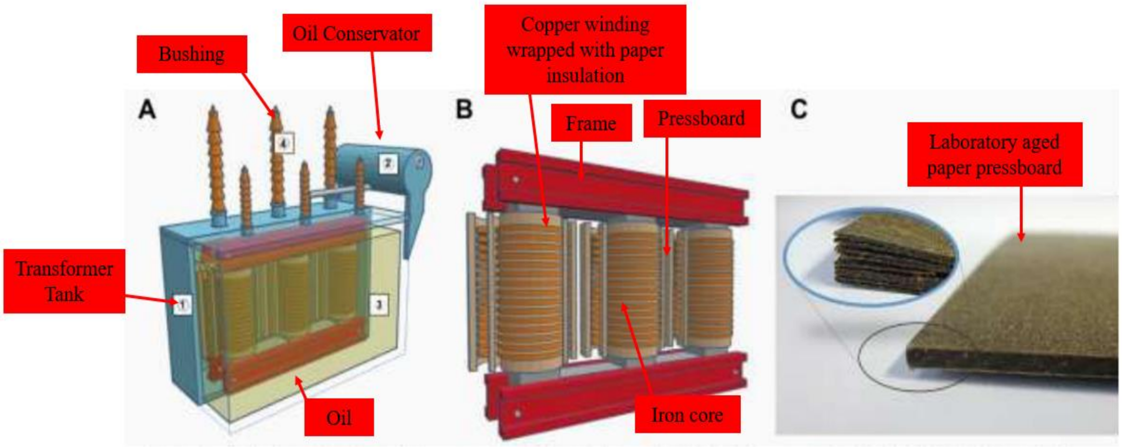

Figure 1–1: Show a) power transformer, b) power transformer core (section between core and winding and c) several kraft paper pressed by pressboard [4].

The failure of insulation system can cause catastrophic transformer failures. It happened when the insulating paper loss their mechanical strength and become brittle. The failure of power transformers can results in a significant economic losses since it involves in repairing and replacement of the materials with new one [2]. Therefore, predicting the lifespan of insulating systems is crucial for a reliable electricity supply [10], [11].

1.2 Motivation

Table 1–1 shows the detailed failure analysis that was conducted on 348 distribution transformers from 2010 to 2015 in a city-based sub division area in India. Core, winding, tank, insulation, oil, and bushing are the main contributors to the transformer failures. Interestingly, approximately 145 cases out of 348 cases of transformer failures were due to insulation failures. Insulation failure (41.67 %) was identified as the main cause of the failure. The failure of transformer has led to loss of property, loss of MVA power, loss in terms of facilities and replacement of transformers and others.

Table 1–1: Annual statistics for transformer component failure from 2010 until 2015 [12].

Component	2010	2011	2012	2013	2014	2015	Total	Percentage
Core	2	3	3	1	2	3	14	4.02%
Winding	6	7	11	9	10	11	54	15.51%
Tank	1	1	2	2	1	2	9	2.59%
Insulation	16	25	21	28	25	30	145	41.67%
Oil	2	4	5	3	5	4	23	6.61%
Bushing	6	9	8	7	9	10	49	14.08%
Other	7	8	10	6	12	11	54	15.52%
Total	41	47	50	66	69	75	348	100%

Even though mineral oil (MO) has a good dielectric and a reasonable cost, it draws some disadvantages to the environment in the case of transformer explosions due to the fact that MO is toxic, and non-biodegradable [13], [14]. Many parties are beginning to consider the use of ester oil as an insulating oil which has less impact on the environment [3]. This is because these oils are environmentally friendly and have advantages over MO in certain aspects [6]. For example, the flash point of ester oil is higher than that of MO [7], [15], [16]. As a result, the risk of fire occurring with ester oil is lower compared to MO.

1.3 Problem Statement

Retrofilling is a process of replacing MOwith new oil, where the MO is drained and will replace with new oil [17]. As compared to MO, ester oil has gained much attention nowadays. This is because retrofilling with ester oil may extend the lifespan of power transformer and reducing the impact on the environment and the risk of fire [18], [19]. Unfortunately, it was reported that within the first six months after the transformer is retrofilled with ester oil, the remnant of MO presence within paper insulation is transferred to the ester oil [2]. In addition, thermal and dielectric properties of the insulating oil will change over time when there is a mixture of both insulating oils. These mixtures may cause the changes in term of its properties [19] (i.e., a reduction in flash and fire points). This was found to occur at a 3.5 % MO content in SE [20].

The remnants of the MO may still remain in the windings, insulating paper, and other components even after being flushed multiple times with the ester oil [16]. Even after multiple flushes, some of the aged MO and contamination will be remained within the materials inside the transformers. The remaining MO, both with and without flushing, typically ranges from less than 4% and more than 7%, respectively [21]. Therefore, it is important to understand the properties of the insulation used in power transformers particularly after retrofilling process in order to reduce the occurrence of breakdown and faults [11]. This project is carried out to investigate the electrical, physical, and chemical properties of transformers' insulating oil, kraft paper and gasket associate with retrofilling using SE.

1.4 Objective

This objectives of this research are:

i. To analyze the effect of retrofilling process using mineral insulating oil on the physical, electrical and chemical properties of transformer insulating oil, insulating paper, and gasket.
ii. To investigate the compatibility of using synthetic ester as retrofiller based on the changes in physical, electrical and chemical properties of insulating oil, insulating paper, and gasket.

1.5 Scope

This scope of this research includes:

i. MO will be retrofilled with MO for first experiment and MO will be retrofilled with SE oil for the second experiment.
ii. The accelerated thermal aging process will be carried out in a tank that replicates the real conditions of power transformers at temperature of 110 °C for 55 hours.
iii. Kraft paper (weighing: 80 g), pressboard (weighing: 320 g), and surface area of the gasket (325 cm^2) will be used for material sizing based on the amount of insulation oil used.

iv. After the set time is up, the paper will be taken and tested to get the difference performance for both experiement in term on electrical, physical, and chemical performance.

v. The physical test carried out is the weight of kraft paper and pressboard before and after drying, tensile strength of kraft paper, shore hardness of gasket and visual observation of pressboard.

vi. The electrical test performed is polarization index while the chemical test is dissolved decay product.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss in detail on the previous studies particularly on retrofilling technique. Initially, retrofilling transformers will be review in Section 2.2. This is followed by the description of insulating oil and material properties in Section 2.3 and Section 2.4, respectively. Section 2.5 and Section 2.6 will briefly describes the theory of polarization index and physical tests. The final section of this chapter which is Section 2.7 will be presenting a theory on dissolved decay product.

2.2 Retrofilling Transformers

Retrofilling is a process of removing the aged oil with a new oil. It shall be noted that fire resistance is the main challenge that is crucial to be addressed. Therefore, additives were added into insulating oil to increase their flash point. Nevertheless, the addition of additives will only increase the flash point from 2 °C – 7 °C. It is worth noting that the addition of additives may also reduce the flash point of insulating oil [22]. Therefore, the retrofilling process is carried out because it is the most practical way in addition to the low operating costs and downtime.

The success rate of the retrofilling process will be depending on how much the aged insulating oil can be removed. It is worth noting that this process will not completely removed the aged oil; a small amount of aged oil will be remained in the transformer which will stick to the solid insulations [3]. Approximately 10% of the aged oil will be remained in the insulation system where it will seep into the pores of the winding, core and transformer board. The aged oil will be mixed with the new oil therefore, it may reduce the dielectric and flash point properties of the retrofilled oil.

A finding reported in [3] revealed that the changes in dielectric properties of the transformer that was retrofilled with ester oil was less than 3%. This is because ester oil can resist oxidation and is able to absorb more moisture than MO and is produced by the degradation of cellulose.

2.3 Insulating Oil Properties

Liquid insulation has good heat dissipation properties compared to gas and solid insulation material where it functions as a good heat transfer [3]. As science and technology advanced, the number of transformer oil types continues to grow. However, MO remained the most preferable choice due to its numerous advantages, including affordability, a low condensation point, low viscosity, and exceptional insulation performance [23].

Insulating oil also function as a carrier of information. It can provide information about insulating paper, especially related to the deterioration and performance of insulating paper [8]. Insulating oil plays an important role in transferring thermal losses to the cooling down power transformers. The lifespan of oil insulation can be extended by filtering, restoring or changing with new oil. It also important to keep the insulating paper in good condition. This is because the condition of insulation paper will determine the lifespan of the transformers. The damaged insulation paper cannot be repaired. However, it can be replaced with a new one to maintain the lifespan of power transformers [11]. Therefore, monitoring the insulation oil is very important in maintaining the health of power transformers.

The insulating oil is made from crude oil extracted from petroleum, is a form of insulating oil commonly used in transformers [3], [23]. Crude oils are intricate combinations of numerous distinct hydrocarbon molecules, and the relative proportions of these compounds can be vary depending on the used crude oils which is coming from various sources [24]. The characteristics of hydrocarbons can be seen in the characteristics of transformer oil. Almost all hydrocarbon compounds in transformer oil are composed of paraffin, naphthene and aromatic hydrocarbons as shown in Figure 2–**1** [25].

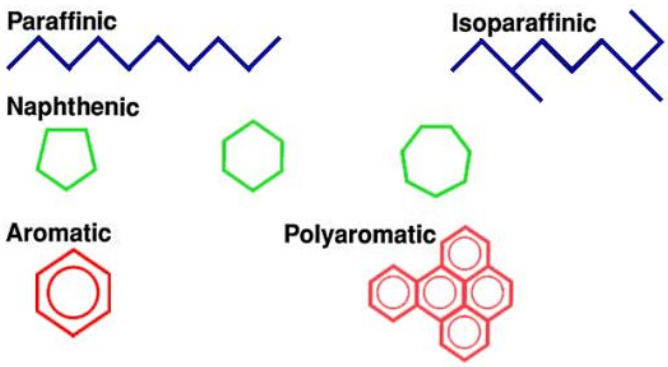

Figure 2–1: Hydrocarbon compound in mineral oil molecules from [25].

Parafinnic-based transformers oil was used in the year before 1925 before being replaced by naphthenic-based transformers oil because it has better properties compared to paraffinic oil [11]. On the other hand, paraffinic is a group of molecules that can exhibit branching or straightness in their structure. Straight paraffins also referred to as normal-alkanes or waxes, wherein the flow of these molecules can become hindered in colder climates, necessitating the removal of normal-alkanes to be used in cold climates. Moreover, paraffin displays a relatively limited solubility for water and oxidation by-products, which can result in the accumulation of deleterious deposits or contaminants [25]. Paraffin molecules have low thermal stability compared to aromatic molecules and naphthenic.

Meanwhile, naphthenic is a group of compounds alternatively referred to as cycloalkanes due to their characteristic, exhibit excellent properties at low temperatures and possess enhanced solvency capabilities when compared to normal-alkanes. Within the naphthenic group, the ring structures can consist of five, six, or seven carbons, although the presence of six carbon atoms within a single ring tends to be the dominant [24], [25]. Furthermore, it is possible for naphthenic molecules to incorporate two or more interconnected ring structures in naphthenic molecules.

Unsaturated ring groups can be found in aromatic hydrocarbons. Aromatic compounds are present in all MO transformers. At least one ring of six carbon atoms with alternate double and single bonds is present in aromatic compounds [25]. Both chemically and physically, they differ greatly from paraffinic and naphthenic molecules. While poly-aromatic hydrocarbons have two or more benzene rings fused together, mono-aromatic hydrocarbons only have discrete benzene ring structures [24].

Oil density is an important property to be considered. This is because at low temperatures, there will be floating ice in the insulating oil of transformers. This causes the presence of free water that is not energized in the transformer. The presence of these foreign objects can lead to transformer failure [25]. Oils that have a high aromatic content have a higher density than oils that have naphthenic and paraffinic molecules. This discrepancy in density arises due to the variations in molecular structures and compositions. The density of oil is inversely proportional to the increase in temperature. In other words, as the temperature rises, the density of the oil decreases. This phenomenon can be attributed to the fact that as the oil molecules experience an increase in temperature, they gain energy, leading to an expansion of their volume and a subsequent decrease in their density.

There are two primary types of mineral insulating oil that are commonly used, namely naphthenic base oil and paraffin base oil. Both mineral based oils share similar compositions primarily consisting of hydrocarbons, but their differentiation were due to the diversity of their compositions [23]. The difference between these two oils can be seen from the scale of the range of paraffinic content in insulating oil from very paraffinic to very naphthenic. Insulating oil that has a paraffinic content of less than 50% is defined as paraffinic while insulating oil that has a paraffinic content of more than 50% is defined as naphthenic [25]. In addition, there are other molecules in insulating MO with a very low percentage. Among of them are nitrogen (N), sulphur (S) and oxygen (O). These elements can also be called heteroatoms that are mostly bound to aromatic structures. Heterocyclic compounds also have those elements that can contribute to oxide instability [24].

Naphthenic MO is preferred over paraffin base MO because naphthenic has various advantages which include a notable enhancement in solubility, an improved capacity to perform effectively at lower temperatures, and a lower kinematic viscosity, all of which collectively contribute to its widespread adoption and extensive utilization across various applications [26].

The use of esters oil as insulating oil and cooling medium has been increasing every year. Ester oil has a biodegradation level that reaches up to 95 %, which is higher than the fire point of MO, and it also possesses high dielectric properties [6]. MO is not suitable for use in sensitive and densely populated areas because it has flammable, explosive, and low biodegradation properties [27]. This is because the combustion of MO can cause air pollution and old MO contains polycyclic aromatic compounds that have carcinogenic properties. There are two types of ester oil that used in the power transformer such as natural ester (NE) where refined from animals and vegetables to produced SE [8]. Many parties have started using ester oils such as SE. SE has become the main choice as insulating oil of the transformer because it is environmentally friendly and has good properties [3], [28]. SE is an organic compound formed by the reaction of plyvent alcohols and fatty acids [27]. SE has better properties than MO where it has a high flash point, good biodegradation, low toxicity, good electrical thermal properties when operating and acts as a good lubricant [7], [15], [27], [28]. The SE oxidation process does not produce sludge but produces organic acids. The content of molecules and products that contribute to low oxidation have contributed to thermal stability. Ester oil has high stability where it has high binding energies. However, ester oil is also exposed to the hydrolysis process due to the moisture content in the oil [3].

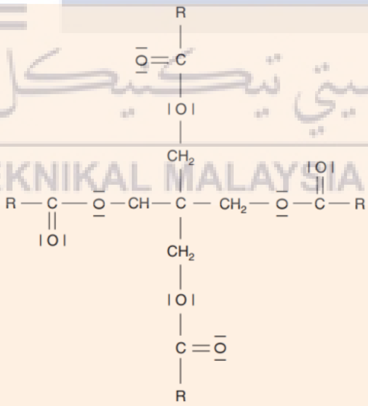

Figure 2–2: Structure of ester molecule [3].

Practically, the remaining MO in the insulating paper and pressboard will be released and mixed with the ester oil when the transformer was retrofilled. The MO content remained in the transformer shows how much contaminant is trapped during the retrofilling process. The higher the amount of sludge, the lower the fire point of the insulating oil [18], [20]. Oil contamination must be below 9 % to prevent the fire point from dropping significantly according to IEC 61039 as shown in Figure 2–3 [18].

Therefore, the remaining sludge content after retrofill must be considered for the retrofilling objective to be achieved.

