RUBBER SELECTION IN THE AUTOMOTIVE FILTRATION INDUSTRY

by

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[redacted]

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Declaration

I hereby declare that this submission is my own work and to the best of my knowledge it neither contains material previously published or written by another person, nor material which to a major extent has been accepted for the award of any other degrees at Durban University of Technology (DUT) or any other educational institution. I also declare that the intellectual content of this dissertation is the product of my own work. Any contribution made to the research by others has been explicitly acknowledged in the dissertation.

[redacted] 25/10/2020

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Abstract

Filters have seals to prevent leakage and to attain service intervals at required temperatures. There are various materials and the correct material must be chosen for the filter to operate efficiently and effectively. Material selection is vital as it can effectively reduce cost and if one material is selected but is more expensive and of higher quality the price can be reduced because of purchasing in large volumes. The overall aim of this study was to produce a process to follow for rubber selection for seals and grommets that would eliminate material identification testing at the automotive filter company, make the best choice based on the design of experiments (DOE) software, and to save costs by eliminating the use of over-engineered products. The objectives were to identify current rubber material types used on oil filters, conduct lab tests to determine the limits of parameters that rubber material can withstand, identify trends of testing, and lastly, determine the rubber that could possibly be used across a range of filters by using the DOE software. Materials tested included nitrile-butadiene 321 (NBR 321), nitrile-butadiene 322 (NBR 322), methyl vinyl silicone 332 (VMQ 332), nitrile-butadiene 333 (NBR 333), polyacrylate 334 (ACM 334), Viton 337, hydrogenated nitrile butadiene 338 (HNBR) and ethylene acrylic 336 (AEM 336). These materials were exposed to mineral oil and synthetic oil at operating conditions ranging from 120 °C to 150 °C and 168 h to 500 h which equated to 10 000 km to 30 000 km service intervals. The DOE software was used to develop the models in order to determine the best fit material for the required service interval and temperature. The conclusions drawn from this thesis indicate that when all these materials are exposed to mineral oil, ACM 334, Viton 337 and AEM 336 have the highest resistance to temperature and longest service intervals which is 120 °C to 150 °C at 30 000 km and, when exposed to synthetic oil, Viton 337 has the highest resistance to temperature and longest service intervals which is 130 °C at 30 000 km and 150 °C at 20 000 km. Further conclusions show that synthetic oil is a stronger fluid as it degrades all materials to a greater extent than mineral oil. It was evident from the DOE software that ACM 334 and Viton 337 were found to be the best solutions. The desired solution is closest to material ACM 334 at a temperature of 124 °C and service interval of 172 h (refer to table E.15). The trends observed were an increase of hardness and change in volume as temperature and exposure periods increased and a decrease of tensile strength and elongation as temperature and exposure periods increased. This is an agreement with findings in the literature (Refer chapter 2, section 2.1.6) which validates these trends.

Dedication

To the four pillars in my life:

- God, without you nothing is possible.
- My mother, for your love, encouragement and motivation.
- My father, for your love and your constant questioning on whether my dissertation is complete.
- My brother, you may not be around physically but your success in life is a motivator.

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Nomenclature

%	Percentage
°C	Degrees Celsius
A	Cross sectional area
a	Thickness
b	Width of narrow parallel portion
b_k	Width of ends
F	Force used to break the dumb bell
g	grams
h	hour
H	Seal or dumb bell height
$KJ.mol^{-1}$.	Kilo Joule per mole
km	kilometre
L	Minimum overall length
L_o	Initial gauge length
l_s	Length of narrow parallel portion
M_1	Initial mass of specimen in air
M_2	Initial mass of specimen in water
M_3	Mass of specimen in air after immersion
M_4	Mass of specimen in water after immersion
MPa	MegaPascal

N	Newton
N/mm^2	Newton per millimetre square
r_1	Small radius
r_2	Large radius
T	Seal or dumb bell thickness
Λ	Lambda
Σ	Tensile strength
wt	weight
F-value	Ratio of variances
Df/df	total degrees of freedom

Abbreviations

ACM	Polyacrylate
AEM	Ethylene acrylic rubber
EPDM	Ethylene propylene diene monomer
DOE	Design of experiments
FKM	Fluroelastomer
FTIR	Fourier-transform infrared spectroscopy
HNBR	Hydrogenated nitrile-butadiene rubber
MO	Mineral oil
NBR	Nitrile-butadiene rubber
RAPRA	Rubber and Plastics Research Association
SO	Synthetic oil
TGA	Thermogravimetric analysis
VMQ	Methyl vinyl silicone rubber
IRHD	International Rubber Hardness Degrees
CI	Confidence Interval
VIF	Variance Inflation Factor

Chapter 1: Introduction

Background

1.1 Importance of filter optimization

The efficiency and cost of a filter is of vital importance in the automotive industry. A target area that is of importance which would aid in optimizing a filter's performance is the study/development of rubber compounds. Rubber compounds play a vital role in the cost and design of a filter. An automotive filter company generally manufactures four types of filters, namely oil, fuel, diesel and air. Rubber compounds have various effects on filter performance depending on the type of filter and application. These rubber types need to be analysed to determine the best choice for the specified filter operating conditions. The purpose of the current study is to understand the relationship between tests and filter operating conditions to develop a technical standard which will aid in the selection of rubber for optimization of filter performance. In the automotive filter industry, rubber compounds are manufactured into seals, grommets and O-rings to be used on filters as a sealing interface to prevent bypass/contamination. Transfer of fluids and loss of fluids are prevented by O-rings as an O-ring seals a passageway (GBSA 2014). Leaks between separate substrate sections in a filter are prohibited by means of a mechanical seal referred to as a gasket (ThomasNet 2014). These rubbers need to withstand various operating conditions i.e. temperature of the oil, diesel and fuel and exposure time. A number of rubbers have to withstand extreme cold and heat; in addition, some have to withstand various chemicals that they may be exposed to (ThomasNet 2014). The design and manufacture of an automobile is imperative to the global market. World car trends of 2014 depict how crucial it is to optimize efficiency. This in turn relates to optimization of filter design in the automotive industry (Kahl 2014). This dissertation will focus on the improvement of rubber selection to potentially reduce costs and to identify limits of rubbers and trends of test results.

1.2 Current process for selection of rubber for filter design

There are original equipment manufactured parts which are benchmarked to identify the type of rubber material that is used. A test report is generated using a technique referred to as Fourier-transform infrared spectroscopy (FTIR). This is a general tool which is used to analyse the chemical composition of a product and is used to observe the chemical functional groups on a molecule. A sample has to be prepared in a translucent film to be physically mixed with a salt to attain an infrared sample. Not all materials can be made into a translucent film, and therefore not all materials can be evaluated using FTIR analysis. When pressed, this mixture will give a translucent window through which an infrared spectroscopy makes use of a photo acoustic cell. The sample is located in a chamber and flushed with ultra high purity helium. The FTIR picks up absorbencies for each functional group. A single functional group produces more than one absorbance band due to the stretching, vibration bond movements and rocking. Overlapping of absorbencies may occur which makes it difficult to definitely allocate an absorbance peak to only one bond. With regards to photo acoustic FTIR, this is the quantity of gas above the sample, the number of scans and the temperature of the sample. In summary, a sample is positioned in a cup holder, permitting a minimum amount of gas above the sample which is flushed with helium to eliminate any air from a sample compartment. A scan requires approximately 15 minutes for temperature to equilibrate in order to obtain a quantitative measurement. The spectrum is mathematically adjusted to compensate for the photo acoustic affect. This test generates a type of material i.e. NBR, ACM. This material is then used as part of the design of the filter for optimization. (Roediger 2015). FTIR is an aid to determine what type of material the rubber is and does not necessarily result in over engineered products.

1.3 Objectives of dissertation

The overall aim of this study was to produce a process to follow for rubber selection that would eliminate material identification testing required, make the best choice based on DOE software and save cost by eliminating the use of over engineered products.

The specific objectives included:

1.3.1 Identify current rubber material types used on oil filters.

1.3.2 Identify process parameters to test rubber material types to.

1.3.3 Optimisation by conducting lab tests to determine parameters that rubber material type can withstand and identify trends of testing.

1.3.4 Determine a rubber that can be used across a range of filters from the tests conducted using the DOE software.

1.4 Approach

The study was conducted in three main stages:

1.4.1 Evaluate existing raw materials of rubber used on oil filters.

1.4.2 Test rubbers to evaluate trends and limits of rubbers. This compilation was accomplished by conducting numerous laboratory tests to determine operating parameters which included temperature ranges, service interval ranges and resistances. These tests were conducted at 120 °C to 150 °C, 10 000 km to 30 000 km and oil submersions.

1.4.3 Make use of the DOE software to select the fit for purpose rubber and to use the DOE software for future selections of rubbers for specifics if required.

1.5 Thesis organization

This thesis contains 6 chapters and is organized as follows:

Chapter 1 presents the general background to the problem being explored and depicts the basis for this study. The objectives and purpose of this study are detailed.

Chapter 2 provides background information from existing literature on the various rubber raw materials that are used for O-rings and seals in automotive filter design, the importance of rubber O-rings and information on developments in rubber research.

Chapter 3 presents the research methodology on the laboratory tests performed on rubber materials to determine each material's limits and trends to input results into DOE software to identify best fit material.

Chapter 4 depicts parameter exposures and testing criteria that were performed to test if the rubber material was within the specification limits required for automotive filter design. It showcases results, discussions, conclusions and recommendations from the laboratory tests that were performed as reported in Chapter 3.

Chapter 5 presents the DOE results.

Chapter 6 draws conclusions and provides an overall summary of the thesis; it summarises the main findings and identifies limitations of the study.

Chapter 7 presents recommendations for future work.