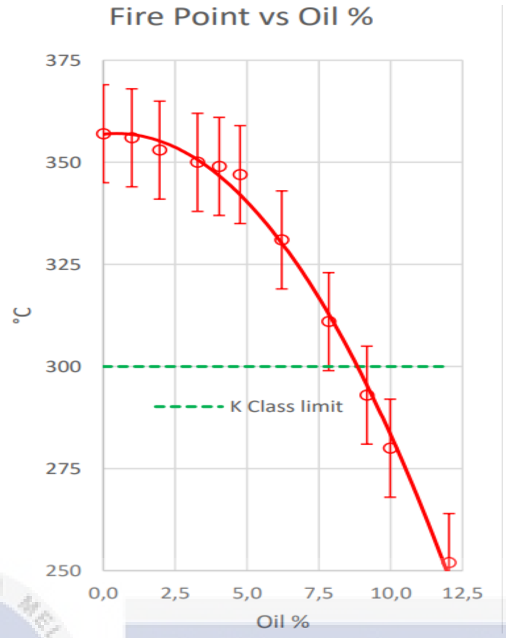

Figure 2–3: The effect of contamination on the fire point of insulating oil with error (±13 ºC) [18].

2.4 Insulating Material

Kraft paper is usually used in power transformers as insulation for winding. Kraft paper consists of 78 % - 80 % cellulose, 10 % - 20 % hemicellulose and 2 % - 6 % lignin where it functions as the main insulation in the winding [2], [29]. Kraft paper will be wrapped around the windings to prevent turn-to-turn short circuit [30]. Kraft paper will usually be impregnated with insulating oil to help transformers absorb heat [2]. However, the use of cellulose-based kraft paper leads to the formation of oxides and impurities when it reacts with insulating oil [31]. This content will become a deposit on the surface of the kraft paper. These impurities degrade the dielectric properties of the oil and create electrical and mechanical stresses on the transformer core and windings, ultimately leading to failure [32]. The characteristics of kraft paper can also determine the effectiveness of insulation along insulating oil [31].

Cellulose is the primary source of insulating paper, and when the transformers is operating, three key processes take place that cause the cellulose to degrade [30]. There are three processes that lead to cellulose deterioration namely pyrolysis, oxidation, and hydrolysis [29], [30]. However, the simultaneous action of several degradation mechanisms makes the phenomenon of deterioration become more complex.

The pyrolysis process refers to a chemical degradation mechanism that takes place within insulation paper when exposed to heat, occurring in the absence of oxidizing and moisturizing agents. This process generates various by-products, including water, carbonyl compounds, solid carbon products, hydroperoxide, carbon oxide, and 1,6-anhydro b-D-glucopyranose. Furthermore, the compound 1,6-anhydro b-D-glucopyranose leads to the formation of different acids such as levulinic acids, acetic acid, pyruvic acid, acetone, methanol, hydrocarbons, and furanic compounds, as depicted in the accompanying as shown in Figure 2–4. Under normal operating conditions, the average maximum range of the hot-spot is between 110 °C to 95 °C, resulting in an average increase in winding temperature of 55 °C to 65 °C. However, during instances of overloading or failure of the cooling system, the hot-spot temperature inside the transformer can surpass 130 °C. At such elevated temperatures, the cellulose surrounding the hot spot becomes susceptible to degradation through pyrolysis [33].

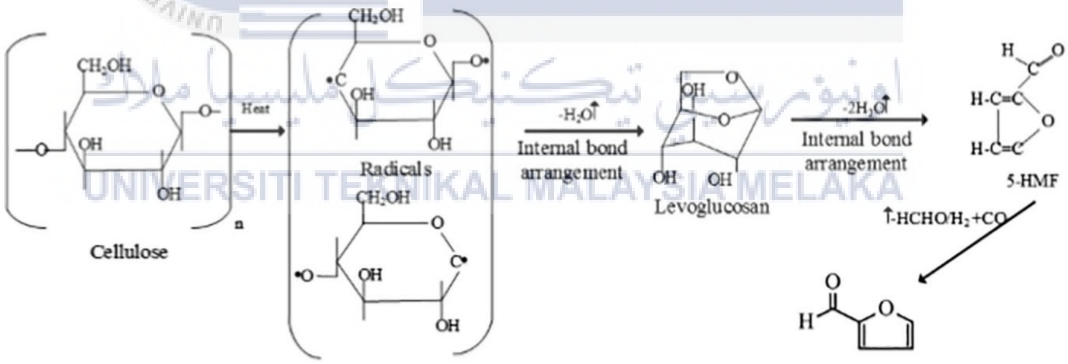

Figure 2–4: Cellulose Pyrolysis Mechanism [33].

Hydrolysis occurs when the insulating paper absorbs moisture from the insulating oil inside the transformer. The moisture will migrate between the insulating oil to the kraft paper causing the moisture in the paper to increase. The increase in humidity causes the dielectric loss to increase which leads to a reduction in the dielectric strength of the insulating paper [34]. The presence of moisture affects the hydrolysis degradation of cellulose insulation. The amount of H+ ions formed as a result of the dissociation of low molecular weight of acids in water can control the hydrolysis [35]. Throughout the hydrolysis process, glucose molecules are formed as a result of glycosidic bonds when there is a reaction between low molecular acid and water [36]. These glucose molecules are unbalanced. It can lead to an increase in the hydrolysis process and form furan content, 5-hydroxymethyl-2-furaldehyde (5-HMF) as shown in Figure **2**–**5**.

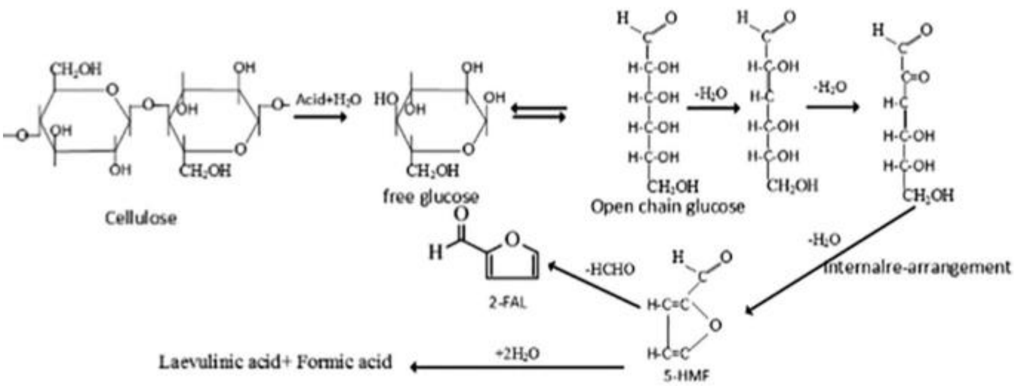

Figure 2–5: Mechanism of hydrolisis cellulose [36].

The oxidation process of cellulose insulation will produce carbon dioxide, water and oxygen. When the transformer is in operated, the reaction of water and oxygen will produce hydrogen peroxide along with copper and iron [33]. This causes the oxidation process to occur and causes cellulose insulation to degrade. Oxidation of insulating oil will produce moisture and acids which are very dangerous to insulating paper because it is able to break the cellulose chain [29]. Acids will also dissolve in the oil and form sludge that reduces the insulating oil dielectric strength and the high amount of ions gathered in the insulating oil will reduce the dissipation factor of the insulating oil.

Pressboard used in the power transformer in order to minimize damage from oxidation, as a removal from released water and as prevention of acidic degradation product [4]. Pressboard is made from a combination of kraft wood and cotton pulp. Pressboard is used in places with a high electric field in transformers such as between the conductor windings where it functions as a mechanical support in the insulation system [33].

2.5 Polarization Index

The polarization index (PI) is perfomed to measure the condition of insulation such as kraft paper and insulating oil. The level of insulation degredation is measured to identify the condition of the insulation material whether it needs to be changed or can still can be used. Degredation of insulation and sludge content high in insulation will cause PI to decrease [37]. PI is a ratio insulation resistance for 10 mins to 1 mins as shown in Equation 2.1. Synthetic oil with biodegradable substance has a PI comparable or better than petroleum-based oil [38].

$$PI = \frac{IR_{10mins}}{IR_{1mins}} \tag{2.1}$$

2.6 Physical Test: Tensile Strength Test, and Shore Hardness

There are several type of physical tests for power transformers. However, the focus of this research is in conjunction to tensile strength and shore hardness tests.

2.6.1 Tensile Strength Test

According to ASTM - D828, the condition of the paper specimen tested should be as specified in ISO 187 because the tensile strength test is very sensitive to changes that occur in the test piece such as moisture content. Paper width is 25.4$\pm$ 0.5 mm and length 254$\pm$1 mm. The tested paper is kept away from water and put in vacuum place. The kraft paper chosen for the tensile test must be in good condition, free from folds, holes, wrinkles, and others that can affect the tensile strength value. Tests are conducted under atmospheric conditions. The test is performed until the test piece breaks. The maximum tensile force applied is recorded. All readings for test pieces that break within 10 mm of the clamp line will be rejected.

2.6.2 Shore Hardness

Shore hardness test is conducted according to ASTM D2240-15 (2016) standard test method, where the measurement will be done as many as five determinations at different positions on the gasket. The reading will be done at room temperature which is 23±2 ^{0}C in order to get an accurate reading. If the durometer is equipped with an electronic indicator, the reading should be recorded at 1±0.3 s. If the durometer is equipped with an analog type indicator, the reading must be recorded immediately while for the durometer that is not equipped with the device, the reading must be made within 1 s.

2.7 Dissolved Decay Product

Dissolved Decay Product (DDP) usually uses the ASTM D6802 standard where this method uses UV-Vis Spectrophotometry to measure the level of dissolved decay product dissolved in insulating oil. When insulating oil is aged, insulation paper will absorb decay products that attack cellulose and cause decomposition that contributes to the increase of dissolved decay products in insulating oil [39].

Although insulating liquid works as a good coolant and has good dielectric properties, it is easily contaminated when the transformer is operating [40]. This is caused by the oil through a chemical reaction that produces gas and sludge. The resulting sludge will cause the function of insulating oil as heat transfer to decrease. The resulting decay product that is not soluble in insulating oil is likely to seep into the insulating paper, causing deterioration of the insulating paper. Small dissolved decay particles will usually be absorbed in insulating oil. DDP has contribute a lot to the failure of transformers [41].

Ester oil is able to reduces the amount of sludge as compared to MO. MO tends to form sludge when oxidized where it can increase DDP that can make the color of the oil becomes cloudy [42]. The increasing in oil turbidity indicates that the increasing in DDP will reduce dielectric strength and thermal performance. Ester oil will polymerize when oxidized and does not tend to form sludge. Therefore, ester oil has a low DDP compared to MO as shown in Figure 2–6.

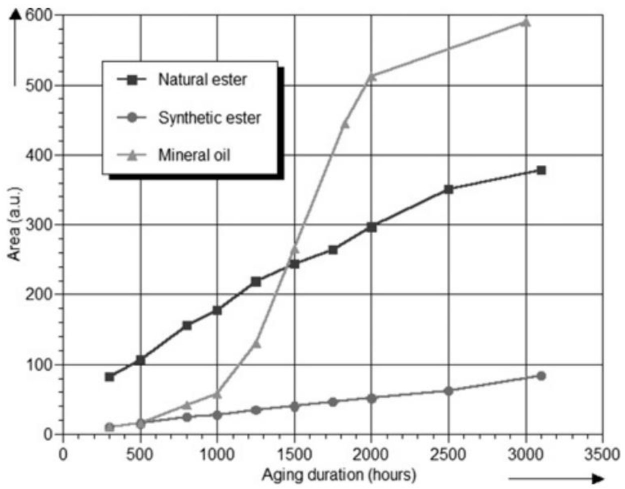

Figure 2–6: DDP of mineral and ester oil.

2.8 Summary

This chapter has discussed previous studies on retrofilling and the tests that have been carried out. The retrofilling transformers have been explained in Section 2.2. In addition, Section 2.3 and Section 2.4 explain with regards to insulating oil and material properties, respectively. Section 2.5 detailed out the theory PI, while the last section, which is section 2.6 was explained the theory on DDP.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will briefly describe the methodology used in this research. Initially, the overview of the experiment will be explained in Section 3.2. Section 3.3 will briefly describe the preparation for insulating oil that will be used in this research. Section 3.4 and Section 3.5 explain the detail of sample's pre-processing process. Thermally aging process will be discussed in Section 3.6. Section 3.7 and Section 3.8 will briefly describe the physical test and electrical test of the insulation materials, respectively. Lastly, Section 3.9 will be explaining the procedure for the chemical test.

3.2 Overview of the Experiment

Figure 3–1 shows the process flow for this research study. The process starts with the oil samples preparation including the process of oil filtration, oil nitrogen treatment and preparation of sizing materials (i.e., kraft paper, pressboard, gasket, and metal catalyst). The aging tank will be cleaned using insulating oil at heated up to 60 - 65 °C before performing the aging process.

The research will be carried out at two different conditions as shown in Figure 3–2, namely, Condition 1 involves MO retrofill with MO, while condition 2 involves MO retrofill with SE. The MO used in this research study is Nynas Nytro Libra, while the synthetic ester used is Midel 7131. It shall be noted that the oil, kraft paper and gasket samples testing will be conducted as soon as the aging process is completed to minimize any unwanted contaminations.

The thermal aging process is carried out at 110 °C for 55 hours. This temperature is selected to meet the requirement of: (1) accelerated aging to shorten aging time (operating temperature of transformers: 65 °C) and (2) aging must be lower than the flash point of both oils (Nynas Nytro Libra: 140 °C and Midel 7131: 260 °C) as shown in Table 3–1.

Table 3–1: Properties of Nynas Nytro Libra and Midel 7131[7], [15].

Insulating Oil	Nynas Nytro Libra	Midel 7131
Melting point/freezing point (°C)	-51	-56
Initial boiling point (°C)	>250	>300
Flash point (°C)	>140	260
Flammability (solid, gas)	N/A	N/A
Vapor pressure (kPa)	<0.01	<1 at 20°C.
Solubility	Insoluble in water.	<1mg/l
Viscosity (cm^2/s) at 40 °C	0.096	0.29

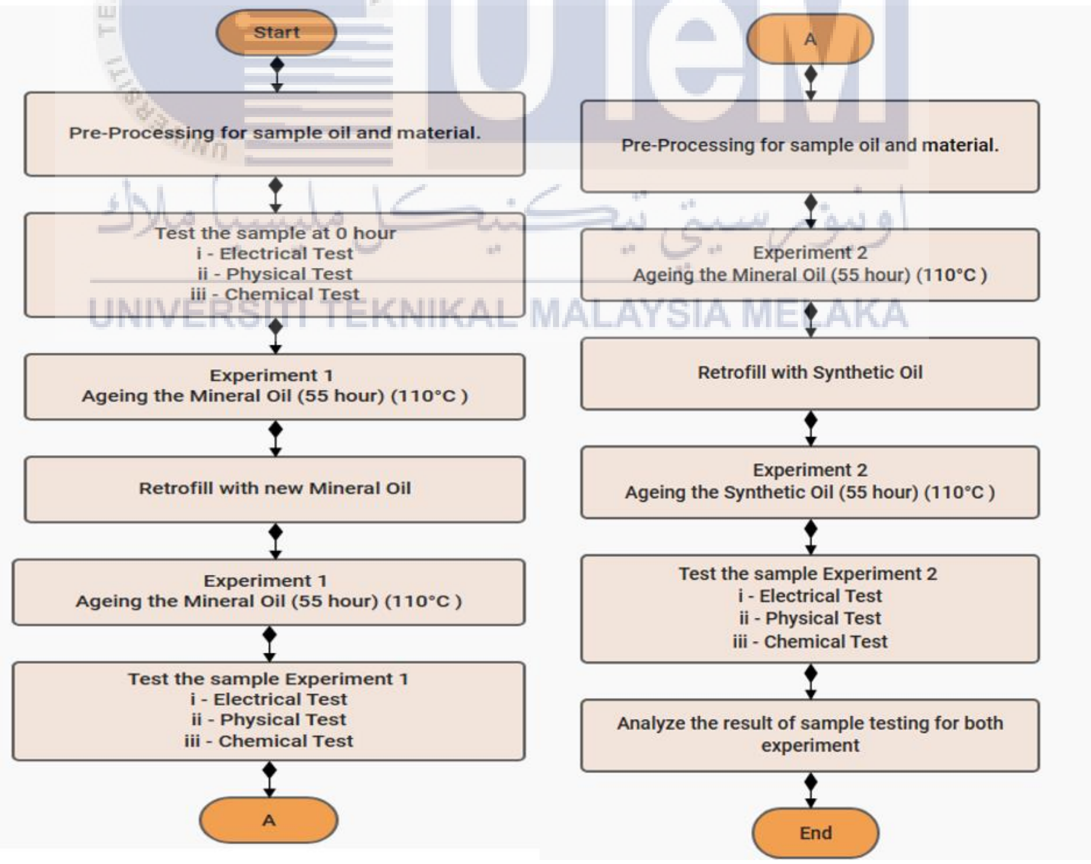

Figure 3–1: Process flow of this research study.