Chapter 2: Literature Review

2.1 Introduction

This chapter presents a review of the literature relevant to this study. The research is presented in five sections. Firstly, filtration technology in general and filtration technology in cars is discussed. Secondly, the importance of oil filters is discussed in general and related to the automotive industry. Thirdly, the importance of rubber applications is presented. Fourthly, studies on rubbers are explained. Fifthly, rubber testing is discussed and lastly, the development of rubber by various organizations is showcased.

2.1.1 Filtration technology

The necessities of life which are water and clean air are dependent on the separation of particles found in fluids. The separation process is key when it comes to the manufacture of foodstuff, articles in a car or home and medicine. A typical example of the importance of filtration is the effect of emissions on the environment namely if power stations and engines clog from particle contamination in received air, lubricating fluids and fuels (Sparks and Chase 2015).

In the automotive industry, air and oil filters are used in each internal combustion engine to eradicate particulates so these filters are extremely important to increase operational efficiency of engines to avoid damage and wear to important parts (Youngk, 2000). Scraba (2019) adds to this by explaining how an oil filter is a key element of the engine in any truck or car or motorcycle, boat, airplane and tractor. As the oil flows through the engine it picks up any number of contaminants. Contaminants can damage the engine and over time cause the engine to break down. Early internal combustion engines did not make use of oil filters and together with the low quality of oil available at the time, vehicles required regular oil changes. The first full-flow oil filtration system was eventually developed. This procedure permitted the oil to move through a filter before reaching the important working components inside the engine. However, in certain circumstances the filter is bypassed. The majority of pressurized lubrication systems located in internal combustion engines incorporate some form of filter by-pass to guard the engine from starvation under particular circumstances, for example, in extremely cold weather. In such a scenario, if the oil is too thick, it is permitted to bypass the filter. Oil can also circumvent the filter when the filter is plugged and because of these events, oil is occasionally not filtered, even when the engine is fitted with a full-flow oil filter. In operation, oil goes into the oil filter through a numberof small holes on the outer edge of the base flange. The oil is then moved through the filter, ultimately making an exit into the engine through a big center hole. Most modern oil filters have an anti-drainback valve. This is normally a form of rubber membrane that covers the perimeter holes in the base flange. When oil enters the filter case, the membrane is forced aside. The rubber membrane covers the holes when the engine is not running. The anti-drainback valves maintain oil within the filter and prevent engine-dry-starts (Scraba, 2019).

The two main types of filters are full-flow filters and by-pass filters (Baldwin Filters, 2017). A full-flow oil filter is the kind of oil filter that is typical on most of the vehicles that are driven every day. The filter eradicates the larger particles of contaminant from the oil that may be dangerous to the engine. A by-pass oil filter is not as common. This kind of filter is found on older applications, or used with a full-flow filter on some engines today. The by-pass filter collects from 10 % to 20 % of the oil that goes to the engine. The medium used in this filter is extremely efficient and is designed to eliminate the smallest particles of contaminant. Oil that goes through a by-pass filter normally gets returned to the sump. Using a full-flow oil filter together with a by-pass oil filter will normally allow for lengthier oil change intervals. As the by-pass filter eliminates the smallest contaminants, cleaner oil gets into the full-flow oil filter. Consequently, the full-flow filter does not clog with impurities as quickly as it would without the by-pass filter. Dual-flow filters are designed together with the full-flow and by-pass oil filter within the same canister.

For a broader perspective, which is not related to the automotive industry, the vital importance of proper filtration is illustrated in an article by Munch et al. (2015) on how the lack of carbon air filtration impacts early embryo development. Their study was conducted in an in-vitro fertilization centre and assessed human fertilization and preimplantation embryo development in the presence and in the absence of carbon filtration. Their findings were that “fertilization, cleavage, and blastocyst conversion rates for fresh cycles all declined during the period of absent carbon filtration and recovered after the restoration of carbon filtration”. Their conclusion was that carbon filtration is essential for the successful operation of a human in-vitro fertilization laboratory.

In the automotive industry the filter medium is central to oil filtration. The thinner the fibre from which the material is manufactured, the smaller the particle will be that is trapped in it. According to Parker Hannifin Corporation (2006) the filter medium is that part of the filter that eradicates contaminants; over 85 % of all filtration failures in systems are caused by contamination. The purpose of hydraulic filtration is to prevent contamination and enable hydraulic fluids to fulfil their functions and reduce or prevent costly manufacturing plant downtime. The four functions of hydraulic fluid are: "1. To act as an energy transmission medium. 2. To lubricate internal moving parts of components. 3. To act as a heat transfer medium. 4. To seal clearances between moving parts." (Parker Hannifin Corporation 2006: 2).

2.1.2 Importance of oil filters

Pollution control is vital and involves continuous prevention of pollution. Pollution control is optimised by effective lubrication, minimised energy loss and enhanced parts' life. Sulphur and ash cause pollution in the environment through emissions from engine exhausts and through evaporation. In order to solve this problem, Gulzar et al. (2017) investigated a chemically active oil filter. The lubrication quality was enhanced by coating a standard filter element with sodium oxide particles. The chemically active filter resulted in no hazardous by-products. Corrosion resistance improved by 14.3 % when using a chemically active oil filter in comparison to a standard oil filter. Friction was reduced by 12.9 % and wear rate was reduced by 9.2 %. A 200 h drain interval was obtained for the chemically active filter compared to 80 h for a standard oil filter.

Figure 2.1 shows the variety of filters used in a motor vehicle, including an oil filter. Figure 2.2 shows a cutaway of an oil filter.

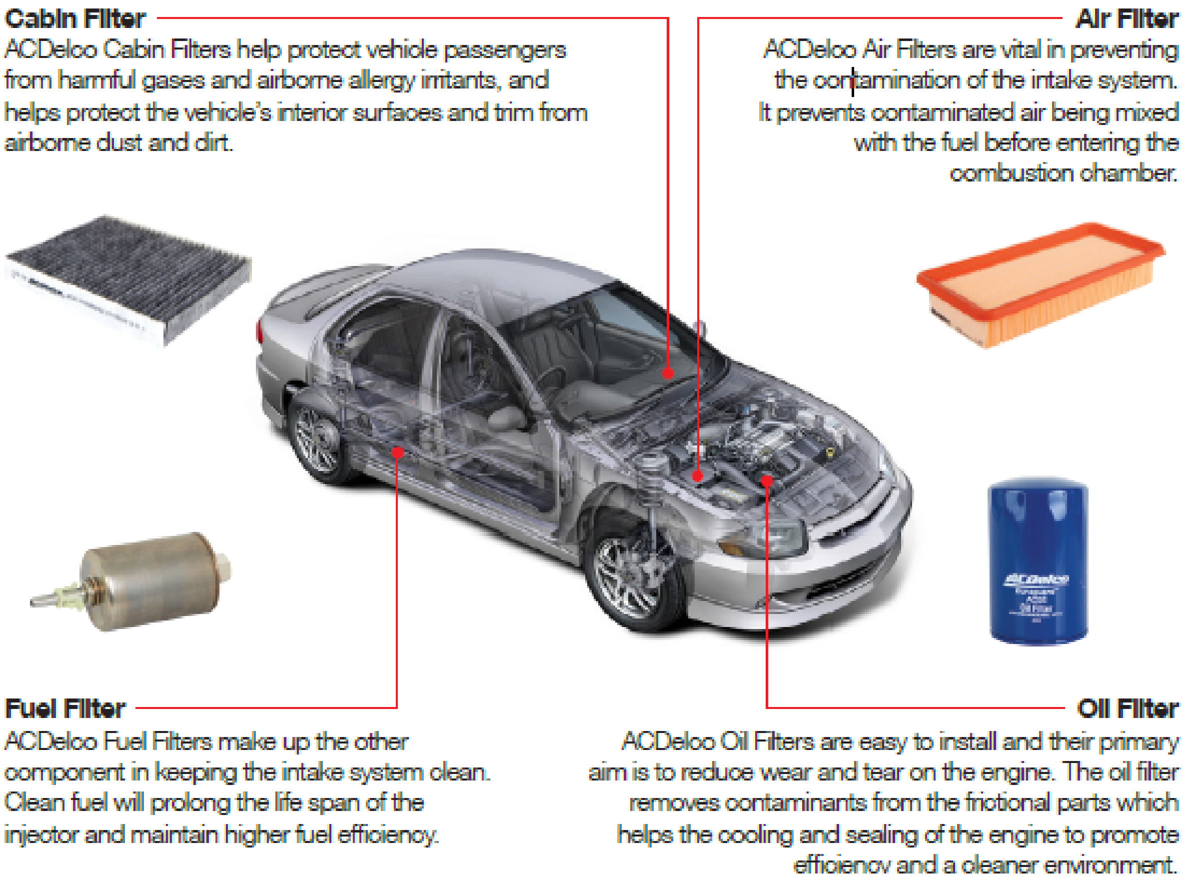


Figure 2.1: Filters used in a motor vehicle
Source: ACDelco (2019)

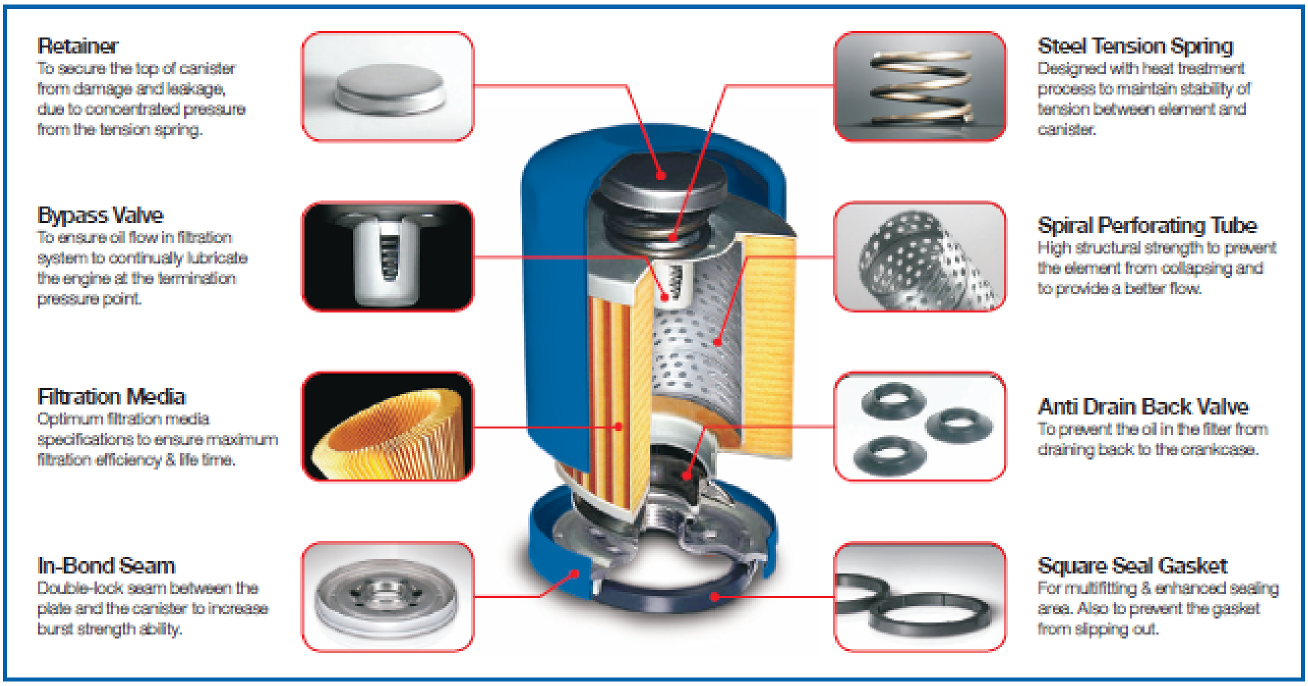


Figure 2.2: Cutaway of an oil filter
Source: ACDelco (2019)

Regular oil filter changes are key when planning on keeping a vehicle for a long time (Bosch, 2010). An oil filter can be taken for granted, but this trivial, low-cost part of a vehicle's lubrication system plays a vital role in shielding the engine from premature wear. Uncontaminated oil is essential for every moving part in the engine and the cylinder walls for correct lubrication and long life. The oil filter cleanses the oil as it passses through the filter element or filtering media. Without a filter, engine oil would soon become saturated with contaminants, requiring frequent filter changes in order to successfully protect the oil pump and engine against damage and wear (Youngk, 2000).

Del-Colle (2012) compares an oil filter to an indispensable organ in the body, emphasising the role of an oil filter in a car in maintaining engine health. The importance of oil filter design is further highlighted by the fact that faulty oil filters can cause car fires. If the rubber gasket seal fails and oil leaks onto the hot manifold and ignites, it can cause a fire which destroys the whole vehicle (Sealing Technology 2004).

According to Ramon Nunez, Director of Filtration for a leading filter manufacturer, it is essential to use advanced technology and materials when designing a filter to make an engine perform efficiently over an extended period of time. An oil filter prevents dirt from damaging an engine. Nunez adds that a good oil filter is efficient in trapping dirt and holding the debris (Bosch 2010).

The design of a filter is critical and the parts such as the tapping plate, anti-drain-back valve, filter medium, center steel tube, relief valve, end disc and retainer are essential in designing a good oil filter. The tapping plate assists in the flow of oil when it enters and exits the filter. The anti-drain-back valve serves to block oil from draining back into the filter when the engine is not on. The filter medium increases the filter's efficiency and durability. It also has resin content to provide stiffness and strength. The centre tube gives stucture and allows filtered oil to go back to the engine. The centre tube ensures that there is less restriction with oil flow. The relief valve helps the engine from starving during cold start up. The end disc prevents leaking of unfiltered oil into the center tube. The retainer ensures a tight fit of the end disc to the tapping plate (Del-Colle 2012).

It is important to change an oil filter regularly (Naskar Group n.d.). Clean oil picks up old deposits and metal flakes from oil passageways and over time the oil starts to oxidise and reactions occur that generate particles as the oil completes many circuits through the engine. The oil filter prevents the metal flakes from entering the passageways by capturing these particles thereby preventing damage to the engine. Oil filters have very little debris capacity and after that capacity has been filled the filter becomes useless. When an oil filter reaches its capacity, the bypass valve is opened by excess pressure which allows unfiltered oil into the lubrication system of the engine where particles can damage bearings and get stuck in lifters and tensioners. Therefore, oil filters should be changed regularly to prevent damage to the engine.

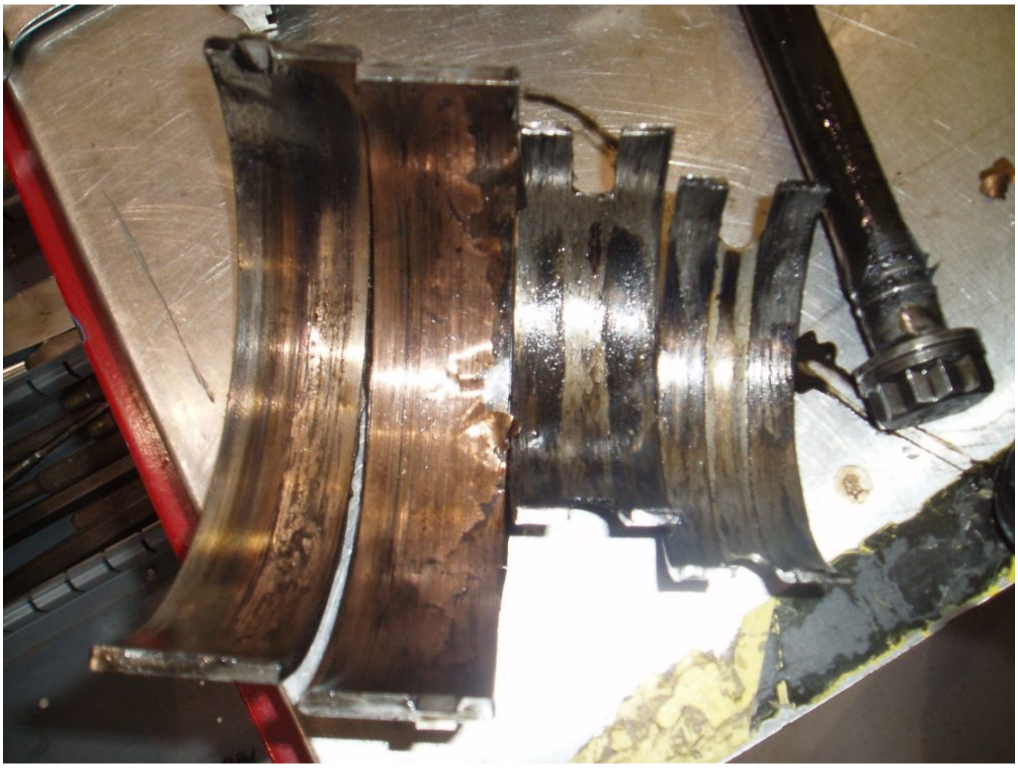


Figure 2.3: Inside of an oil filter that requires changing
Source: Naskar Group (n.d.)

Digital Writers (2018) explain the importance of choosing the right oil filter. Many vehicle drivers assume that oil filters are a generic, unaware of the importance of an oil filter. An oil filter assists in removing contaminants. Picking out the corrrect oil filter for the vehicle is an important first step. The engine is protected from damage when an oil filter works properly. Contaminants accumulate over time, so when oil is left unfiltered for some time, the engine is open to harm. These engine components are expensive and therefore choosing the right filter is important for the engine to last longer. Synthetic filters trap small particles over long periods of time and service intervals. Some synthetic filters include blends of rubber which are designed to last longer. Synthetic oil filters can last for 40 000 km between changes when compared to the more common 15 000 km change interval.

2.1.3 Importance of rubber applications

Rubber compounds are used in challenging applications such as extremely high temperatures or extremely low temperatures and overdue service interval changes. Complicated design methodology, new compounding practices and new materials have been introduced to fulfil the demand for enhanced performance and because of the increased harshness of service conditions on a variety of rubber products. This review emphasizes the process of failure-analysis and the various sources of failure. The key advantage of publishing areas of failure is the ability to learn from these areas and put in place appropriate countermeasures. Various examples can be used to illustrate the definition of failure, such as the rupture of an elastic band and an overdue service interval of a seal in a racing car. In the final analysis, the level of a property has to be understood to be able to define rubber failure. For example, with reference to the elastic band, the optimum extent to which it can be stretched has to be determined. With reference to the racing car, the reasonable service interval required has to be determined. A seal of a racing car may only need to be productive for the race duration whereas a road car requires extended service intervals. There may be a difference of opinion between an installer and a purchaser regarding whether or not rubber failure has taken place (Brown 2002).

A good starting point is the study of past failures to identify root causes to solve these problems. Lewis (2001) illustrates various rubber product failures by highlighting failures such as polybutene piping in hot water systems, acetal fittings and polyester TPE seals in radiators. If defective rubber products are used, high failure rates are to be expected. This can be minimised by vigilant quality control and meticulous testing in the design and prototype period. The necessities to conduct failure analysis are to correctly observe evidence; to collect facts and to have sufficient knowledge of the properties and behaviour of the material. Brown (2002) provides a basic example of failure analysis which is a rubber hot water bottle that has split, and which gave the appearance, after analysis by visual examination, of extended use. However, it was only a few weeks into its service life. The test bottle was cut open and appeared to be in immaculate condition. The technologist was aware of the general trend of oxidation of rubber resulting in the degradation of rubber hot water bottles which is accelerated by heat and trace metals present in water, and this prompted further inspection of the inside of the bottle. This analysis and conclusion did not consider the use of the bottle by the end user which resulted in an incorrect diagnosis. It was discovered that the bottle returned was being filled with cold water and heated in a gas oven which resulted in rapid deterioration of the bottle. This was only picked up due to a policy put in place by the supplier of further examining goods returned more than twice which prompted a complete study. This establishes the point that emphasis must be placed on the requirements stated earlier of preventing failure with tests being arranged accordingly (Brown 2002).