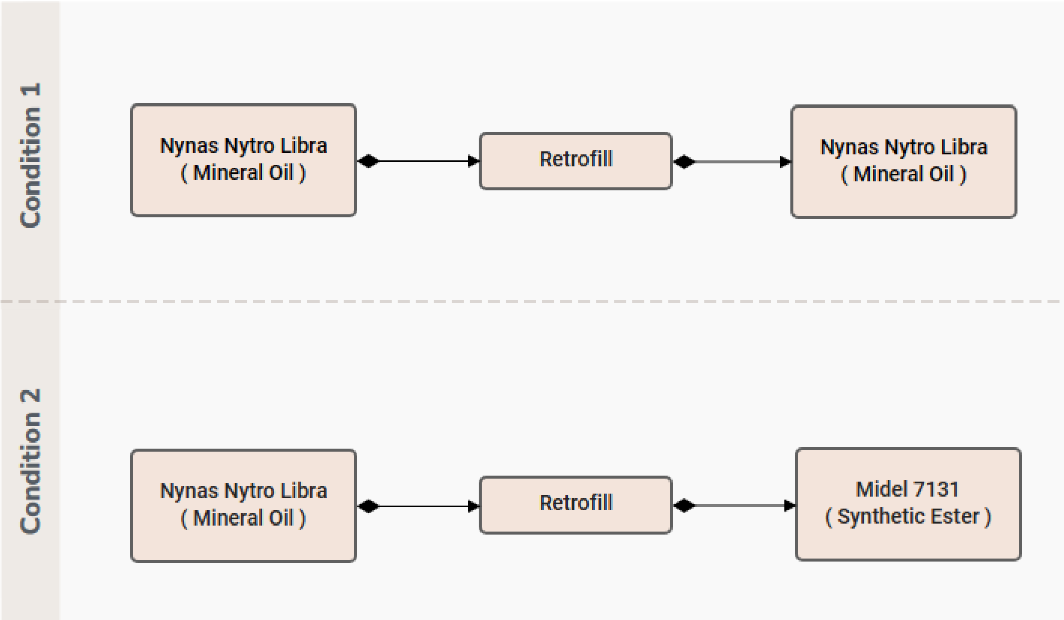

Figure 3–2: Retrofiling involving two conditions.

3.3 Sample Materials Size Determinations

Figure 3–3 shows the illustration for the thermal aging tank used in this research. The length of the dimension is measured by using a measuring tape where it is found that the inner diameter of the heater tank is 20.5 cm, while the height of the oil from the grille (where the material is placed) when 4 liters (L) of oil is added is 5.5 cm. Therefore, the size of materials used shall not be exceeding 5.5 cm in height. This measurement process is done by pouring water into the heater tank before the experiment is performed. The height of the oil from the grille in the heater tank will be increased by 3 cm for every 1 L (i.e., 4 L of oil is 5.5 cm, 4 L of oil is 8.5 cm, and 5 L of oil is 11.5 cm) as shown in Table 3–2. After this measurement is completed, the heater and retrofilling tank will be cleaned and left to dry. Then, the heater and retrofilling tank will be rinsed with the insulating oil.

Table 3–2: Level of oil from iron grille

Volume of oil (L)	Level of oil from iron grille (cm)
4	5.5
5	8.5
6	11.5
7	14.5

Several research studies used the same materials as in this project. The reference for material preparation follows the standards used by them, as shown in Table 3–3. The weight of each material in these references will be considered because of the results they have obtained, the detailed information, and the availability of materials for the preparation to facilitate the execution of this experiment in order to achieve the research objectives.

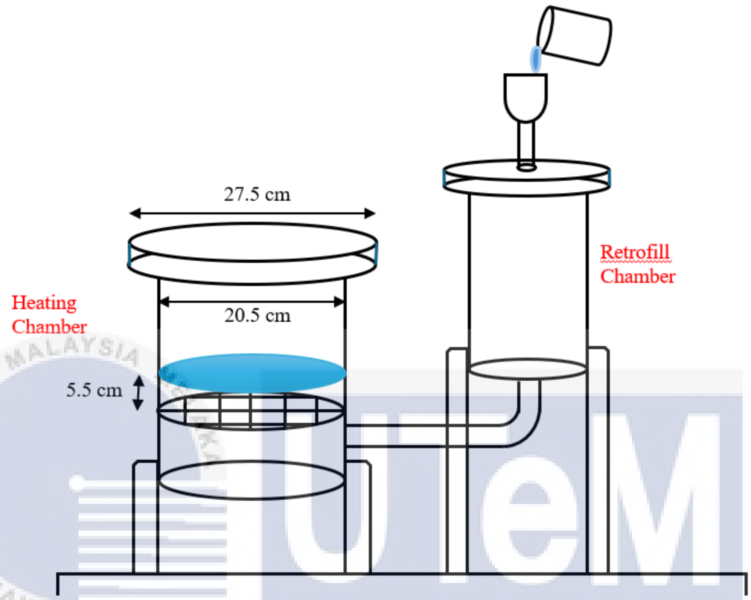

Figure 3–3: Illustration for the aging tank.

Table 3–3: Sizing material set-up.

Reference	Tenbohlen and Koch, 2010	Akmal, 2006	Nur Lidiya, 2020	Used in this research study
Oil volume (L)	1	1	1	4
Weight of kraft paper (g)	100	-	20	20
Weight of pressboard (g)	100	80	80	80
Weight of metal catalyst (g) - Copper, Cu - Iron, Fe - Zink, Zn - Aluminium, Al	 2.5 2.5 0.5 0.5	 2.5 2.5 0.5 0.5	 2.5 2.5 0.5 0.5	 10 10 2 2

Table 3–4: Calculation for sample material.

Sample	Reference	This research	Total amount used in this research
Oil volume (L)	0.4	4	MO: 12 SE: 4
Kraft Paper [43]	20g for 1000ml	$= \frac{4000\text{ml}}{1000\text{ml}} \times 20\text{g}$ $= 80\text{g}$ Size: 30cm × 2cm	160g
Gasket (NBR) [44]	65 cm^2 for 800ml	$= \frac{4000\text{ml}}{800\text{ml}}$ $\times 65cm^2$ $= 325cm^2$ Size: 25cm × 13cm To: 13cm × 5cm	650 cm^2
Pressboard [43]	80g for 1000ml	$= \frac{4000\text{ml}}{1000\text{ml}} \times 80\text{g}$ $= 320\text{g}$ Size: 18cm × 5cm	640g
Metal Catalyst [43]	Cu: 2.5g for 1000ml Fe: 2.5g for 1000ml Zn: 0.5g for 1000ml Al: 0.5g for 1000ml	Cu: 4 × 2.5g = 10g Fe: 4 × 2.5g = 10g Zn: 4 × 0.5g = 2g Al: 4 × 0.5g = 2g	Cu: 10g Fe: 10g Zn: 4g Al: 4g

3.4 Pre-Processing of Insulating Oil

The oil samples will be filtered (Figure 3–4) to remove all contaminations presence in the oils. The oil samples will be filtered using membrane filter paper with size of pore 0.22 µm. The oil samples being filtered will be covered with aluminum foil to prevent dust from entering into the oil samples during the filtering process. The MO filtering process takes ∼ 30 mins for every 300 ml, while Midel 7131 takes ∼ 120 mins for every 300 ml due to the variety in the viscosity of both oil samples.

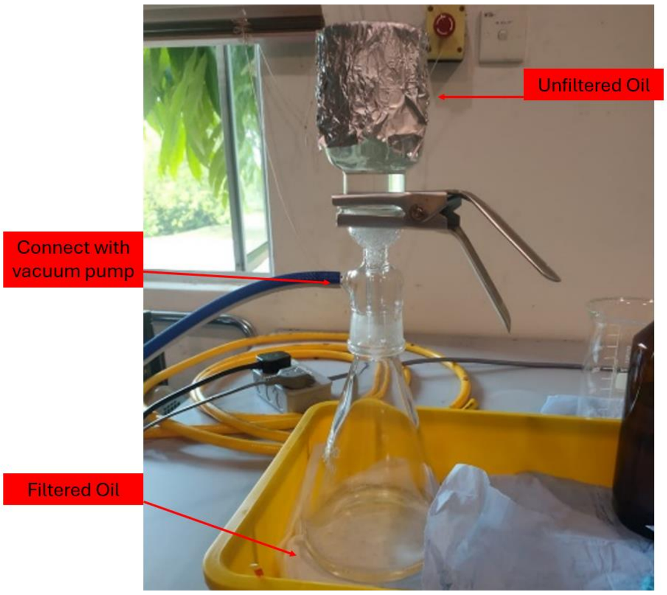

Figure 3–4: Process of filtering samples oil.

Once the oil samples have been filtered, it is crucial to carried out the oil nitrogen saturation process (Figure 3–5) to prevent the formation of gas, water, or compounds that can reduce the dielectric of insulating oil. Karl Fischer Titration will be used to measure the level of moisture content in insulating oil to ensure that the moisture content is at a low level based on the standard (< 30 ppm: MO and < 200 ppm :SE). MO will be tretaed using nitrogen saturation process for ~10 mins [44] for every 250 mL and synthetic oil takes ~ 30 mins.

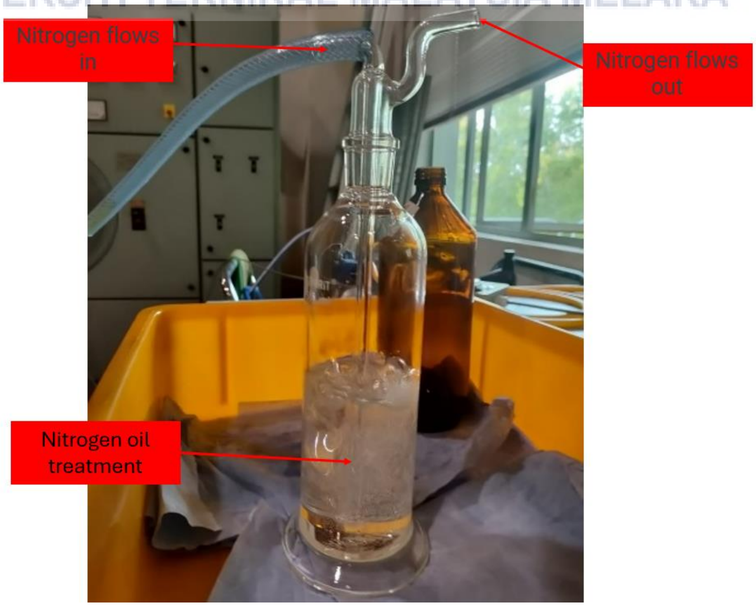

Figure 3–5: Nitrogen saturation process for oil sample.

3.5 Pre-Processing of Solid Samples

The pre-processing for solid samples will undergo a few steps before the aging process started.

Step 1: Drying process according to the thickness of kraft paper and pressboard.

Each sample thickness will be measured for the purpose of determining the time required for the drying process, as shown in Table 3–5. The thickness of kraft paper and pressboard will be measured using an electronic digital caliper.

Table 3–5: Duration for material drying [43].

Thickness,T (mm)	$\ll 0.5$	$0.5 < T \ll 1.5$	$1.5 < T \ll 5$	> 5
Duration, t (h)	12	24	48	72

Kraft paper and pressboard that have been weighed will be placed in the oven for the drying process, as shown in Figure 3–6. Each kraft paper and pressboard will be dried for 12 hours and 24 hours, respectively in the vacuum oven, based on Figure 3–5. These samples will be then heated at 105°C accoding to the BS EN 60641 (2004) standard test method.

Figure 3–6: Material drying process in vacuum oven.

After the drying process is completed, kraft paper and pressboard (which have been weighed) will be placed inside a vacuum bag or desiccator to prevent them from being exposed to an environment where moisture can be absorbed into the kraft paper and pressboard. Ideally, during the measurement of the weight of the kraft paper and pressboard, the ambient temperature should be at room temperature to ensure that water content and humidity in the environment are absorbed into the kraft paper and pressboard in significant amounts. The weighing apparatus will be sealed during the weighing process to obtain accurate readings, as shown in Figure 3–7.

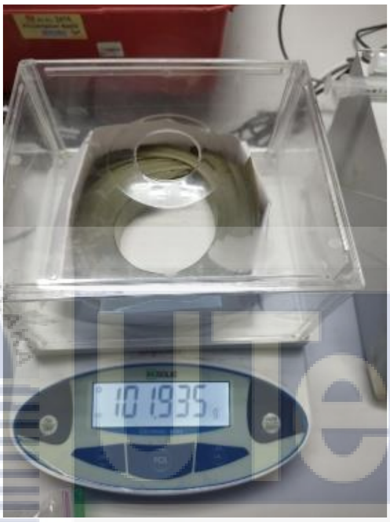

Figure 3–7: Measure the weight of kraft paper.

Step 2: Sizing determination for Nitrile Butadiene Rubber (NBR) Gasket.

According to the ASTM D3455 2002, gasket materials shall be tested at a ratio of 65 cm^2 surface area per 800 mL of oil. The gasket is made of Nitrile Butadiene Rubber (NBR) with an area of 325 cm^2 or 25 cm x 13 cm based on 4000 mL of oil. The gasket will be cut into five pieces, each measuring 13 cm x 5 cm, due to the limited space in the aging tank, which has a diameter of 20.5 cm and an oil level height of 5.5 cm (starting from the iron grill or the place where the material will be placed) as shown in Figure 3–8. The hardness of the gasket will be measured by using shore hardness tester (durometer) for before and after aging as shown in Figure 3–9. The durometer has three buttons which are hold, on/off and zero (reset the reading to zero).

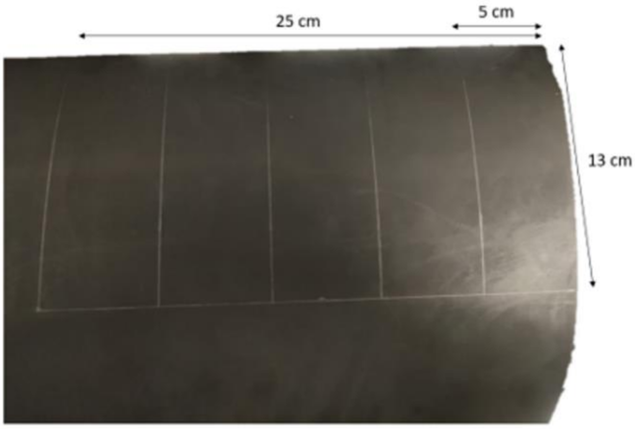

Figure 3–8: Sizing for gasket nbr.

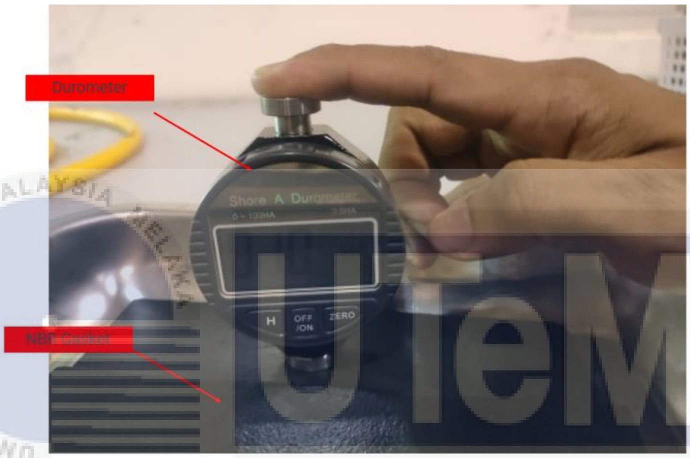

Figure 3–9: Shore hardness measurement.

Step 3: Sizing determination for kraft paper.

The width of the kraft paper used follows the original width, which is 2 cm. The kraft paper is cut into a length of 30 cm (Figure 3–10) to ensure that the tensile strength machine can grip the kraft paper properly because the length of kraft paper that state in standard BS 4415 and ASTM-D828 is 250 mm ± 1 mm. The size of the kraft paper used is 30 cm x 2 cm x 0.075 cm. The length of the kraft paper must exceed 250 mm. This paper will be cut so that it reaches a weight of 80 g after the drying process, as shown in Table 3–3.

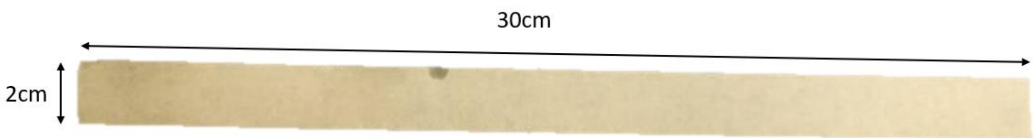

Figure 3–10: Size of kraft paper.

Step 4: Sizing for pressboard.

Based on Table 3–3, the weight of pressboard is 80 g for 1000 mL volume of oil sample.The weight of the pressboard to be used is 320 g for oil sample volume of 4000 mL. The width and length of the cut pressboard should be less than 5.5 cm and 20.5 cm, respectively because of the sample oil's level and diameter of heating tank. Therefore, the length of the pressboard to be used is 5 cm x 18 cm as shown in Figure 3–11.

Figure 3–11: Sizing for pressboard.

Step 5: Preparation for metal catalyst.

Each type of metal catalyst will be weighed according to the quantities indicated in Table 3–4. The weight of iron (Fe) and copper (Cu) is 10 g each, while the weight of zinc (Zn) and aluminum (Al) is 2 g each, based on previous research as shown in Table 3–3. All four metal catalysts will be placed on filter paper with diameter 12 cm before wrapping to prevent them from spilling during immersion and the thermal aging process as show in Figure 3–12. The metal catalyst will be placed on five filter papers because the total weight of the metal catalyst is 24 g, making the filter paper unable to be wrap well where there is metal catalyst that can comes out. Each filter paper will have a weight of 2 g (Fe and Cu) while the weight of Zn and Al is 0.4 g each. Total weight of the metal catalyst for each filter paper is 4.8 g.

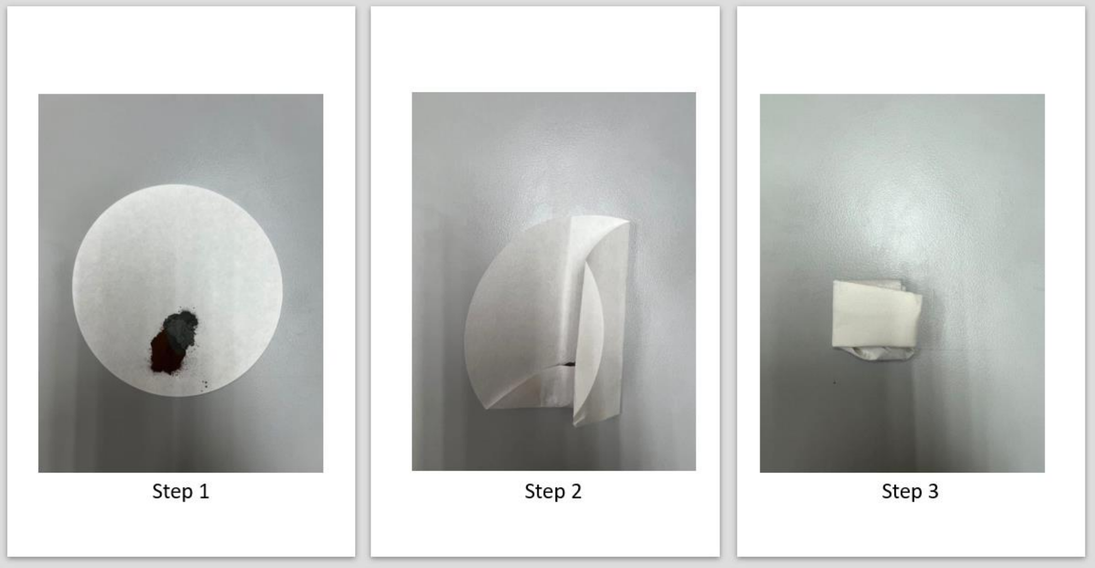

Figure 3–12: Steps to wrap a metal catalyst.

3.6 Thermal Aging Process

Figure 3–13 shows the thermal aging tank which consist of two tanks (heating and retrofilling) and one control panel. The aging process took place when the heating tank is filled up with the insulating oil and solid insulations as shown in Figure 3–14. The desired aging temperate will be controlled using the control panel. Meanwhile, the retrofilling process is carried out through the retrofilling tank. It is worth noting that the retrofilling tank should be closed every time after it is used to prevent any contamination from entering into it.

The detail procedure of using the aging tank is as follow:

Step 1: Insert 4-L of insulating oil into the heating tank through the retrofilling tank to ensure that the oil level is higher than the thermostat level.
Step 2: Set the initial temperature to 30 ºC.
Step 3: Once the tank reached this temperature, incrementally increase the aging temperature by 2 °C each time until it reaches the desired aging temperature.
Step 4: Turn off the heater if the process is over.

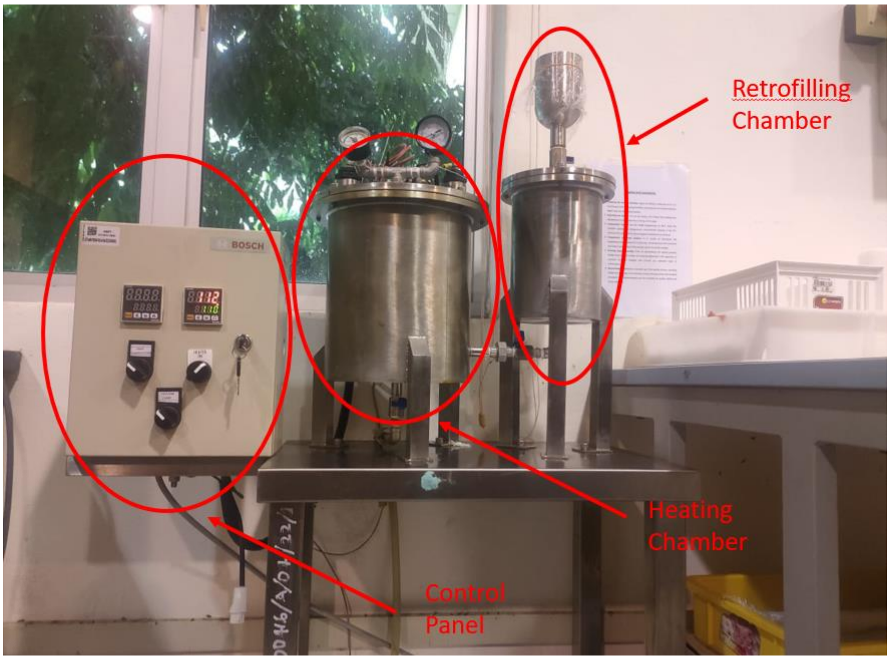

Figure 3–13 : Thermal aging tank.

Figure 3–14: The arragement of the solid insulations and gasket in the aging tank.

3.7 Physical Test Procedure

The physical properties of solid insulations will be performed by comparing the weight of kraft paper and pressboard (before and after drying), measurement of the gasket hardness, and investigation of the tensile strength of kraft paper insulation.

3.7.1 Weighing Process of Solid Insulations

The weight of solid insulations (i.e., kraft paper and pressboard) will be recorded before and after the drying process to ensure that they are compeletely dried. The solid insulations are considered dried when there are no changes in their weight. The weighting measurements carried out at room temperature to ensure that the ambient air is not affect the water content in the solid insulations. The measurements are carried out according to the following steps:

Step 1: Turn on the scale and make sure that the reading value is zero.

Step 2: Place the kraft paper on the scale.

Step 3: Properly cover the scale (as shown in Figure 3–15) with its cover to avoid any external interference that can affect the readings values.

Step 4: Record the weight of the kraft paper.

Step 5: Repeat steps 1 to 4 by changing the kraft paper to pressboard.

Figure 3–15: Measuring the weight of kraft paper.

3.7.2 Hardness of Gasket

The shore hardness of NBR gasket will be measured using a durometer as shown in Figure 3–16. The gasket before and after aging will be measured to make a comparison. The hardness measurement is carried out according to the following steps:

Step 1: Make sure the surface of the gasket is clean and wipe the surface of the gasket until it is completely dried (gaskets after aging).

Step 2: After the durometer is turned on, press the zero button to confirm that the shore value hardness before the measurement is zero.

Step 3: Place the durometer on the gasket and press to it.

Step 4: Record the value for shore hardness (, press the H" button to hold the reading.

Step 5: Repeat steps 3 and step 4 for 5 times at different position of gasket. Calculate the average value.

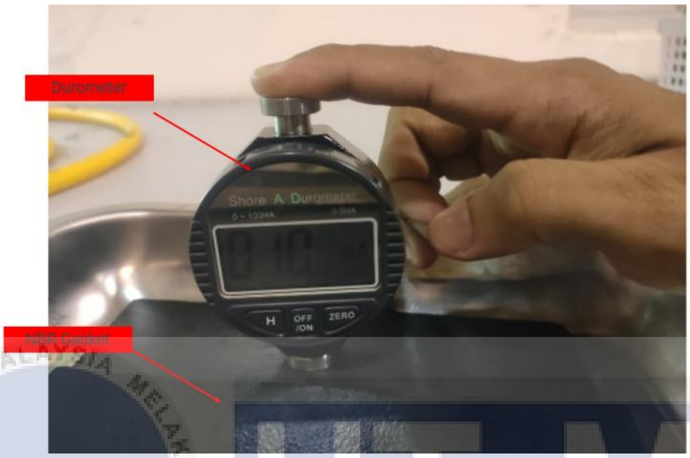

Figure 3–16: Measure shore hardness using a durometer.

3.7.3 Tensile Strength Test

According to standard BS 4415 and ASTM-D828, standard test method , the measurement of tensile strength for kraft paper need to carried out 10 times to get their average value. It is crucial to clean the aged kraft paper with acetone before the measurement is carried out. The tensile strength measurement is carried out according to the following steps:

Step 1: Turned on the tensile machine. Make sure that the software in the computer opened.

Step 2: Set the distance between upper and lower clamper to 250 mm before placing the kraft paper on the clamper.

Step 3: Make sure that kraft paper is clamped correctly (i.e., the angle of the kraft paper and the upper surface of the clamper is 90±1^{o} to get the true value of tensile strength).

Step 4: Make sure that the readings of tensile strength and the elongation zero (in the software) before the measurement is done.

Step 5: Record the reading of tensile strength (Mpa) and elongation (%) for kraft paper.

Step 6: Repeat step 2 to step 5 for 10 times to get the average reading.

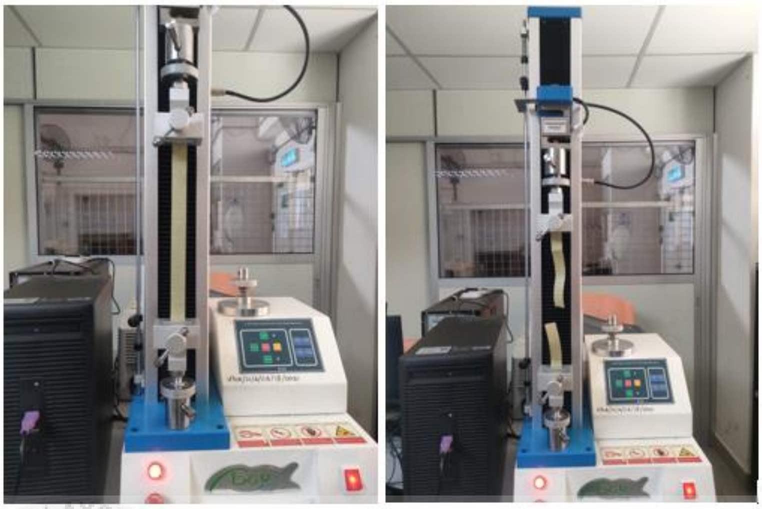

Figure 3–17: Tensile Test Machine.

3.8 Electrical Test Procedure (Polarization Index)

ASTM D1816, Standard test method which is the standard used for voltage breakdown is used to conduct the polarization index test because the polarization index for insulating oil does not have a set standard. Mushroom shaped electrode with 1 mm gap is used. Voltage 500 V was chosen for this test. The polarization index measurement is carried out according to the following steps:

Step 1: Insert 500 ml of insulating oil into the chamber until it submerges the electrode as shown in Figure 3–18.

Step 2: Connect the live and neutral cable to the electrode and tester.

Step 3: Turn on the polarization index tester.

Step 4: Set mode to PI and up the voltage to desired level.

Step 5: Push the test button until the red light is turn on.

Step 6: Record the reasing after 10 mins.

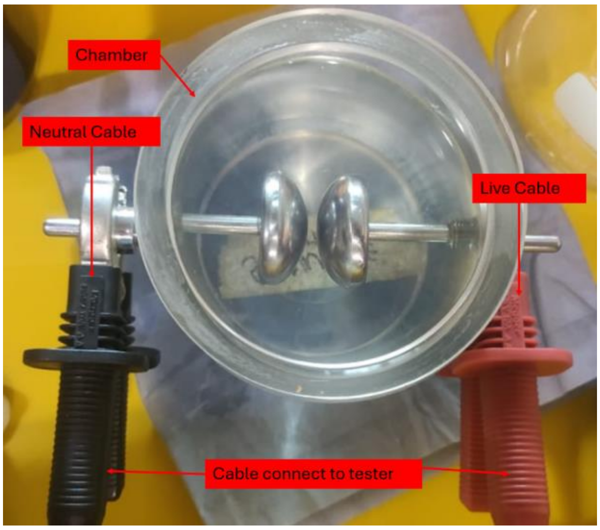

Figure 3–18: Chamber for polarization index testing.