The characteristics of rubber can change due to various environmental influences which can cause the rubber material to fail and not fulfil its function. In many industries the service life of rubber components is vital and therefore it is important to have knowledge of how long the rubber will last. One of the key factors to note is temperature effects on rubber, where high temperatures may result in differential thermal growth issues and where low temperatures may result in loss of sealing capability and elasticity. Rubbers are also exposed to factors such as creep, chemical attack, stress/relaxation and fatigue. Failures of degradation, softening, extrusion, hardening, cracks and fracturing may occur. These factors are linked to the type of aging that may occur. Temperature is associated with thermo-oxidation; cross-linking and additive migration; ultraviolet light to photo-oxidation; ionising radiation to cross-linking and radio-oxidation; humidity to hydrolysis; fluids to swelling; cracking, chemical degradation and additive extraction; and mechanical stress and pressure to fatigue; stress relaxation and creep. Tests carried out to determine the service life of rubbers include the acceleration of the thermally induced chemical variances in the material by increasing the temperature. This method is used to determine the effect of temperature on property changes. Physical properties of the rubber are likely to change after accelerated or natural ageing. The observations of those changes are crucial and require physical tests to be conducted (Brown 2000).

Seals are important as field failures are usually a result of leakages. The reliability and durability of a system is greatly impacted by the rubber O-ring. Leakage takes place when the applied oil pressure is greater than the contact pressure. A study referred to as finite element analysis is used to determine the mechanical properties of rubber. This study conducted takes into account finite element analysis incorporating time dependence. This method is used to investigate the degradation of rubber. The degradation of rubber materials is the main cause of O-ring leakages over particular time frames and therefore the correct rubber should be selected for particular applications and time frames to prevent leakages (Zeng 2013).

2.1.4 Studies conducted on rubber

Gas and oil fields make use of rubber O-rings for sealing purposes. Sour gas field developments have shown the impact of high temperature, pressure and increasing amounts of steam and acid on the accelerated ageing of rubbers. Accelerated ageing of rubber can result in seal failures. Seal failures can cause gas leaks thereby threatening the safety of gas production and employees. Tensile properties, compression set and hardness are the core performance indicators of O-rings.

Elongation and tensile strength are key properties. Sealing proficiency of O-rings after extended service intervals are measured by conducting a compression set. Values of a compression set indicate the extent of corrosion damage. The lower values show less extent of corrosion damage. Studies have been conducted on the effect of fillers, shapes and content of carbon black on the characteristics of rubber. The effect of environmental factors has been included. Isothermal compression stress relaxation methods have been used to determine the lifetime of rubber in air environments. Studies have been conducted on nitrile butadiene rubber to determine the effect of hydrogen gas exposure at a specified pressure. Such tests have indicated that the rubbers without fillers have a more prominent effect (Zeng, 2016).

Kwon et al. (2014) conducted a study on engine head gaskets manufactured from polyacrylate with chlorine cure sites. Carboxyl cure sites were used to increase the lifetime of the rubber gasket. Testing was conducted using a method referred to as the highly accelerated life test which was conducted between temperatures of 150 °C and 180 °C using a compression rate of 25 %. The highly accelerated life test identifies design weaknesses by accelerated degradation of rubber. Development costs are reduced by using this method as it improves product reliability. The Arrhenius model is more effective to predict lifetime than the Eyring model. When the compression rate is 25 % for extended time frames and the recovery rate is equal to the target value of 60 %, the lifetime of the rubber gasket can be determined. Most studies do not include obtaining a recovery curve. In this study linear regression for the Arrhenius plot was conducted to deduce the lifetime at a specified temperature. The degrees to which each regression model differed from the experimental data were determined. Both carboxyl and chlorine cure sites showed similar results. In terms of service intervals, the carboxyl cure sites were more effective than the chlorine cure sites.

Rubbers are important for sealing. They can be classified into three forms, namely, natural rubbers, synthetic rubbers and a blend of natural and synthetic rubbers. Natural rubbers are mediocre when compared to synthetic rubbers when considering thermal stability and resistance to petroleum commodities. Kwon, Jun and Song (2015) conducted a lifetime analysis of a methyl vinyl silicone rubber (VMQ) automotive radiator gasket. Up until now the general material used has been ethylene propylene diene monomer (EPDM). Commonly three methods are used for lifetime predictions of rubber gaskets. The most effective method is referred to as the highly accelerated life test. This method is practical and applies temperatures higher than the service temperature over a shorter period. The highly accelerated life test was conducted on VMQ at temperatures between 150 °C and 200 °C with a 30 % compression set, and at -70 °C with a 30 % compression set. The reason to test VMQ was to improve the lifespan of the gaskets. The recovery rate curves for VMQ were generated using the successive zooming genetic algorithm. Results were comparable.

Lv, Wang and Wang (2015) conducted an experiment in which samples with two different acrylonitrile weights (18 wt% and 41 wt%) were exposed to cyclohexane to investigate wear and static swelling. The interaction between wear and swelling induced ageing was investigated to determine the wear mechanism of nitrile in cyclohexane at different loads. Results indicated that increased swelling times deteriorated the surface properties of nitrile. The wear volume of the swollen nitrile lowered the shearing strength which resulted in a higher wear volume of the swelled nitrile compared to the original nitrile. Results of the lower load showed that the wear loss was low and results of the higher load showed that the wear loss was significantly higher. The 41 wt% sample depicted superior wear resistance and swelling induced ageing to cyclohexane due to the 41 wt% sample having a higher crosslink density.

Zhu et al. (2015) investigated the compatibility of nitrile butadiene rubber to biodiesel when nine fuels were tested. The fuels consisted of waste cooking oil methyl ester, diesel fuel, soybean oil methyl ester, palm oil methyl ester, methyl palmitate, methyl oleate, methyl stereate, and methyl laurate and ethyl oleate. The static immersion test was used to conduct this experiment. The structures of the nitrile butadiene rubber were made to be similar to an actual product. The immersion test was consistent for each fuel and was conducted at a room temperature of 25 °C for 168 h. The samples' characteristics were measured before and after the immersion test to determine changes in mass, volume, tensile strength, tearing strength and elongation. The changes in mass, volume and mechanical properties of the nitrile butadiene rubber samples indicated that biodiesel was less compatible than diesel fuel. The results showed that soybean oil methyl ester caused the largest increase in mass when compared to the other biodiesel compounds.

The rigidity of seals when used in relation to dangerous product containers is vital and some require extended service intervals to prevent leakage to maintain safety. An ageing experiment was conducted on compressed and uncompressed hydrogenated nitrile butadiene rubber (HNBR) and EPDM seals to study the effect of seal properties during ageing. The aged samples underwent hardness, compression stress and relaxation and compression set tests. The rubbers were exposed to 100 °C to 150 °C. Results indicated that both EPDM and HNBR show increased hardness with ageing time and temperature which could be due to crosslinking reactions, higher polarity due to oxygen incorporation, and plasticiser loss. HNBR resulted in higher hardness increases which can be confirmed in results of testing which produced an effect after 10 days at 125 °C and 150 °C compared to 100 days at 150 °C for EPDM (Kömmling, Jaunich and Wolff 2016).

2.1.5 Rubber testing

The tensile stress/strain property test determines various valuable parameters such as elongation, stress at given strain, strength, and work to rupture. Rubber specifications often include tensile stress/strain characteristics. ISO 37 is normally followed when determining tensile stress/strain properties. Hardness tests are commonly performed for the purpose of quality control. ISO 48 is normally followed. Shore instruments make use of a spring for a force to be applied. The measure of stiffness is defined as hardness and can be associated with Young’s Modulus. Hardness tests, which are cheap, simple and non-destructive, are commonly used to measure degradation. Stress relaxation tests are performed by measuring compression and tension. The accelerated ageing properties of rubbers are determined by stress relaxation measurements in tension. The test entails observing the stress in a rubber sample while exposing it to an accelerated ageing procedure. There are two techniques, one which entails continuous relaxation where the sample is stretched during the test, and the other which is intermittent relaxation where the sample is stretched for short intervals to take measurements. The stress decay in continuous relaxation gives degradation measurements. Intermittent relaxation provides the total effect of cross linking and degradation measurements. Continuous measurements do not cause any new stress with the formation of new networks as it is in equilibrium with the main network. An intermittent measurement is when the stiffness changes over time frames. ISO 6914 is generally followed when practicing continuous and intermittent methods. Compression stress relaxation is commonly performed for sealing applications. The sealing force is observed. In this test continuous relaxation is generally used and the test is focussed on sealing rather than ageing resistance. Rubber samples are often exposed to liquids to determine sealing performance. ISO 3384 is generally used to determine stress compression relaxation. Compression set involves the level of set which is dependent on the period taken for the rubber sample deformation, the period for the rubber sample to recover and the test temperature. The test involves applying a compressive force to cylindrical disks generally at a fixed strain level. The formula applied is:

$$Set\% = \frac{(d_o - d_2)}{(d_o - d_1)} x100 \qquad \textbf{Equation 2.1}$$

Where d_o represents the original thickness of the rubber sample, d_1 represents the compressed state thickness and d_2 represents the thickness at the removal stage. Ageing is observed through compression set due to its importance to sealing applications. ISO 815 is generally used to determine compression set (Lv, Wang and Wang 2015).