3.9 Chemical Test Procedure (Dissolved Decay Product (DDP))

According to ASTM D6802 (2010) standard test method, the wavelength need to be set from 360 to 600 nm. The procedure is carried out at room temperature (25 ± 5 ºC). Firstly, the cuvette is washed and dried for 30 mins at 110 ºC to ensure that the cuvette is cleaned from any contamination. It is crucial to ensure that the bright side of the cuvette is cleaned to ensure that the UV rays are not obstructed by any contamination during the emission of UV rays to the samples. The oil samples will be poured into the cuvette until it reaches the 40 mm (Figure 3–19) to ensure that all of the emitted UV rays hit the oil samples.

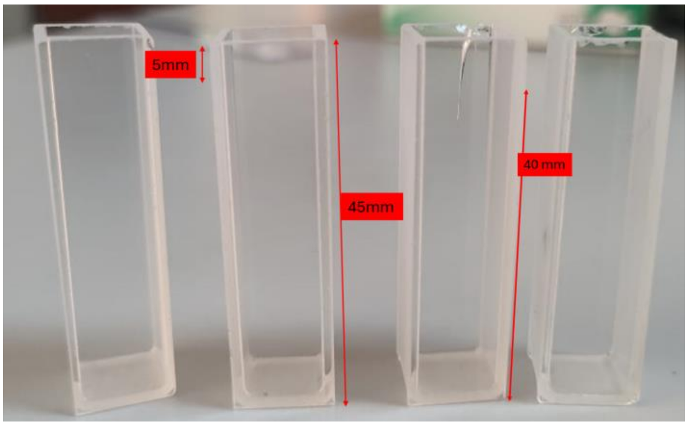

Figure 3–19: Measurement of cuvette height.

The measurement of DPP is carried out using Ultraviolet–visible spectroscopy shown in Figure 3–20 according to the following steps:

Step 1: Turn on the software and UV-Vis spectroscopy. Wait until the UV-Vis spectroscopy is ready before performing the measurement.

Step 2: Press "Enter" and "PC Control" to control UV-Vis spectroscopy using the software.

Step 3: Press the “Connect” button in the software to connect the software with UV-Vis spectroscopy.

Step 4: The cuvette containing the insulating oil before aging will be placed in the cuvette reference and sample place.

Step 5: Close the cover and press auto zero until the absorbance and wavelength values become zero.

Step 6: Set wavelength to 360-600 nm.

Step 7: Baseline will be pressed as the baseline for this oil specimen to be recorded.

Step 8: The cuvette containing the aging insulating oil will be placed in the cuvette sample place and press start to obtain a graph of absorbance, a.u versus wavelength, nm.

Step 9: Save the obtained graph in the form of a point pick table.

Step 10: Repeat step 8 and Step 9 using insulating oil (after retrofilling).

Figure 3–20: Ultraviolet–visible spectroscopy

According to ASTM D6802 (2010) standard test method, the area under the graph of the absorbance curve for the wavelength from 360 to 600 nm is the value of the (DDP) which can be calculated using the integration formula. Microsoft origin will be used to obtain the accurate values of DDP. The reading for DPP can be calculated according to the following steps:

Step 1: Insert the saved data (A(X) for wavelength, nm and B(Y) for absorbance (a.u) as shown in Figure 3–21.

Step 2: Go to plot and select line.

Step 3: Go to analysis and select mathematics then select integration.

Step 4: Record the obtained value of Dissolved Decay Product (DDP).

Step 5: Repeat Step 1 until Step 4 with another data to make a comparison.

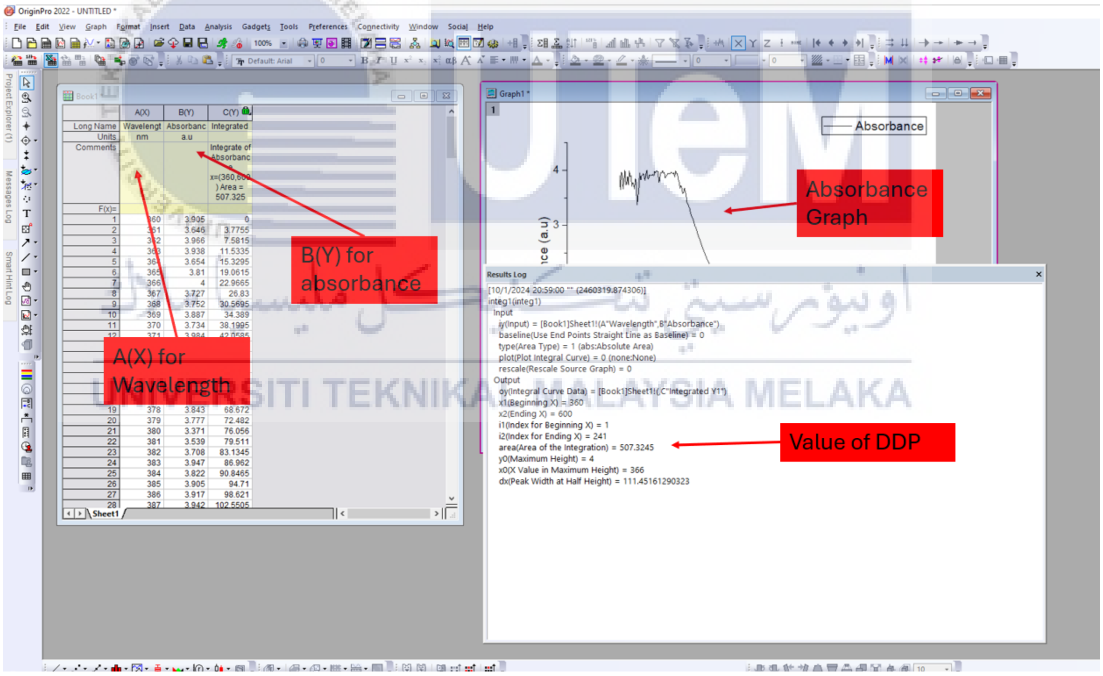

Figure 3–21: Microsoft Origin.

3.10 Summary

This chapter discussed the methodology used in this research. Firstly, an overview of the experiment was explained in Section 3.2. The sample materials size determination was briefly described in Section 3.3. Meanwhile pre-processing for insulating oil and solid samples were elaborated in Section 3.4 and Section 3.5, respectively. Section 3.5

explained the details of thermal aging process. Finally, the physical, electrical, and chemical tests were detailed out in Section 3.7 to Section 3.9.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will briefly describe the results of this research. Initially, the results of the physical test will be explained in Section 4.2. Section 4.3 will briefly describe the results of the electrical test. Lastly, Section 4.4 explains the detail results of the chemical test of this research.

4.2 Results of Physical Test

Section 4.2.1 presents the obtained weight of kraft paper and pressboard (before and after dried in vacuum oven) for both conditions (i.e., Condition 1: MO retrofilled with MO and Condition 2: MO retrofilled with SE. Section 4.2.2 revealed the results of tensile strength for kraft paper before aging and after retrofilled. Section 4.2.3 describes the results of hardness test of NBR gasket. Lastly, Section 4.2.4 detailed out the visual conditions of the pressboard.

4.2.1 Results of Weight Test

Figure 4–1 shows the weight of kraft paper and pressboard before and after drying for both conditions. For Condition 1, the weight of kraft paper decreased by 6.15 % from 100.74 g to 94.91 g while the weight of pressboard decreased by 8.85 % from 396.53 g to 364.27 g. The significant decrement in the weight of kraft paper and pressboard revealed that initially, there was a presence of water in both insulations.

On the other hand, for condition 2, the weight of kraft paper is dropped by 7.8 % from 100.53 g to 93.25 g while the weight of pressboard is dropped by 8.52 % (Figure 4–2). The difference percentage of the weight materials before and after drying was calculated by using formula:

$$\textbf{Difference Percentage}, \% = \frac{M_{before} - M_{after}}{M_{after}} \times 100\% \qquad (4.1)$$

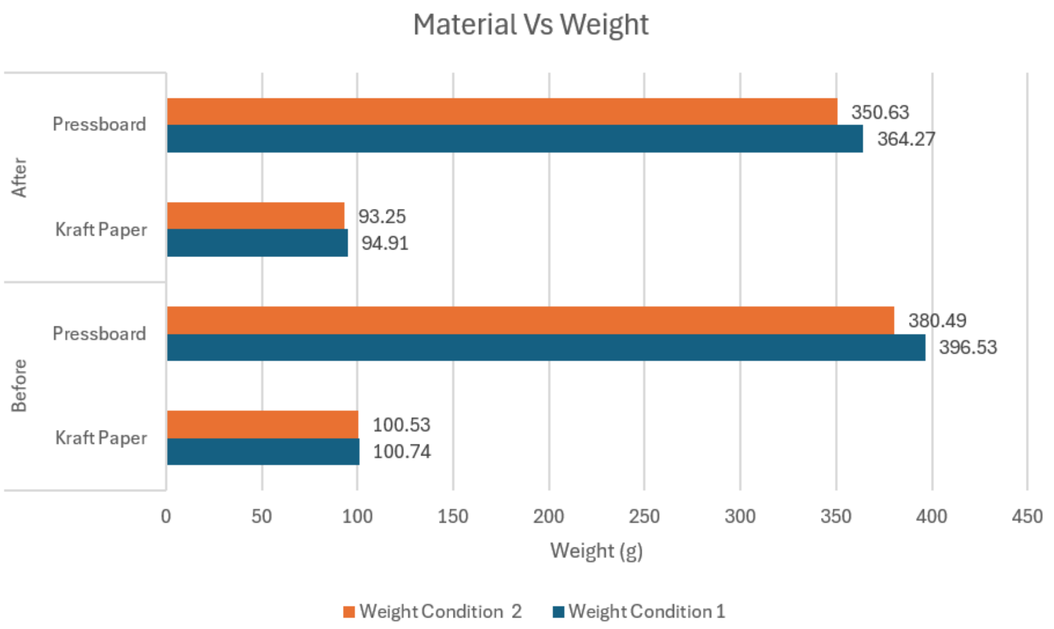

Figure 4–1: Graph for weight of kraft paper and pressboard before and after drying.

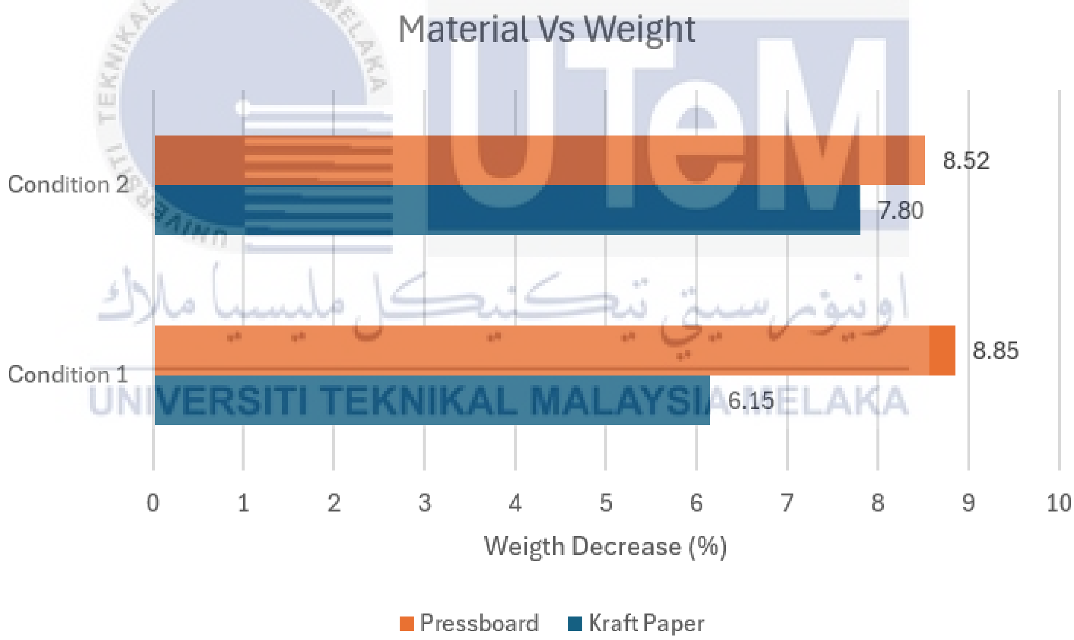

Figure 4–2: Weight decrease after drying in percentage for kraft paper and pressboard.

4.2.2 Results of Tensile Strength

Figure 4–3 shows the tensile strength of kraft paper for initial (before aging) and after retrofilled with MO. The value of tensile strength for kraft paper after retrofilled with MO (Condition 1) is reduced from 134.36 Mpa to 126.51 Mpa where the decrease is 7.85 Mpa or 5.84 %. In addition, the degredation of kraft paper also happen for after retrofilled with SE (Condition 2), where the tensile strength is dropped from 134.36 Mpa to 125.85 Mpa which is 8.51 Mpa or 6.34 %. There is only a slight difference between the tensile strength of kraft paper after retrofilled with MO and SE which is 0.66 Mpa or 0.5% as shown in Figure 4–4.

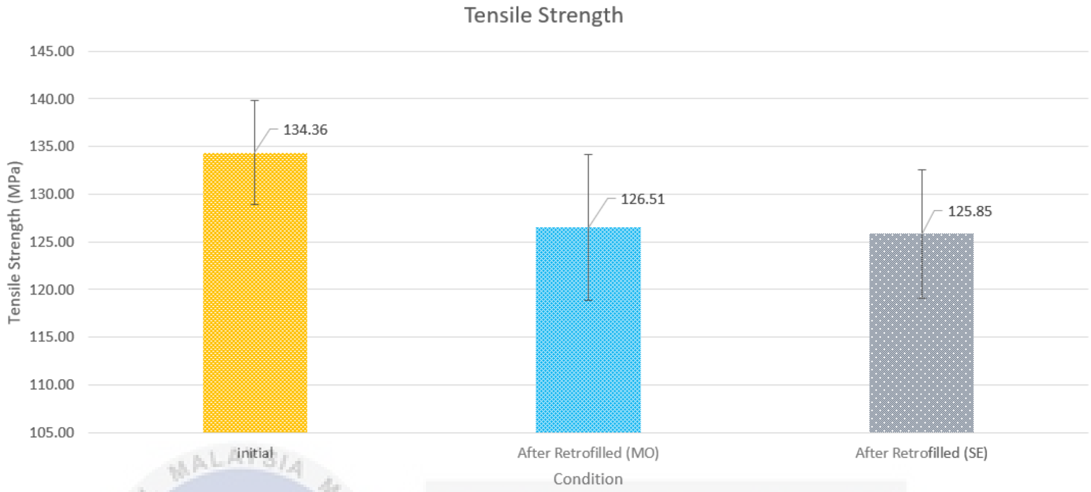

Figure 4–3: Tensile strength of kraft paper for initial and after retrofilled.

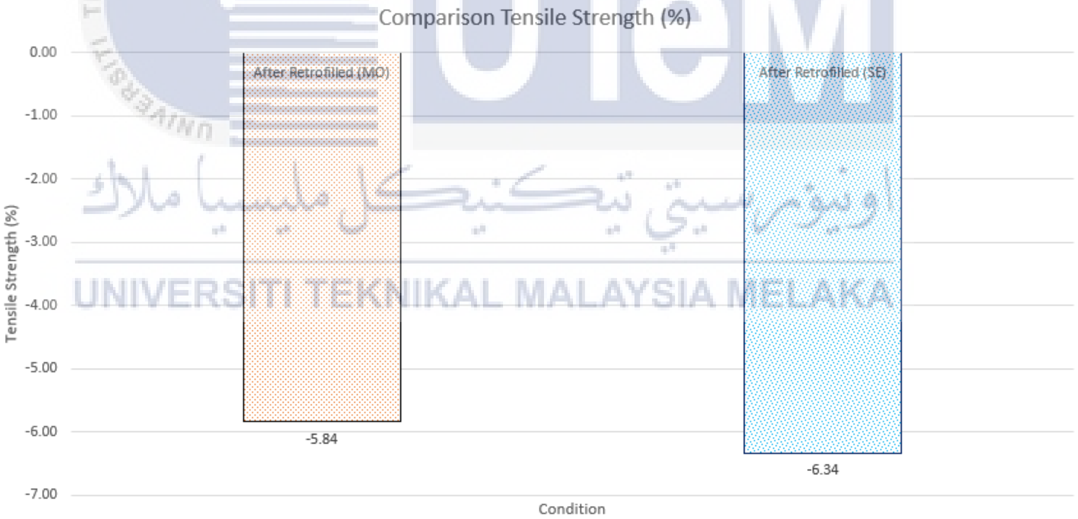

Figure 4–4: Comparison of tensile strength between initial and after retrofilled for both condition in percentage.

A decreasing trend can be clearly seen in the elongation values of the Kraft paper (as shown in Figure 4–5) after MO was retrofilled with MO and SE. The decreased in elongation after retrofilled with MO is higher than after retrofilled with SE. The decreased in elongation for insulating oil after retrofilled with MO is 44.4 % which is almost half of the initial value, while after retrofilled with SE is 25.92 % as shown in Figure 4–6.

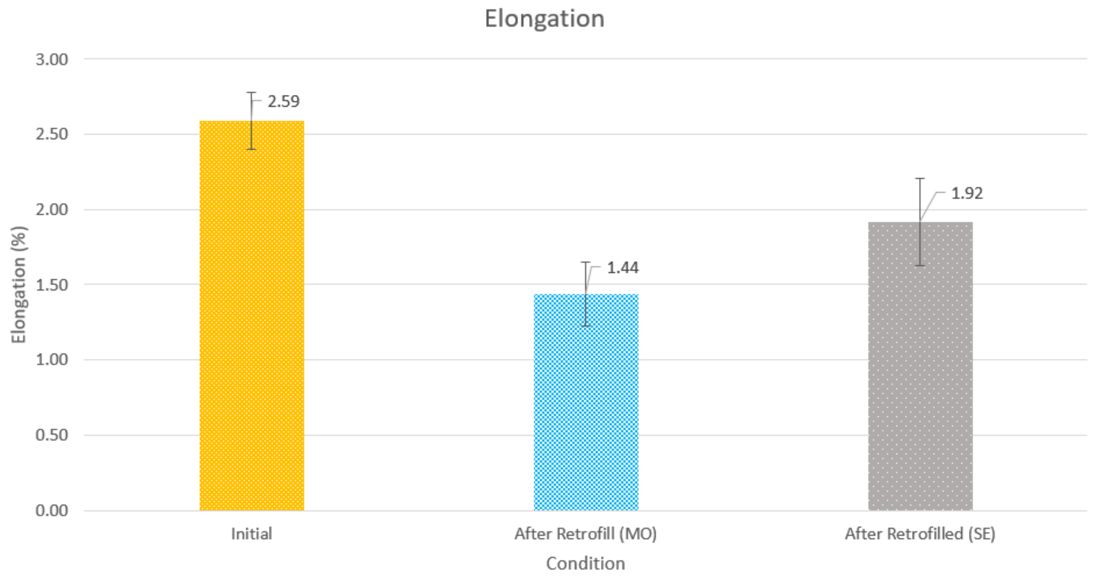

Figure 4–5: Elongation of kraft paper for initial and after retrofilled.

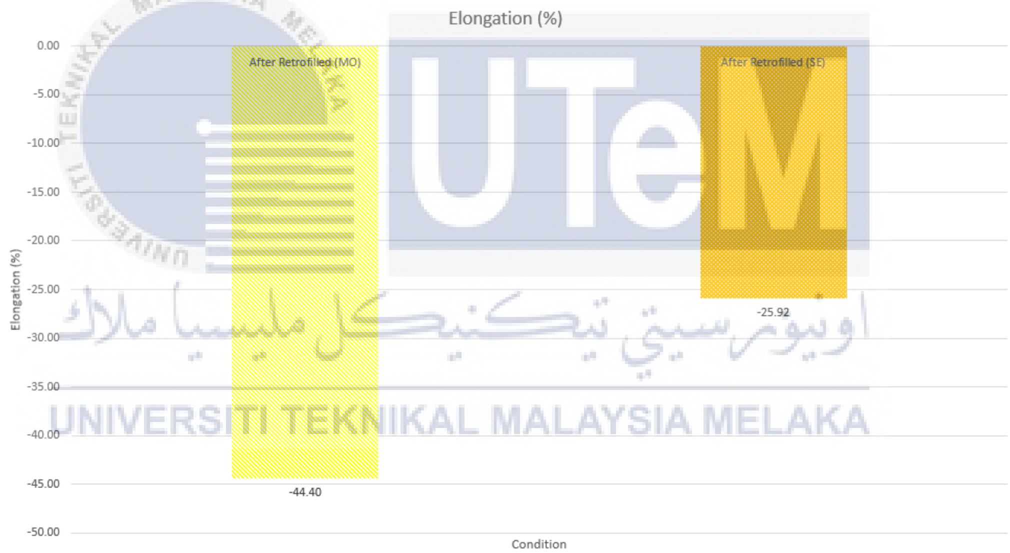

Figure 4–6: Comparison of elongation between initial and after retrofilled for both condition in percentage.

Figure 4–7 show the comparison for kraft paper between a) initial condition, b) after retrofilled with MO and c) after retrofilled with SE. The color of the kraft paper after retrofilling is slightly darker, and there are burn marks on the surface of the kraft paper. There is no significant difference in terms of color for kraft paper after retrofilled with MO and SE. The burn marks and the change in color indicate that the kraft paper has undergone degradation, where tensile strength and elongation have decreased compared to the kraft paper before aging. Furthermore, the presence of sluges on the surface of the kraft paper also indicated that sludges are also one of the degradation factor for kraft paper.

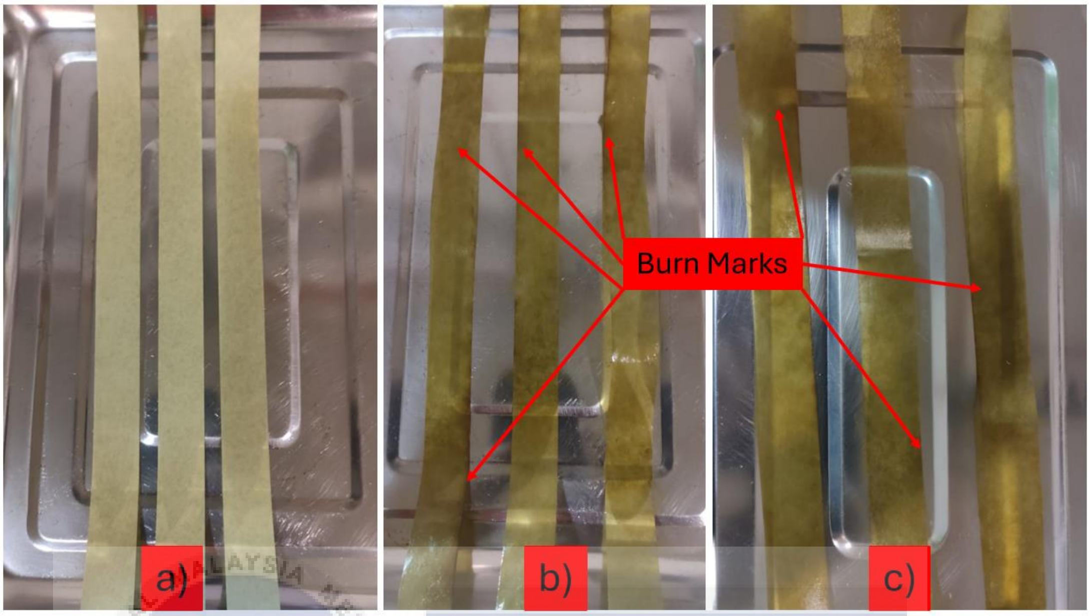

Figure 4–7: Comparison kraft paper a) initial condition,b) after retrofilled with MO and c) after retrofilled with SE.

4.2.3 Results of Shore Hardness Test

Figure 4–8 shows the shore hardness of the initial and after retrofilled for Condition 1 and Condition 2. The readings for shore hardness were taken five times to obtain the average readings to improve the measurements accuracy. For Condition 1, (MO retrofilled with MO), there is a dropped in shore hardness of the NBR gasket by 80.37 % (from 73 HA to 16.94 HA) while the shore hardness is deacresed by 72.98 % (from 73 HA to 19.72 HA) for condition 2 (MO retrofilled with SE) as shown in Figure 4–6. This decrease is due to the degradation of the NBR gasket during the aging process due to the reaction of the insulation oil with the gasket.

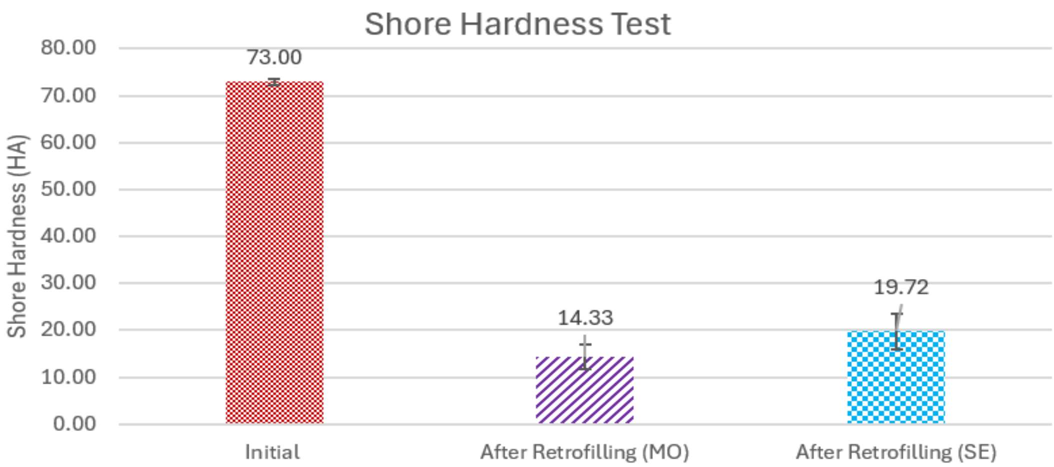

Figure 4–8: Shore hardness of the NBR gasket for a) initial, b) after retrofilled (MO) and c) after retrofilled (SE)

The percetage decreased of NBR gasket shore hardness after retrofilled with MO is bigger than after retrofilled with SE with difference of 7.39 % as shown in Figure 4–9. This proves that SE is able to reduce the degredation of NBR gaskets better than MO.

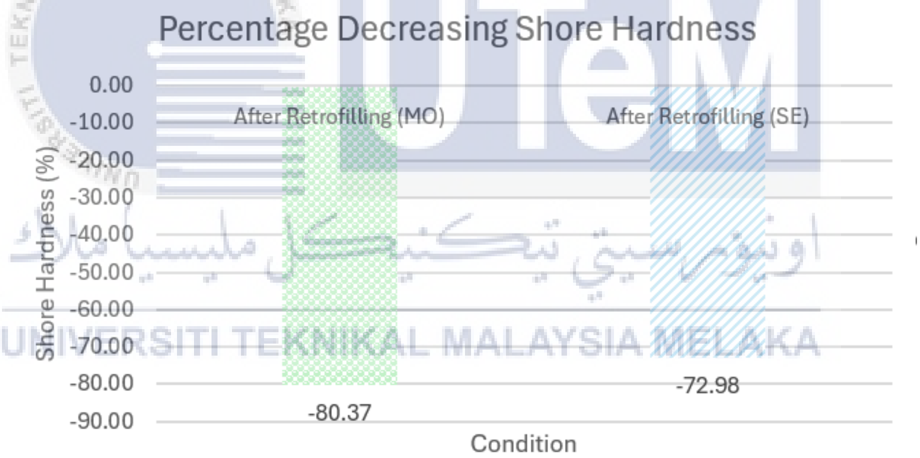

Figure 4–9: Percentage of decreasing shore hardness of the NBR gasket for after retrofilled with MO and SE.

Figure 4–10 shows the comparison of NBR gasket; a) initial (before aging) and b) after retrofilled with MO. The surface of the gasket before aging was smooth and firm. However, the sturcture of the gasket was significantly changed after the retroflling with MO was carried out. The condition of gasket after retrofilled with SE also significantly changed but the surface of the gasket is not as soft as after retrofilled with MO when the gasket is held.

In addition, there were a cracks pilled off spotted on the surface and edge of the gasket for condition 1 (MO retrofilled with MO) and condition 2 (MO retrofilled with SE). There is a difference in cracks occurring in both conditions where the cracks in condition 2 are thicker than condition 1 as shown in Figure 4–10. However, the surface of the gasket in condition 2 is harder than condition 1. The surface of the gasket that comes out has seeped into the insulating oil and is also a factor in the insulating oil becoming darker and dirty.

Figure 4–10: Comparison for condition of NBR gasket for a) initial and b) after retrofilled with MO and c) after retrofilled with SE.

4.2.4 Visual Observation of Pressboard.

Figure 4–11 shows the condition of pressboard (initial, after retrofilled with MO and after retrofilled with SE) observed visually. It can be clearly seen that the color of the pressboard changes from milky white to brown and has black deposits on the surface of the pressboard. There is no color difference for the pressboard after retrofilled with MO and SE and both has black deposits on the surface. The changes indicate that temperature plays a crucial role in degrading the condition of the pressboard. Sludge that generated from the aging process has been deposited on the surface of the pressboard and some of it has absorbed into the pressboard where it can reduces the properties of the pressboard.

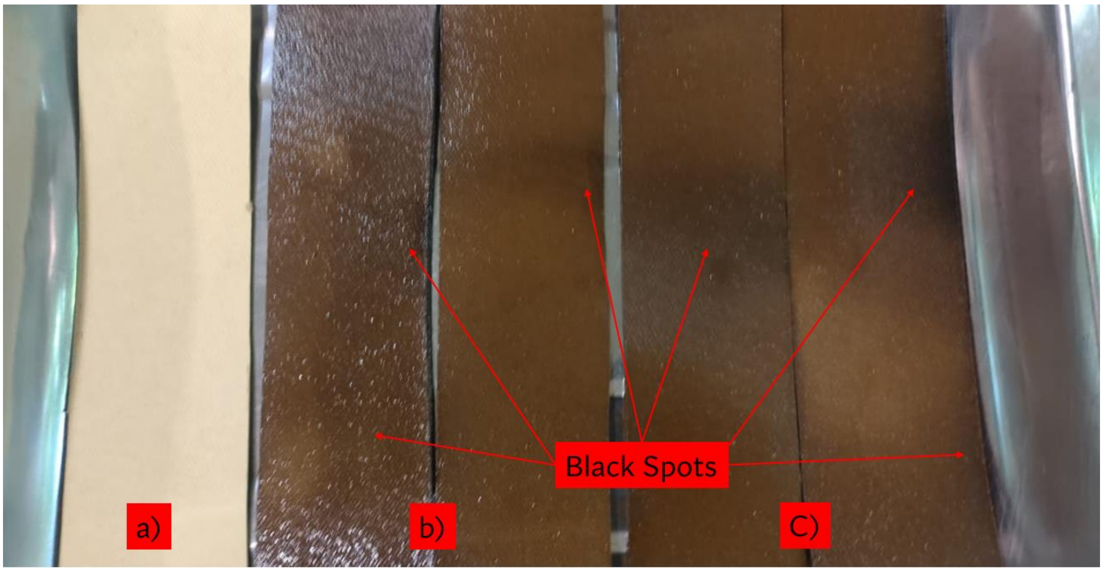

Figure 4–11: The color changes of the pressboard observed visually for a) initial, b) after retrofilled with MO and c) after retrofilled with SE.