Degradation of a rubber sample can also be determined by chemical analysis, which aids in determining its effects on physical properties. Thermogravimetric analysis (TGA) and pyrolysis gas chromatography mass spectrometry PY-GC/MS practices are generally used to assist in chemical analysis. Fourier-transform infrared spectroscopy (FTIR) is used to determine degradation of rubbers. TGA focuses on the stabilisation and degradation of rubbers. This practice records a mass change of a sample under dynamic conditions and isothermal conditions of heating. The curve that depicts weight loss highlights the stability of the rubber. Quantitative methods are used to determine the volatilisation and decomposition of the rubber sample at a particular temperature. The filler amount in a rubber sample can be established at high temperatures due to the total decomposition of the rubber sample. Organic additives are also made visible when using the TGA technique. The pyrolysis temperature peak aids in identifying the type of polymer. FTIR falls under spectroscopic methods. FTIR records surface oxidation after heat ageing or natural ageing. This is a qualitative method to measure degradation as it analyses the vibration of chemical clusters. The infrared beam sources vibrations and the radiation released is studied by the spectrometer. The FTIR is not suitable for rubbers that contain a high amount of carbon black fillers or inorganic fillers (Brown 2000).

2.1.6 Developments of rubber

The chemical composition of rubber O-rings is a source of nutrients for microbial nutrition and maturation. This chemical constitution makes O-rings susceptible to bacterial and fungal attack. Antimicrobial additives are blended into the elastomer to minimize microbial growth. The drawback to this is chemical leaching which results in certain areas being unprotected thereby diminishing the properties of the O-ring over time. A business referred to as the Specialty Elastomers of Milliken Chemical has produced a new biocide which has a trade name, Antimicrobial Alphasan. This product is used in antimicrobial rubber compounds. The rubber parts are pervaded by a silver sodium-zirconium-phosphate ion-exchange resin which is stable at a maximum temperature of 800 °C and is non-leaching. The traditional biocide deteriorates at a temperature of 250 °C. The biocide works when Ag+ ions are steadily released and interchanged for other cations. The Ag+ ions are a common non-hazardous biocide (Ondrey 2003).

A rubber compound, Fluroelastomer FKM, is a sealing material that withstands high temperature scenarios which are present in internal combustion engines of different types, has been developed by a company called Freudenberg Simirt GmbH. The material is exposed to high temperature environments which are in contact with water and oil. Research has shown that the FKM compound can withstand temperatures up to 150 °C while in constant contact with cooling water and oil. This improvement is based on the FKM O-ring which could withstand temperatures up to 125 °C and could only be in contact with cooling water. The original FKM had lead as one of its compounds. This has been eliminated in the new FKM development which promotes the environment footprint as it is deemed safe for its service life from compounding and processing to the final product, including recycling (Sealing Technology 2011).

The Atomic Weapons Establishment at Aldermaston, Reading, the United Kingdom, uses nitrile butadiene rubber (NBR) O-rings on a wide range of vessels. The Rubber and Plastics Research Association (RAPRA) has conducted work that found that if NBR is compressed for 40 years to 25 %, 80 % of its sealing ability will be lost when aged in temperate conditions. An additional study showed that the identical materials would deplete about 16 % of their sealing ability over the same time frame. This study was based on an accelerated ageing concept which shows a longer service interval when compared to normal practice. RAPRA worked with an equation that is not aligned with the normal Arrhenius method. It is referred to as the dose rate equation. A technique was used to indicate the activation energy. This technique involved oxygen intake experiments. Results showed that the activation energy for nitrile rubber was about 83.7 $kJ.mol^{-1}$ for oxygen consumption whilst the traditional methods of surface modulus and tensile elongation resulted in a value of 92$kJ.mol^{-1}$. It was concluded that the correlation indicated that the oxidative degradation of the NBR was the predominant degradative process involved. This is of importance for O-rings that are used to seal vessels from the atmosphere for long intervals (Morrell, Patel and Skinner 2003).

Kim et al. (2007) highlights the relationship between properties of rubber when exposed to service intervals and temperature by conducting a study on the forecasting of the service lifetime of NBR gaskets used in fuel cells. The material was exposed to increasing temperatures at 120 °C, 140 °C and 160 °C with time intervals from 3 h to 600 h. The materials were exposed to increased amounts of sulphuric acid which were 5.6.7 volume % and 10 volume %. Material and acid heat aging tests which were accelerated were conducted to predict the service life of the NBR compound. Critical areas investigated included tensile, hardness and elongation at break to aid in the study of acid heat aging on the performance properties of the NBR compounds. The Arrhenius model was used to determine lifetime predictions. This model can establish thermo-oxidative maturing or the nonexistence of mechanical stress and the chemical degradation of polymers. This time-temperature model was developed by carrying over an elementary chemical property to a composite, a speed invariable to a lifetime, and a concentration of chemical types to various physical properties. An end-of-life condition is used to establish the lifetimes. This is based on physical measurements which are in relation to the actual product. It is vital to establish and understand the material's properties trend curves inclusive of testing times for various experimental environments in order to determine a useful lifetime. The time used for a chemical or physical property to achieve a reliable threshold with the end-of-life measure can be defined as the lifetime of a rubber product. The endurance profile is often made with reference to an Arrhenius plot which is the relation between the absolute temperature and the lifetime. Results indicate that the hardness of the NBR compound decreases with increasing sulphuric acid concentrations and temperatures. This is clearly indicated at temperatures of 120 °C and 140 °C. This is due to the NBR compound absorbing large amounts of water when exposed to sulphuric acid for lengthy time frames and at increased temperatures. The absorption of water causes the material to swell which results in material softening. At a temperature of 160 °C, the hardness of the NBR compound decreases rapidly in a short interval at various sulphuric acid concentrations. At extended time intervals, the hardness of the NBR compound starts to augment. This can be due to the NBR compound becoming hard and brittle from the development of new cross links subsequent to acid heat aging. Figures 2.3, 2.4 and 2.5 depict the above results.

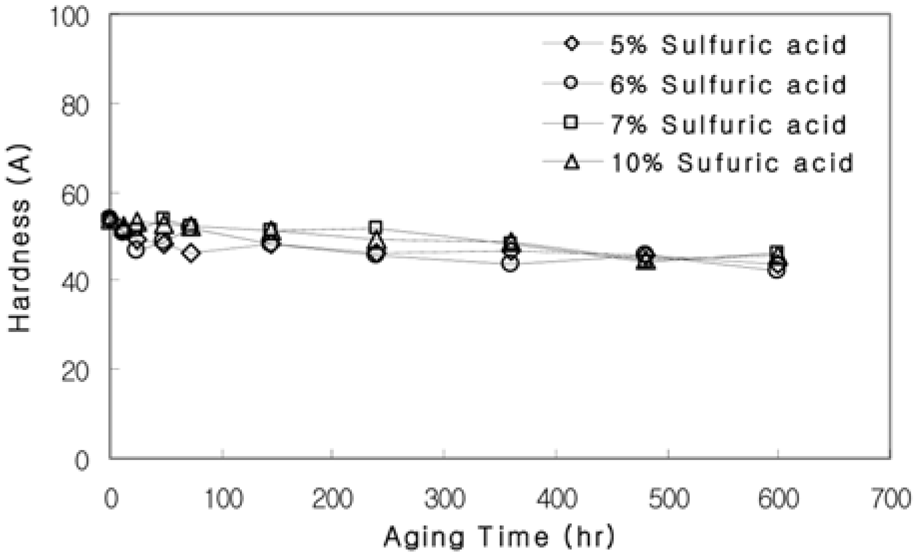


Figure 2.4: Effect of aging time on hardness exposed to different acid concentrations @ 120 °C
Source: Kim et al. (2007)

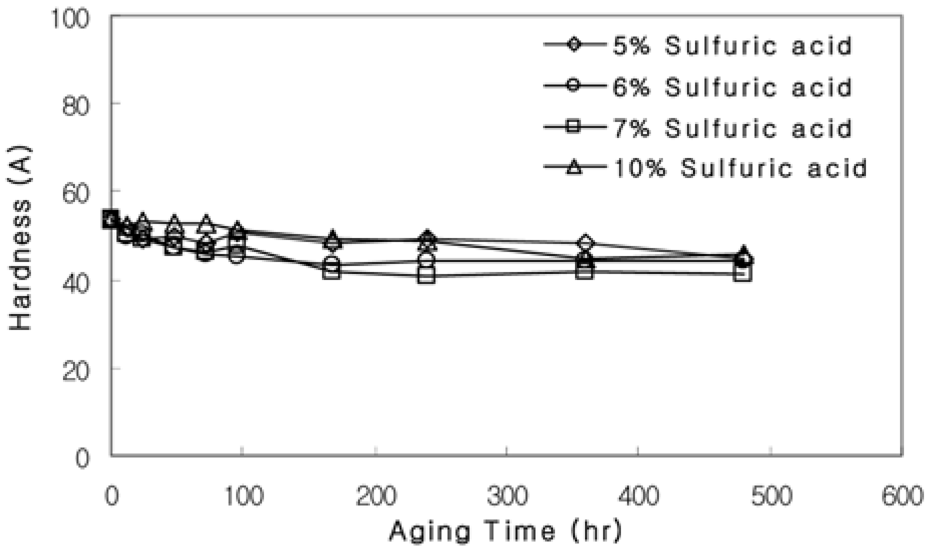


Figure 2.5: Effect of aging time on hardness exposed to different acid concentrations @ 140 °C
Source: Kim et al. (2007)

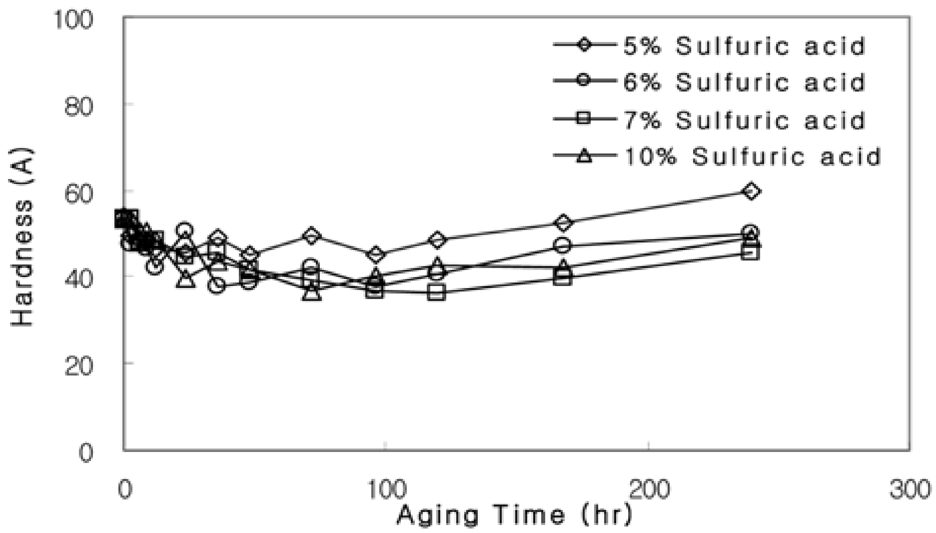


Figure 2.6: Effect of aging time on hardness exposed to different acid concentrations @ 160 °C
Source: Kim et al. (2007)

The tensile strength-aging time association is represented in Figures 2.8, 2.9 and 2.10.