4.3 Results of Electrical Test (Polarization Index)

Table 4–1 show the result of polarization index (PI) for condition 1 (MO retrofilled with MO) and condition 2 (MO retrofilled with SE). The PI value in the initial condition (before aging) is above 1.0. The PI value exceeds one because the PI tester cannot read insulation resistance values that exceed 1.5 TΩ. The PI of MO before retrofilled dropped to 0.9975 which indicated that the insulation resistance of MO decreases when going through the aging process. The value of PI after retrofilled with MO is larger than PI after retrofilled with SE by 2.1 %. The value of PI after retrofilled with MO and SE decreased by 0.5 % and 2.6 %, respectively compared to the value of PI before retrofilled.

Table 4–1: Result of polarization index.

Condition	Condition 1 (MO retrofilled with MO)	Condition 2 (MO retrofilled with SE)
Initial	>1.000	
Before	0.9975	
After	0.9925	0.9722

4.4 Results of Chemical Test (Results of Dissolved Decay Product(DPP))

Figure 4–12 shows the color of MO (Condition 1) for a) before aging process, b) after aging process and c) after retrofilled process. The color of MO before the aging process is bright white because MO is still in good condition without any contaminations. It can be clearly seen that the color of MO after the aging process become brownish. This is due to the presence of dissolved decay product due to the reaction between solid insulation (i.e, gasket, kraft paper, and pressboard) and insulating oil. Interestingly, the color of MO after retrofilled with MO is yellowish.

The color of insulating oil for condition 2 is shown in Figure 4–13, where the color of MO before retrofilled is darker than SE after retrofilled. This also shows that the condition of the oil after retrofilled MO oil with SE is better which can reduce the contamination in the insulating oil. The color of the insulating oil after retrofilled with SE is brighter than after retrofilled with MO. This determines that contaminants in insulating oil after retrofilled with MO are higher compared to after retrofilled with SE.

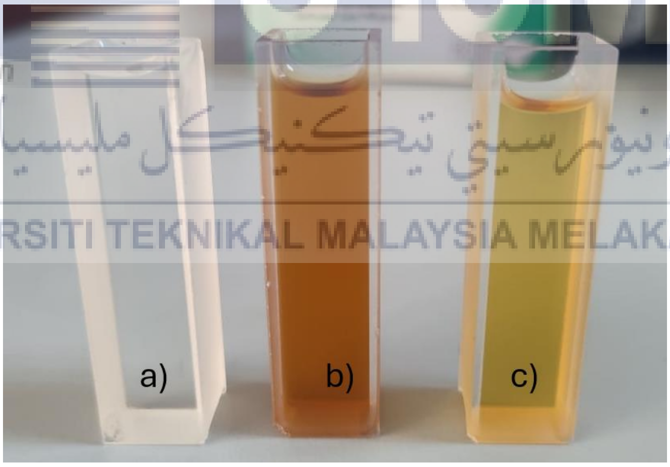

Figure 4–12: Color of insulating oil for Condition 1: a) MO before aging, b) MO before retrofilled and c) MO after retrofilled.

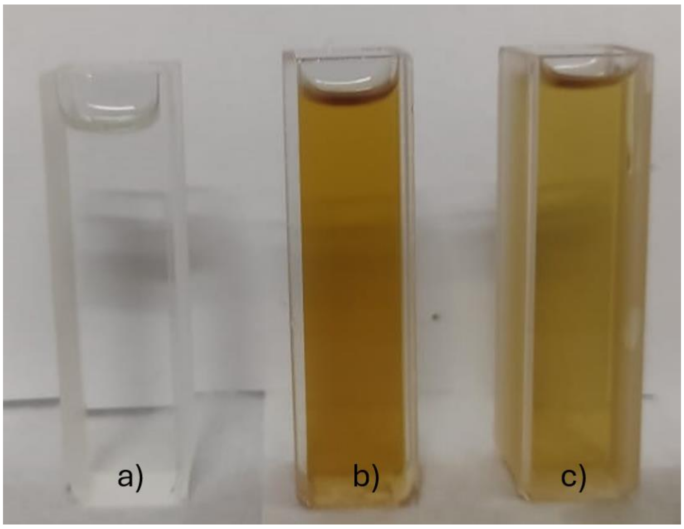

Figure 4–13: Color of insulating for Condition 2: a) MO before aging, b) MO before retrofilled and c) SE after retrofilled.

Figure 4–14 shows the quantitative analysis to confimed the qualitative analysis performed through visual observations. A high absorbance values in MO before retrofilling indicates that the amount of dissolved decay product in the oil is high which can be visually seen from Figure 4–12. The same trend is also shown in the absorbance curve (Figure 4–15) for insulating oil for condition 2, where the absorbance value of insulating oil after retrofilled with SE is lower than after retrofilled with MO. The higher the level of dissolved decay product of the insulating oil, the higher the absorbance value. The more contaminated an oil is, the lower the breakdown voltage of the oil. Therefore, MO after retrofilled is better than MO before retrofilled due to the dirt content in MO after retrofilled being lower than MO after retrofilled.

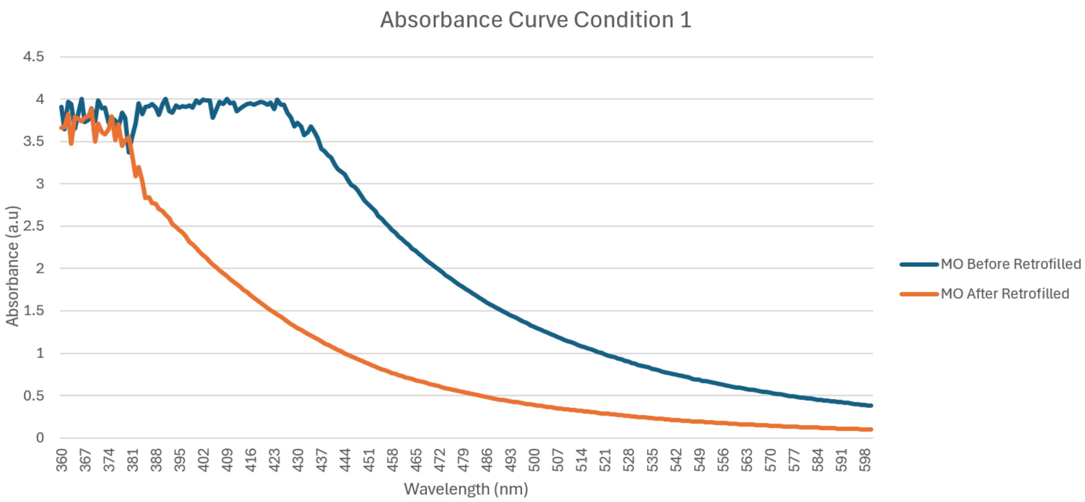

Figure 4–14: The absorbance characteristics of insulating oil (before and after retrofilled with MO) for condition 1.

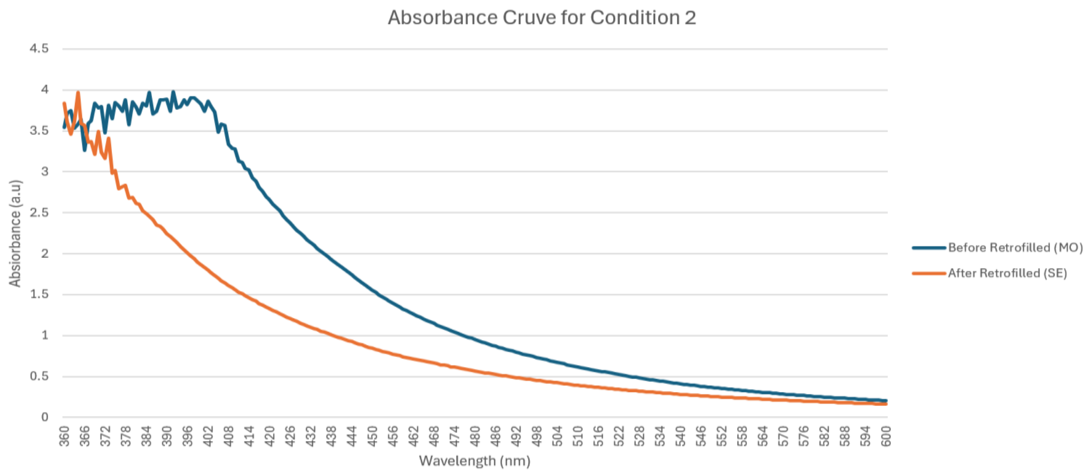

Figure 4–15: The absorbance characteristics of insulating oil (before and after retrofilled with SE) for condition 2.

Figure 4–16 shows the DDP for the insulating oil for condition 1 (before and after retrofilled MO). In general, the DDP of the oil after retrofilled to be lower than before retrofilled. There was a significant reduction (50.17 %) in the DDP values after the aged oil was retrofilled with MO. This is happened due the degradation level of insulating oil and material during the aging process before retrofilled is high. The reduction of DDP indicates that the retrofilled process reduces the contamination level (dissolved products such as NBR gasket, kraft paper, pressboard) of the insulating oil caused by the aging. The generated thermal pressure cause insulating materials and MO to degrade, resulting in both disolve and undisolve products. Disolve products absorbed and mixed with MO while undissolved products will deposited on the insulating material and tank. This sludge product will attack kraft paper and gaskets which causes an increase in DPP in MO.

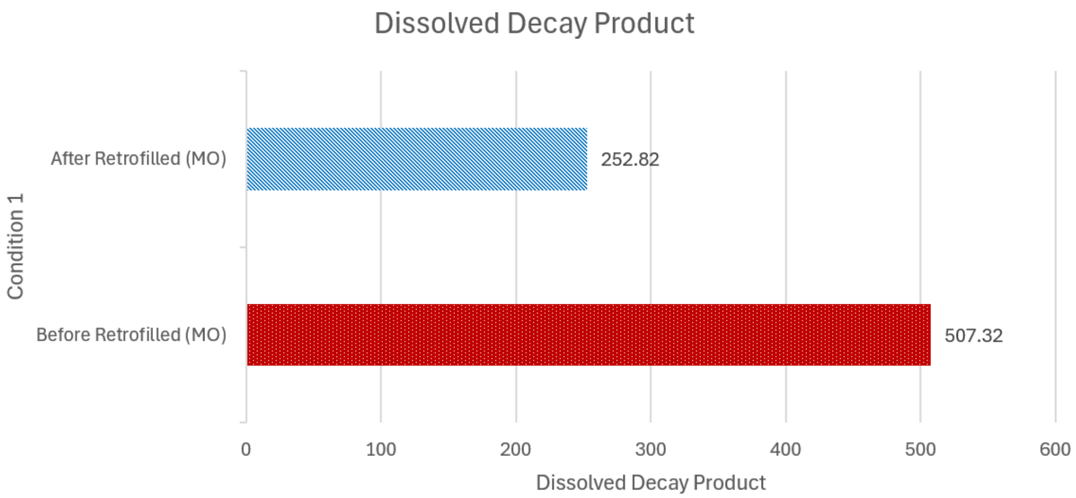

Figure 4–16: DDP values of insulating oils for before and after retrofilled with MO.

Similarly, DDP values for insulating oil for condition 2 (before and after retrofilled with SE) also shows a downward trend where DDP is reduced by 37.31% as shown in Figure 4–17. The decrease in DDP after retrofilled with SE shows that SE is also able to reduce sludge in insulating oil. As a result, the lifespan of the oil can also be extended. DDP value for insulating oil after retrofilled with SE is lower than after retrofilled with MO with a difference of 21.05.

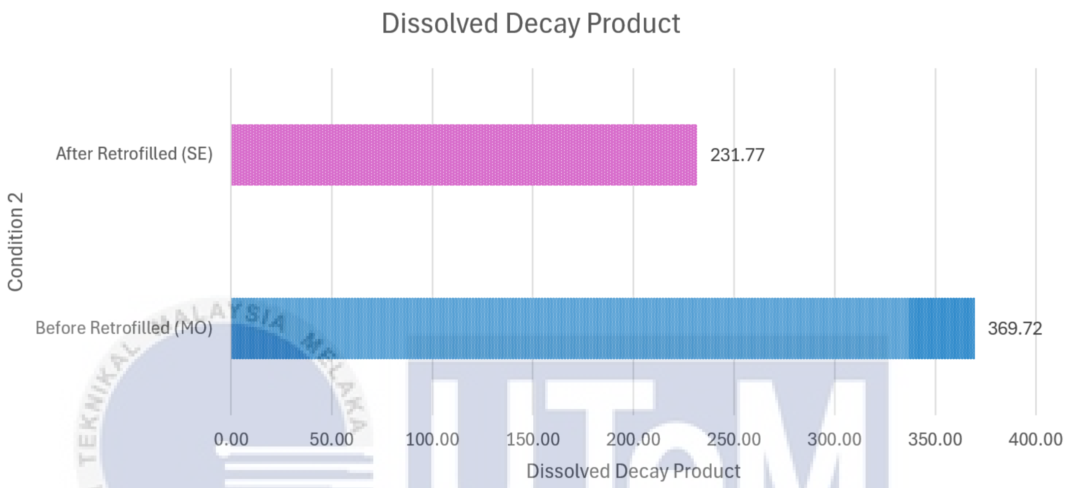

Figure 4–17: DDP value of insulating oils for before and after retrofilled with SE.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objective of this research study has been achieved. The changes of properties of insulation materials for kraft paper, pressboard, NBR gasket and insulating oil show changes for the initial, before and after retrofilled. Transformer insulation materials' electrical, chemical, and physical characteristics are all greatly impacted by the retrofilling process. In comparison to MO, SE performs better at maintaining the characteristics of NBR gaskets and minimize DDP in insulating oil after retorfilled process. MO shows good performance in maintaining tensile strength of kraft paper and insulation resistance of insulating oil. Retrofilling process can lower the level of contamination that can enhance the lifespan and durability of the insulation materials.

5.2 Recommendations

Further research should be carried out to identify the ability of MO and SE as retrofilled agents for the transformers. This is important to improve the properties and lifespan of the insulating of the transformers. The performance of MO and SE as a retrofilled agent should be studied over a longer period of time at various temperature and the possibility of the presence of unpredicted compounds in insulating oil to investigate the ability of MO and SE in maintaining the properties and improving the performance of transformer's oil, insulating paper and gasket. Tests performed on insulating oil and material should not be limited and expanded to see the ability of the oil to maintain the performance of transformers.