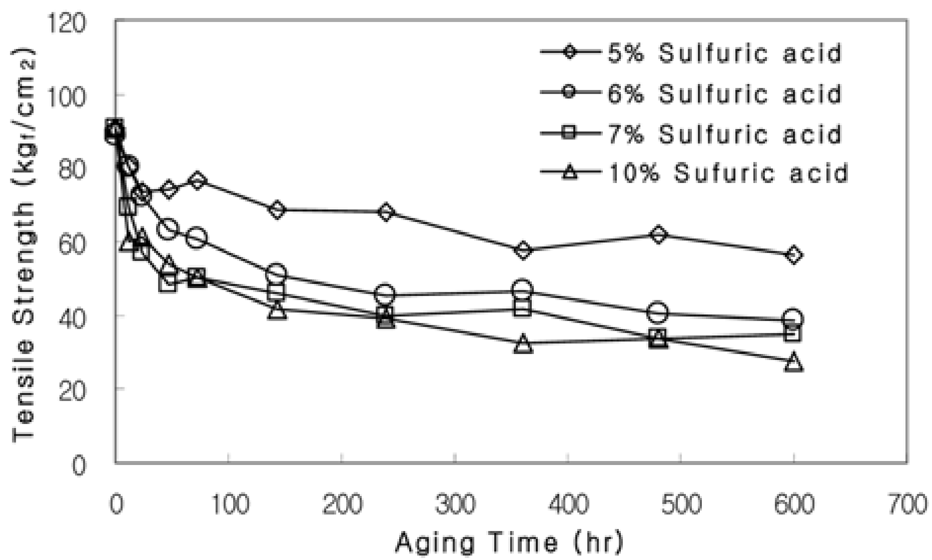


Figure 2.7: Effect of aging time on tensile strength exposed to different acid concentrations @ 120 °C
Source: Kim et al. (2007)

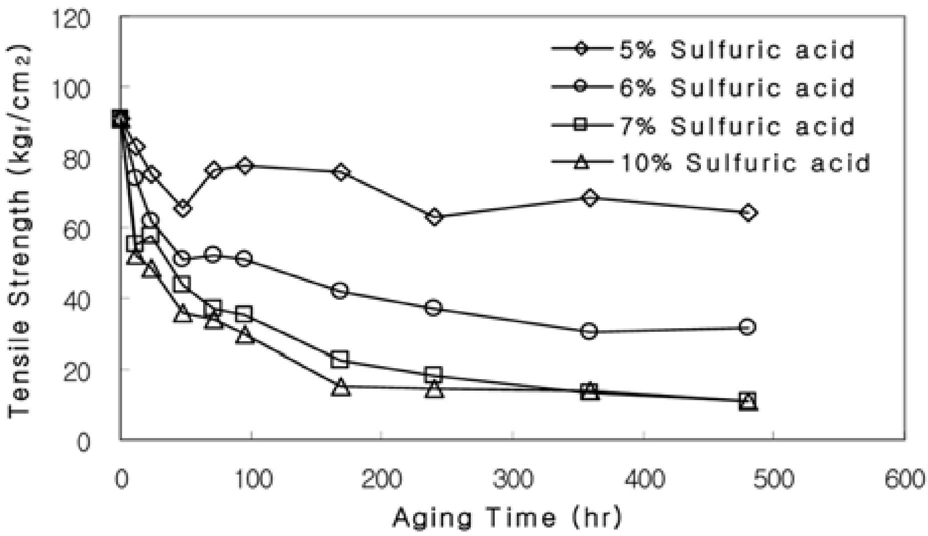


Figure 2.8: Effect of aging time on tensile strength exposed to different acid concentrations @ 140 °C
Source: Kim et al. (2007)

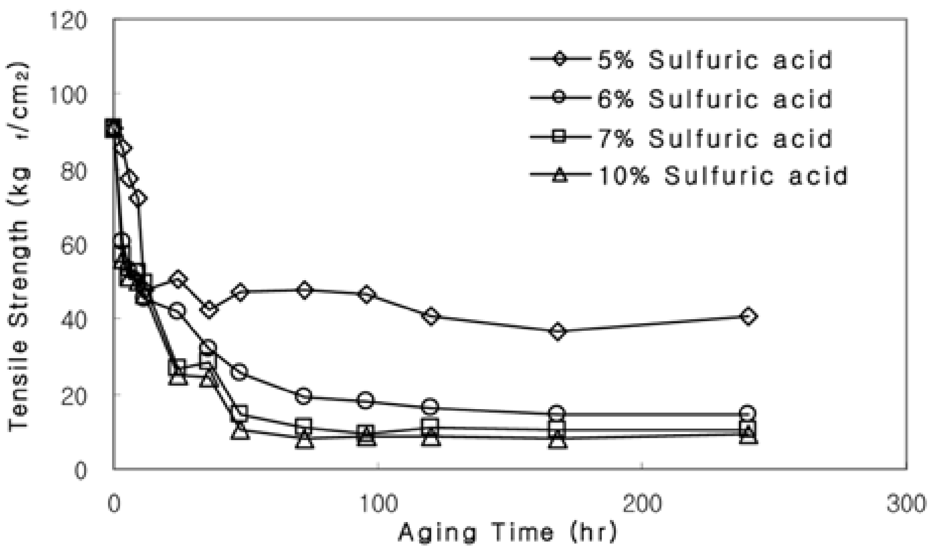


Figure 2.9: Effect of aging time on tensile strength exposed to different acid concentrations @ 160 °C
Source: Kim et al. (2007)

Results show that as temperatures increase and sulfuric acid concentrations increase the tensile strength decreases. When NBR compounds are in contact with sulfuric acid and temperature tis results in broad changes in molecular structure which is in relation with changes seen when the product is heat aged. A major function of the rubber is to stretch to numerous times its natural length. Figures 2.10, 2.11 and 2.12 depict the elongation at break-aging time association for NBR compounds.

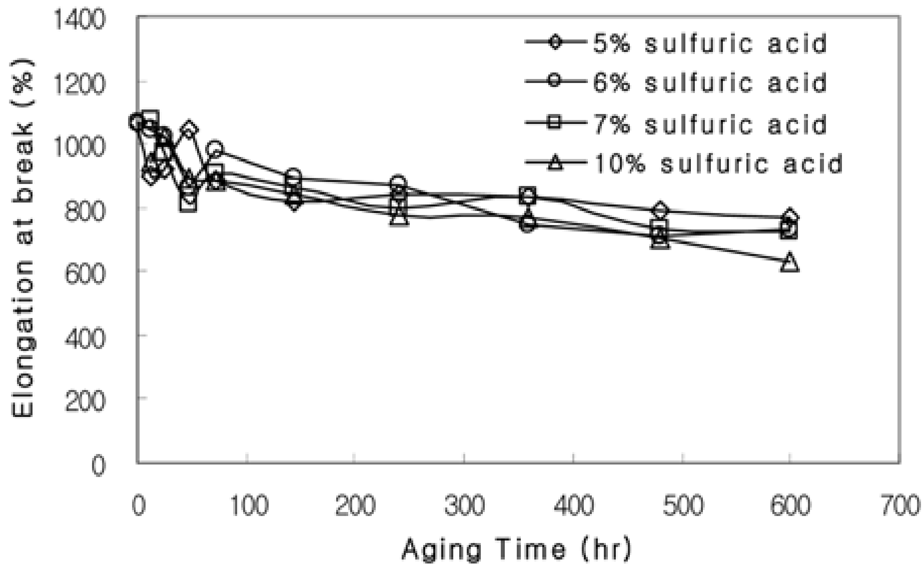


Figure 2.10: Effect of aging time on elongation at break exposed to different acid concentrations @ 120 °C
Source: Kim et al. (2007)

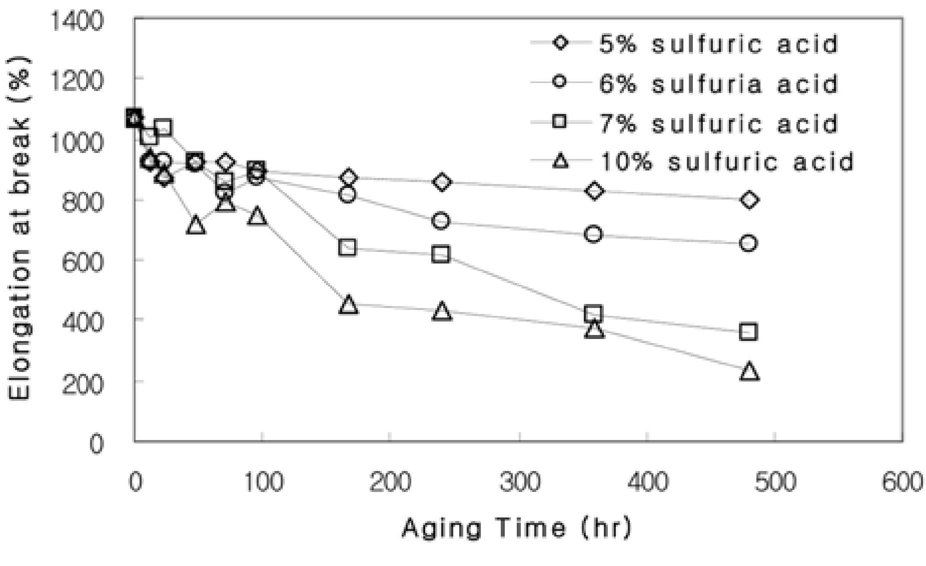


Figure 2.11: Effect of aging time on elongation break exposed to different acid concentrations @ 140 °C
Source: Kim et al. (2007)

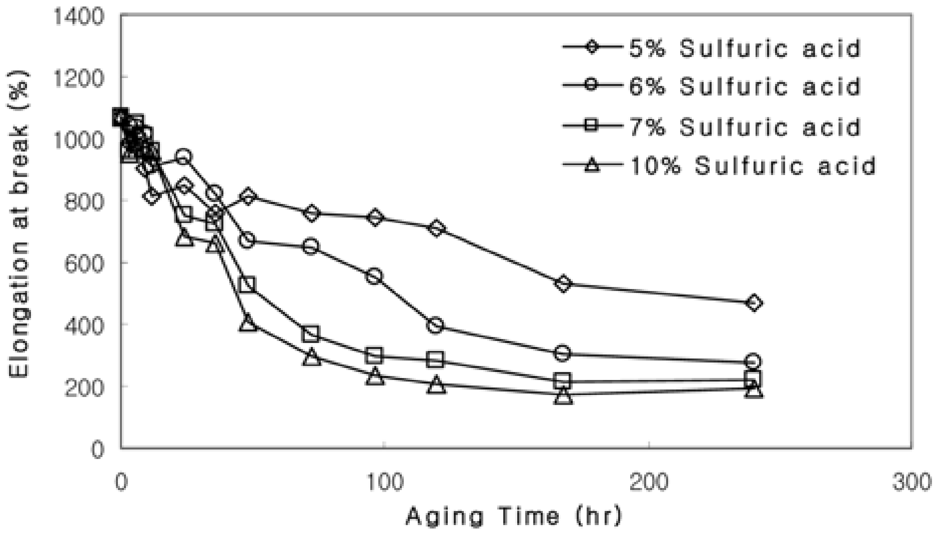


Figure 2.12: Effect of aging time on elongation break exposed to different acid concentrations @ 160 °C
Source: Kim et al. (2007)

Figure 2.12 is indicative of a decrease in elongation break as aging time increases. It is also indicative of a decrease of elongation break due to increasing sulfuric acid concentrations and temperature (Kim et al. 2007).

Choi et al. (2005) explain that natural rubber has a tendency to become hard and lose its damping potential when it is used for a lengthy period. This aging progression affects the life of natural rubber. This article presents experiments conducted relating to the aging effects on the material property of vulcanised natural rubber. Compression tests and tensile tests for natural and heat aged rubber samples were used to plot a load-stretch ratio curve to determine the aging effects on the material property. Rubber samples were test-conditioned by conducting heat aged tests conducted in an oven set at temperatures ranging from 50 °C to 90 °C for a time frame from 2 days to 16 days. Material tests conducted involved tensile tests where the deflection was depicted by a stretch ratio which is the relation of the combined length to the undeformed length. Four loadings were conducted and it was essential to use the fourth loading to depict the load-stretch ratio curve due to the first load stretch not being an accurate measurment and due to the difference in the second and first loading which is representative of a mechanical conditioning which is a stretch ratio $\lambda = 1.7$ and a mechanical conditioning which is stretch ratio $\lambda = 3$. The stretch ratio of 1.7 was used because the automobile rubber bush had a stretch ratio that was more or less 1.7 as simulated. The importance of specifying the maximum stretch ratio is sample indicative as the curve with the more mechanically conditioned sample is lower owing to strain softening. Another material test conducted was compression set. The third loading was used due to it being similar to the second loading stretch ratio curve. Friction between the loading plate and the sample results in barrelling which is avoided by applying a lubricant on the surfaces of the sample. A material test referred to as a shear test was conducted using the fourth loading and was only considered successful when the rubber sheet was not disconnected from the plastic plates. At high stretch ratios a divergence was seen. Heat aging was conducted to determine material property changes. Cyclic loading causes rubber hardening as the temperature increases. This aging results in chemical degradation and mechanical property change. Hardness is considered important when determining mechanical property changes as it is easily identifiable. Rubber has a tendency of becoming hardened when it is heated at high temperatures for lengthy periods. This can result in cracks on the surface. Three tensile samples were heat aged at 48 h, 96 h and 192 h at 90 °C. A study was carried out to determine hardness change due to heat ageing. The rubber specimens were heat-aged and measurements of hardness were taken. Tests were conducted at temperatures ranging from 50 °C to 90 °C for a time frame ranging from 48 h to 384 h. Rubber samples were heat-aged at various temperatures. It was shown that an increase in hardness occurs as the temperature or time exposure increases. The Arrhenius equation represents an inversely proportional relationship of the materials properties' logarithmic value to temperature. The hardness equation for prediction was established taking into account the time and temperature as follows:

$$k_1 = LOG\left(\frac{T}{23}\right)^{2.958}$$ **Equation 2.2**

$$k_2 = \left(\frac{t}{477.2}\right)^{0.5263}$$ **Equation 2.3**

$$IRHD = 62 \times EXP[k_1 \times k_2]$$ **Equation 2.4**

K_1 and K_2 represent the effect of temperature and time. T represents the temperature of the heat ageing in °C and t is indicative of the extent of time of heat ageing in h. The value 62 which is the constant in equation 2.4 represents the virgin rubbers hardness without ageing. Equations 2.2 and 2.3exponents were established by making use of the least squares method. Figure 2.4 to 2.6 curves are indicative of the predictions of hardness using equation 2.4. Subsequent to this, samples were heat aged at two varying conditions. Multiple samples were heat aged for 384 h at

50°C and 70°C and thereafter at 90°C for various periods. Equation 2.4 was amended to determine the hardness change in the scenario as follows:

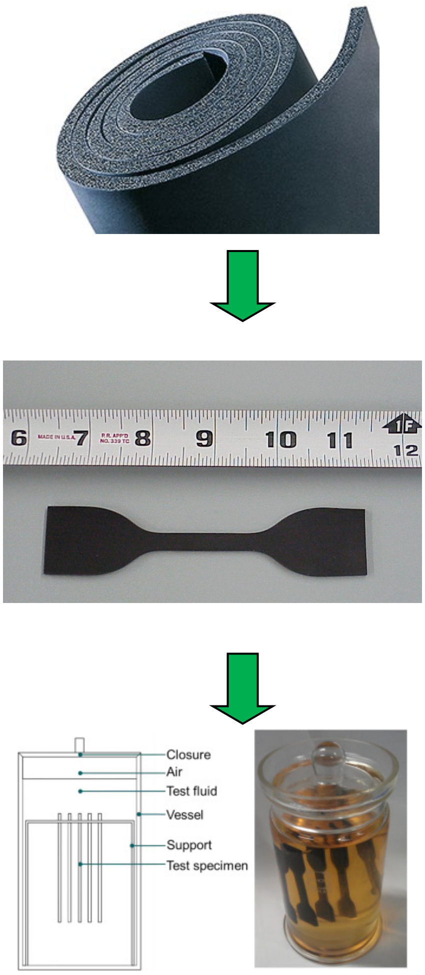
$$IRHD = (62 + K1 + K2) \times Exp[K1^{I} \times K2^{I}]$$ **Equation 2.5**

K_1 and K_2 represent the damage caused by the initial heat ageing and K_1^I and K_2^I depicts the damage due to heat ageing that has taken place after the initial heat ageing process.

Chapter 3: Methodology

3.1 Introduction to methodology

Rubber slabs were tested at suppliers and then some of these were brought in and tested as part of the current study to validate some results of the supplier. These rubber slabs were prepared and exposed to oil. These rubber slabs were put into a convection oven at temperatures ranging from 120 °C to 150 °C and time frames of 168 h to 500 h. Figure 3.1 shows a flow diagram describing the study methodology.



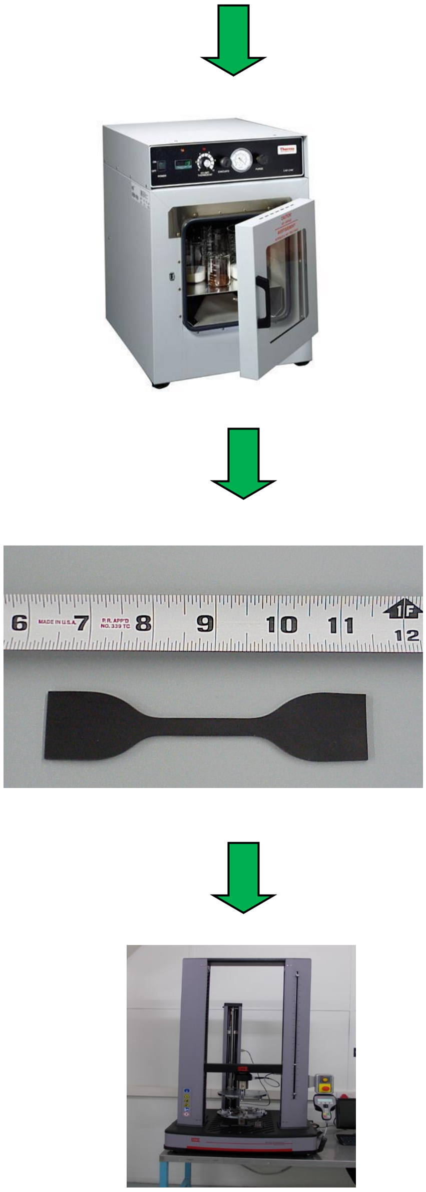


Figure 3.1: Flow diagram of the testing methodology

3.1.1 Tensile strength and elongation test method

The dumb-bells were prepared by using a 100 mm x 100 mm rubber slab. Samples are conditioned in the laboratory 24 h prior to testing. An S_2 dumb-bell cutter and a pneumatic press were used to cut test pieces to the dimensions illustrated in Figure 3.2.