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APPENDICES

Nynas Nytro Libra Properties

Nytro Libra

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

Appearance	
Physical state	Liquid.
Colour	Light yellow
Odour	Odourless/Light petroleum.
Odour threshold	Not available.
pH	Not applicable.
Melting point/freezing point	-51°C
Initial boiling point and boiling range	>250°C
Flash point	Closed cup: >140°C [Pensky-Martens.]
Evaporation rate	Not available.
Flammability (solid, gas)	Not available.
Upper/lower flammability or explosive limits	Not available.
Vapour pressure	<0.01 kPa [room temperature]
Density	0.88 g/cm³ [15°C]
Solubility(ies)	Insoluble in water.
Partition coefficient: n-octanol/water	Not available.
Auto-ignition temperature	>270°C
Decomposition temperature	>280°C
Viscosity	Kinematic (40°C): 0.096 cm^2/s (9.6 cSt)
Explosive properties	Not available.
Oxidising properties	Not available.
DMSO extractable compounds for base oil substance(s) according to IP346	< 3%

Midel 7131 Properties

9.1 Information on basic physical and chemical properties

Appearance: Pale amber liquid.
Odour: Faintly sweet.
pH: Not applicable.
Freezing point: -56°C.
Initial boiling point and boiling range: >300°C.
Flash point: 260°C (closed cup).
Flammability (solid, gas): Non-flammable.
Upper/lower flammability or explosive limits: Data not available.
Vapour pressure: <0.001Pa at 20°C.
Vapour density: Not applicable.
Relative density: 0.97 at 20°C.
Water solubility: <1mg/l.
Solubility: Not applicable.
Partition coefficient: log Pow: >10.
Auto-ignition temperature: No auto-ignition expected.
Decomposition temperature: Data not available.
Kinematic viscosity: 29mm^2/s at 40°C.
Explosive properties: Non-explosive.
Oxidising properties: Non-oxidising.

9.2 Other information

Surface tension: No data available.
Particle size: No data available.

Weight of kraft paper and pressboard before and after drying.

Condition	Material	Weight	
		Condition 1	Condition 2
Before	Kraft Paper	100.74	100.53
	Pressboard	396.53	380.49
After	Kraft Paper	94.91	93.25
	Pressboard	364.27	350.63

Dissolved Decay Product

Condition 1				Condition 2			
Before Retrofilled (MO)		After Retrofilled (MO)		Before Retrofilled (MO)		After Retrofilled (SE)	
360	3.905	360	3.66	360	3.539	360	3.835
361	3.646	361	3.67	361	3.713	361	3.608
362	3.966	362	3.823	362	3.75	362	3.46
363	3.938	363	3.472	363	3.533	363	3.616
364	3.654	364	3.785	364	3.582	364	3.971
365	3.81	365	3.773	365	3.638	365	3.589
366	4	366	3.737	366	3.265	366	3.57
367	3.727	367	3.78	367	3.589	367	3.362
368	3.752	368	3.798	368	3.622	368	3.369
369	3.887	369	3.883	369	3.841	369	3.211
370	3.734	370	3.496	370	3.783	370	3.495
371	3.984	371	3.708	371	3.795	371	3.241
372	3.889	372	3.608	372	3.476	372	3.164
373	3.903	373	3.587	373	3.813	373	3.415
374	3.716	374	3.645	374	3.646	374	2.985
375	3.781	375	3.796	375	3.845	375	3.013
376	3.745	376	3.511	376	3.802	376	2.793
377	3.666	377	3.702	377	3.738	377	2.818
378	3.843	378	3.444	378	3.882	378	2.839
379	3.777	379	3.518	379	3.579	379	2.681
380	3.371	380	3.548	380	3.858	380	2.685
381	3.539	381	3.359	381	3.792	381	2.61
382	3.708	382	3.087	382	3.711	382	2.603
383	3.947	383	3.195	383	3.841	383	2.519
384	3.822	384	3.024	384	3.807	384	2.488
385	3.905	385	2.835	385	3.972	385	2.456
386	3.917	386	2.841	386	3.709	386	2.415
387	3.942	387	2.773	387	3.744	387	2.352
388	3.897	388	2.763	388	3.876	388	2.334
389	3.815	389	2.7	389	3.883	389	2.298
390	3.938	390	2.681	390	3.887	390	2.243
391	4	391	2.634	391	3.744	391	2.209
392	3.853	392	2.591	392	3.978	392	2.178

393	3.842	393	2.526	393	3.777	393	2.137
394	3.925	394	2.491	394	3.794	394	2.091
395	3.897	395	2.454	395	3.876	395	2.05
396	3.915	396	2.422	396	3.823	396	2.013
397	3.907	397	2.376	397	3.901	397	1.972
398	3.925	398	2.314	398	3.902	398	1.94
399	3.898	399	2.282	399	3.874	399	1.898
400	3.985	400	2.247	400	3.834	400	1.866
401	3.954	401	2.201	401	3.744	401	1.831
402	3.994	402	2.156	402	3.864	402	1.8
403	3.98	403	2.129	403	3.798	403	1.763
404	3.98	404	2.082	404	3.732	404	1.732
405	3.777	405	2.048	405	3.483	405	1.701
406	3.881	406	2.01	406	3.582	406	1.67
407	3.97	407	1.979	407	3.564	407	1.642
408	3.945	408	1.941	408	3.333	408	1.613
409	3.997	409	1.907	409	3.284	409	1.586
410	3.952	410	1.873	410	3.279	410	1.559
411	3.96	411	1.84	411	3.131	411	1.532
412	3.859	412	1.814	412	3.117	412	1.508
413	3.889	413	1.778	413	3.045	413	1.485
414	3.916	414	1.747	414	3.026	414	1.462
415	3.943	415	1.72	415	2.924	415	1.439
416	3.946	416	1.69	416	2.883	416	1.417
417	3.936	417	1.654	417	2.811	417	1.391
418	3.946	418	1.625	418	2.761	418	1.369
419	3.97	419	1.595	419	2.697	419	1.349
420	3.956	420	1.568	420	2.662	420	1.328
421	3.932	421	1.538	421	2.602	421	1.307
422	3.96	422	1.509	422	2.564	422	1.286
423	3.885	423	1.482	423	2.523	423	1.266
424	3.993	424	1.454	424	2.465	424	1.247
425	3.937	425	1.429	425	2.419	425	1.227
426	3.936	426	1.402	426	2.379	426	1.208
427	3.834	427	1.375	427	2.332	427	1.189
428	3.785	428	1.35	428	2.285	428	1.171
429	3.673	429	1.325	429	2.248	429	1.153
430	3.723	430	1.299	430	2.209	430	1.136
431	3.673	431	1.277	431	2.172	431	1.12
432	3.576	432	1.253	432	2.134	432	1.104
433	3.606	433	1.23	433	2.103	433	1.088
434	3.678	434	1.207	434	2.066	434	1.072
435	3.605	435	1.185	435	2.033	435	1.055
436	3.543	436	1.163	436	1.997	436	1.04

437	3.41	437	1.141	437	1.963	437	1.025
438	3.388	438	1.12	438	1.93	438	1.01
439	3.335	439	1.1	439	1.9	439	0.995
440	3.306	440	1.079	440	1.868	440	0.981
441	3.224	441	1.059	441	1.838	441	0.967
442	3.173	442	1.039	442	1.804	442	0.953
443	3.136	443	1.02	443	1.773	443	0.938
444	3.11	444	1	444	1.739	444	0.924
445	3.04	445	0.981	445	1.708	445	0.91
446	2.982	446	0.962	446	1.676	446	0.896
447	2.959	447	0.944	447	1.645	447	0.883
448	2.914	448	0.926	448	1.615	448	0.87
449	2.853	449	0.908	449	1.584	449	0.856
450	2.801	450	0.891	450	1.554	450	0.844
451	2.758	451	0.875	451	1.527	451	0.832
452	2.717	452	0.858	452	1.498	452	0.82
453	2.675	453	0.843	453	1.471	453	0.808
454	2.618	454	0.827	454	1.445	454	0.796
455	2.58	455	0.812	455	1.418	455	0.785
456	2.541	456	0.798	456	1.394	456	0.774
457	2.497	457	0.783	457	1.369	457	0.763
458	2.454	458	0.77	458	1.346	458	0.752
459	2.418	459	0.756	459	1.323	459	0.742
460	2.379	460	0.743	460	1.302	460	0.732
461	2.348	461	0.731	461	1.281	461	0.723
462	2.314	462	0.719	462	1.261	462	0.714
463	2.279	463	0.707	463	1.241	463	0.705
464	2.238	464	0.695	464	1.221	464	0.696
465	2.206	465	0.684	465	1.203	465	0.687
466	2.173	466	0.673	466	1.184	466	0.678
467	2.143	467	0.662	467	1.165	467	0.67
468	2.107	468	0.651	468	1.147	468	0.661
469	2.076	469	0.64	469	1.129	469	0.653
470	2.044	470	0.629	470	1.111	470	0.644
471	2.014	471	0.619	471	1.094	471	0.636
472	1.983	472	0.609	472	1.077	472	0.628
473	1.951	473	0.599	473	1.06	473	0.619
474	1.922	474	0.589	474	1.044	474	0.612
475	1.895	475	0.579	475	1.028	475	0.604
476	1.865	476	0.57	476	1.012	476	0.596
477	1.835	477	0.56	477	0.996	477	0.588
478	1.808	478	0.551	478	0.98	478	0.581
479	1.78	479	0.541	479	0.965	479	0.573
480	1.754	480	0.533	480	0.95	480	0.566

481	1.729	481	0.524	481	0.936	481	0.559
482	1.703	482	0.516	482	0.922	482	0.552
483	1.678	483	0.508	483	0.909	483	0.545
484	1.653	484	0.499	484	0.895	484	0.538
485	1.628	485	0.491	485	0.882	485	0.531
486	1.605	486	0.483	486	0.869	486	0.525
487	1.581	487	0.476	487	0.856	487	0.518
488	1.559	488	0.468	488	0.844	488	0.512
489	1.536	489	0.461	489	0.832	489	0.506
490	1.515	490	0.454	490	0.821	490	0.5
491	1.493	491	0.447	491	0.809	491	0.494
492	1.471	492	0.44	492	0.797	492	0.487
493	1.452	493	0.434	493	0.786	493	0.482
494	1.431	494	0.427	494	0.775	494	0.476
495	1.411	495	0.421	495	0.764	495	0.47
496	1.391	496	0.414	496	0.753	496	0.465
497	1.372	497	0.408	497	0.743	497	0.459
498	1.352	498	0.402	498	0.732	498	0.453
499	1.333	499	0.396	499	0.722	499	0.448
500	1.314	500	0.39	500	0.712	500	0.443
501	1.296	501	0.384	501	0.702	501	0.437
502	1.278	502	0.378	502	0.692	502	0.432
503	1.261	503	0.373	503	0.682	503	0.427
504	1.243	504	0.367	504	0.673	504	0.422
505	1.225	505	0.362	505	0.663	505	0.416
506	1.208	506	0.356	506	0.654	506	0.411
507	1.192	507	0.351	507	0.644	507	0.407
508	1.176	508	0.346	508	0.635	508	0.402
509	1.16	509	0.341	509	0.627	509	0.397
510	1.145	510	0.337	510	0.618	510	0.393
511	1.13	511	0.332	511	0.61	511	0.388
512	1.115	512	0.327	512	0.601	512	0.384
513	1.1	513	0.323	513	0.593	513	0.379
514	1.086	514	0.318	514	0.585	514	0.375
515	1.072	515	0.314	515	0.577	515	0.371
516	1.058	516	0.31	516	0.569	516	0.367
517	1.044	517	0.305	517	0.561	517	0.363
518	1.029	518	0.301	518	0.554	518	0.358
519	1.016	519	0.296	519	0.546	519	0.354
520	1.002	520	0.292	520	0.539	520	0.35
521	0.989	521	0.288	521	0.531	521	0.346
522	0.975	522	0.284	522	0.524	522	0.343
523	0.963	523	0.28	523	0.517	523	0.339
524	0.95	524	0.276	524	0.51	524	0.335

525	0.937	525	0.272	525	0.502	525	0.331
526	0.924	526	0.268	526	0.495	526	0.327
527	0.911	527	0.264	527	0.489	527	0.324
528	0.899	528	0.26	528	0.482	528	0.32
529	0.888	529	0.256	529	0.476	529	0.317
530	0.876	530	0.253	530	0.469	530	0.313
531	0.864	531	0.249	531	0.463	531	0.31
532	0.854	532	0.246	532	0.457	532	0.307
533	0.842	533	0.242	533	0.451	533	0.303
534	0.831	534	0.238	534	0.445	534	0.3
535	0.82	535	0.235	535	0.439	535	0.297
536	0.81	536	0.232	536	0.434	536	0.294
537	0.798	537	0.228	537	0.427	537	0.291
538	0.787	538	0.225	538	0.421	538	0.287
539	0.778	539	0.222	539	0.416	539	0.285
540	0.768	540	0.218	540	0.411	540	0.282
541	0.758	541	0.215	541	0.405	541	0.279
542	0.748	542	0.212	542	0.4	542	0.276
543	0.739	543	0.209	543	0.395	543	0.273
544	0.729	544	0.206	544	0.39	544	0.27
545	0.72	545	0.203	545	0.385	545	0.267
546	0.711	546	0.201	546	0.38	546	0.265
547	0.702	547	0.198	547	0.375	547	0.262
548	0.693	548	0.195	548	0.37	548	0.259
549	0.685	549	0.192	549	0.366	549	0.257
550	0.676	550	0.19	550	0.361	550	0.254
551	0.668	551	0.187	551	0.357	551	0.252
552	0.66	552	0.185	552	0.353	552	0.249
553	0.652	553	0.182	553	0.348	553	0.247
554	0.644	554	0.18	554	0.344	554	0.244
555	0.636	555	0.177	555	0.34	555	0.242
556	0.628	556	0.175	556	0.336	556	0.24
557	0.621	557	0.173	557	0.332	557	0.237
558	0.613	558	0.17	558	0.328	558	0.235
559	0.606	559	0.168	559	0.324	559	0.233
560	0.599	560	0.166	560	0.32	560	0.231
561	0.592	561	0.164	561	0.317	561	0.229
562	0.586	562	0.162	562	0.313	562	0.227
563	0.579	563	0.16	563	0.309	563	0.225
564	0.572	564	0.158	564	0.306	564	0.223
565	0.566	565	0.156	565	0.302	565	0.221
566	0.559	566	0.154	566	0.299	566	0.219
567	0.552	567	0.152	567	0.296	567	0.216
568	0.546	568	0.15	568	0.292	568	0.214

569	0.54	569	0.148	569	0.289	569	0.213
570	0.534	570	0.146	570	0.285	570	0.211
571	0.527	571	0.144	571	0.282	571	0.209
572	0.521	572	0.142	572	0.279	572	0.207
573	0.515	573	0.14	573	0.276	573	0.205
574	0.509	574	0.138	574	0.273	574	0.203
575	0.503	575	0.136	575	0.269	575	0.201
576	0.497	576	0.135	576	0.266	576	0.199
577	0.492	577	0.133	577	0.263	577	0.197
578	0.486	578	0.131	578	0.26	578	0.196
579	0.48	579	0.13	579	0.257	579	0.194
580	0.475	580	0.128	580	0.254	580	0.192
581	0.47	581	0.126	581	0.252	581	0.191
582	0.464	582	0.125	582	0.249	582	0.189
583	0.459	583	0.123	583	0.246	583	0.187
584	0.454	584	0.122	584	0.243	584	0.186
585	0.449	585	0.12	585	0.241	585	0.184
586	0.444	586	0.119	586	0.238	586	0.182
587	0.439	587	0.117	587	0.235	587	0.181
588	0.435	588	0.116	588	0.233	588	0.179
589	0.43	589	0.114	589	0.23	589	0.178
590	0.425	590	0.113	590	0.228	590	0.176
591	0.421	591	0.112	591	0.226	591	0.175
592	0.416	592	0.11	592	0.223	592	0.173
593	0.412	593	0.109	593	0.221	593	0.172
594	0.407	594	0.108	594	0.218	594	0.171
595	0.403	595	0.106	595	0.216	595	0.169
596	0.398	596	0.105	596	0.214	596	0.168
597	0.394	597	0.104	597	0.212	597	0.166
598	0.39	598	0.103	598	0.209	598	0.165
599	0.386	599	0.101	599	0.207	599	0.164
600	0.382	600	0.1	600	0.205	600	0.162