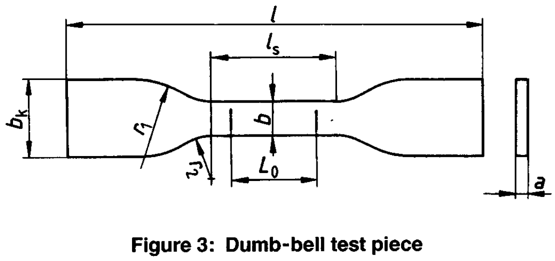


Figure 3.2: Dumb-bell test piece

Key:
Minimum overall length, l = 75 mm
Width of ends, b_k = 12.5 mm
Length of narrow parallel portion, l_s = 25 mm
Width of narrow parallel portion, b (±0.05)
Small radius, r_1 = 12.5 mm
Large radius, r_2 = 8 mm
Thickness, a = 2±0.2 mm
Initial gauge length, L_O = 20 mm

The following figures (Figure 3.3 to Figure 3.13) show images of the equipment used.

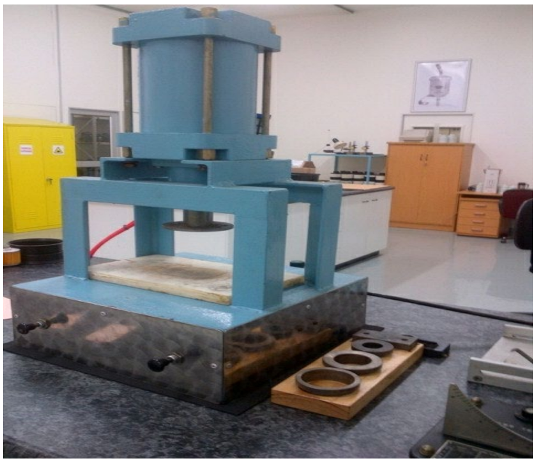


Figure 3.3: Pneumatic press

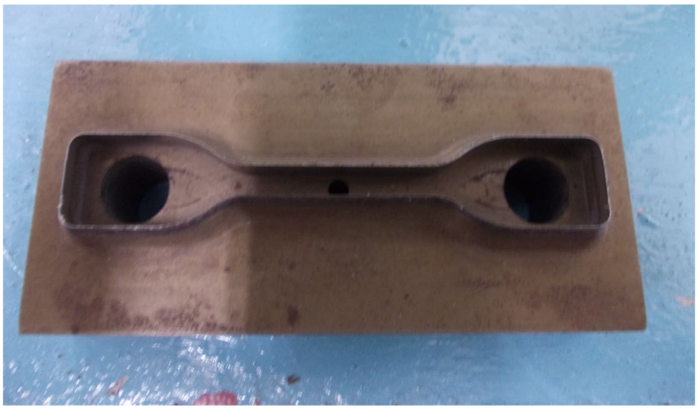


Figure 3.4: Pneumatic press

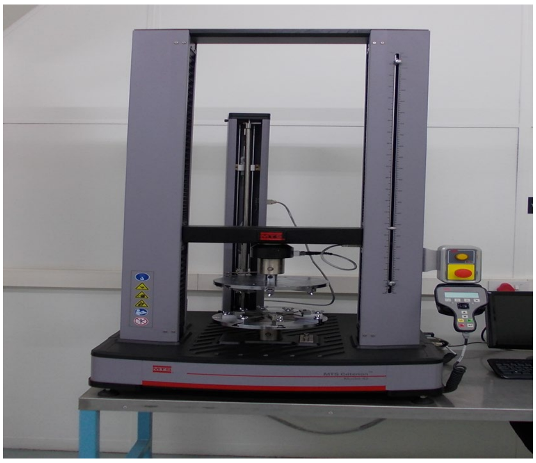


Figure 3.5: MTS tensile tester

Figure 3.6: Extensometer

Figure 3.7: Load cells

Figure 3.8: 20 mm guage block

Figure 3.9: Sample grips for cut ring seals

Figure 3.10: Vernier

Figure 3.11: Adjustable divider

Figure 3.12: Steel ruler

Figure 3.13: Sample grips for dumb-bells

Procedure:

1. A tensometer is used to attain tensile and elongation values.
2. The correct load cell is fitted onto the tensometer frame.
3. The extensometer is attached to the tensometer.
4. A 20 mm gauge block is used to set the adjustment screw rod.
5. The height and width of the sample is determined. The sample is kept straight and clamped between jig grips.
6. The knife edges are clamped onto the dumb-bell.
7. The software is opened and set to specified requirements. The material description and supplier is entered into the software.
8. The test proceeds until the sample breaks. The cross heads are returned to initial position. The tensile results are then displayed on to the screen.
9. For elongation results, dividers are used.
10. The tensometer is switched on and the correct load cell is fitted on the tensometer frame.
11. The sample is marked at 20 mm using a pen that is compatible with the material.

12. The height and width of the sample is determined.
13. The sample is kept straight and clamped between jig grips.
14. The description, supplier, height and width of the sample are entered into the software and the test commences.
15. An adjustable divider is used to follow the 20 mm mark on the sample until it breaks which concludes the test.
16. The cross heads are allowed to return to their initial position.
17. The tensile strength displayed on the screen is divided by two to attain the correct tensile strength since the area is double the original area.

Formulas that are generally used to calculate the tensile strength of a rubber specimen include the calculation of the cross-sectional area of the rubber seal or dumb bell which is determined by:

$$A = h \times t \qquad \textbf{Equation 3.1}$$

Where:

A = cross sectional area in mm^2

h = seal or dumb-bell height in mm

t = seal or dumb-bell thickness in mm

The tensile strength of dumb-bells is determined by the formula:

$$\sigma = \frac{F}{A}$$ **Equation 3.2**

Where:

σ = tensile strength in N/mm^2

F = force used to break the dumb-bell in N

A = cross sectional area of the dumb-bell in mm^2

3.1.2 Change in volume

Procedure:

This test method measured the comparative ability of a rubber test sample to withstand the effects of various liquids.

1. The test specimens are exposed to the influence of various liquids under definite conditions of temperature and time.
2. The resulting deterioration is determined by noting the changes in physical properties before and after immersion in test liquid. Dumb bell samples must be 36.6 mm in diameter and 2 mm ± 0.2 mm thick. The step-by-step procedure was as follows:
3. The test specimen is weighed in air (M_1) to the nearest mg.
4. The same specimen is weighed in distilled water (M_2) at room temperature.
5. Each specimen is quickly dipped in alcohol to remove water and blotted dry with lint free paper. Thereafter, specimens are placed in the test liquids.
6. Each test specimen is checked to ensure that it is fully immersed and does not touch the bottom or the sides of the immersion apparatus.
7. After immersion for the required temperature and time, the specimen is removed from the oven.
8. The test specimens are cooled to room temperature by transferring the specimens to a cool clean portion of the test liquid for 30 minutes to 60 minutes.

9. In the case of highly viscous liquids, the samples are removed from the warmest test agent and wiped with wood free paper.

10. In the case of volatile liquids, air evaporation is permitted for 10 seconds.

11. Thereafter the specimen is dipped quickly in ethanol at room temperature.

12. It is blotted lightly and weighed (M_3). It is then removed and weighed in distilled water. (M_4). A stoppered weighing bottle is used to weigh in air, when utilizing liquids that volatilise at room temperature. There is no need to use acetone. The specimen must be weighed within 30 seconds from removal from test solution.

The formula used for change in volume is as follows:

$$\% = \frac{(M_3 - M_4) - (M_1 - M_2)}{M_1 - M_2} \times 100$$ **Equation 3.3**

Where:

M_1 = initial mass of specimen in air, g

M_2 = initial mass of specimen in water, g

M_3 = mass of specimen in air after immersion, g

M_4 = mass of specimen in water after immersion, g

3.1.3 Change in hardness test method

Procedure:

The Shore hardness test is an indication of the decrease or increase of hardness with time, under specific temperature conditions when under stress. The test is conducted on all rubber which performs the sealing function of oil, air and fuel applications.

1. The test specimen must be at least 6 mm in thickness and must measure at least 25 mm in any lateral dimension.

2. The specimen is placed on a smooth, hard and horizontal surface.

3. The specimen is centred by applying pressure.

4. The instrument is pressed down with one finger which applies sufficient pressure which obtains firm contact with the specimen.

5. The scale is read after 10 seconds.
6. The Shore hardness is expressed as Shore A.

3.1.4 DOE software

Mineral oil and synthetic oil were used as immersion substances in tests conducted. Mineral oil is sourced from the ground where as synthetic oil is artificial and made up. Mineral oil results were used for the DOE software as the same trends were found when mineral oil results were compared to synthetic oil results. The only difference is that synthetic oil showed to be harsher onto the rubber. The DOE software was chosen as results could be inputted which would generate equations. These equations would be used to draw up graphs of predicted vs. actual which would lead to determining which rubber from a variety of rubbers was the best fit for the requirements. Results obtained of tensile strength, change in volume, change in hardness and elongations are represented in Appendix E.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter presents the results obtained from the methodology as explained in Chapter 3. The effects of temperature and exposure periods on the characteristics of the polymer are discussed. In addition, the specifications required and whether each polymer at different temperatures and exposure periods are within specification, are noted. The specifications come from car manufacturers and cannot be altered. These specifications are not drawn up internally at the chosen company. The chosen company has to work to those specifications and are not allowed provided details on how the specifications are developed.

4.1.1 Nitrile 321

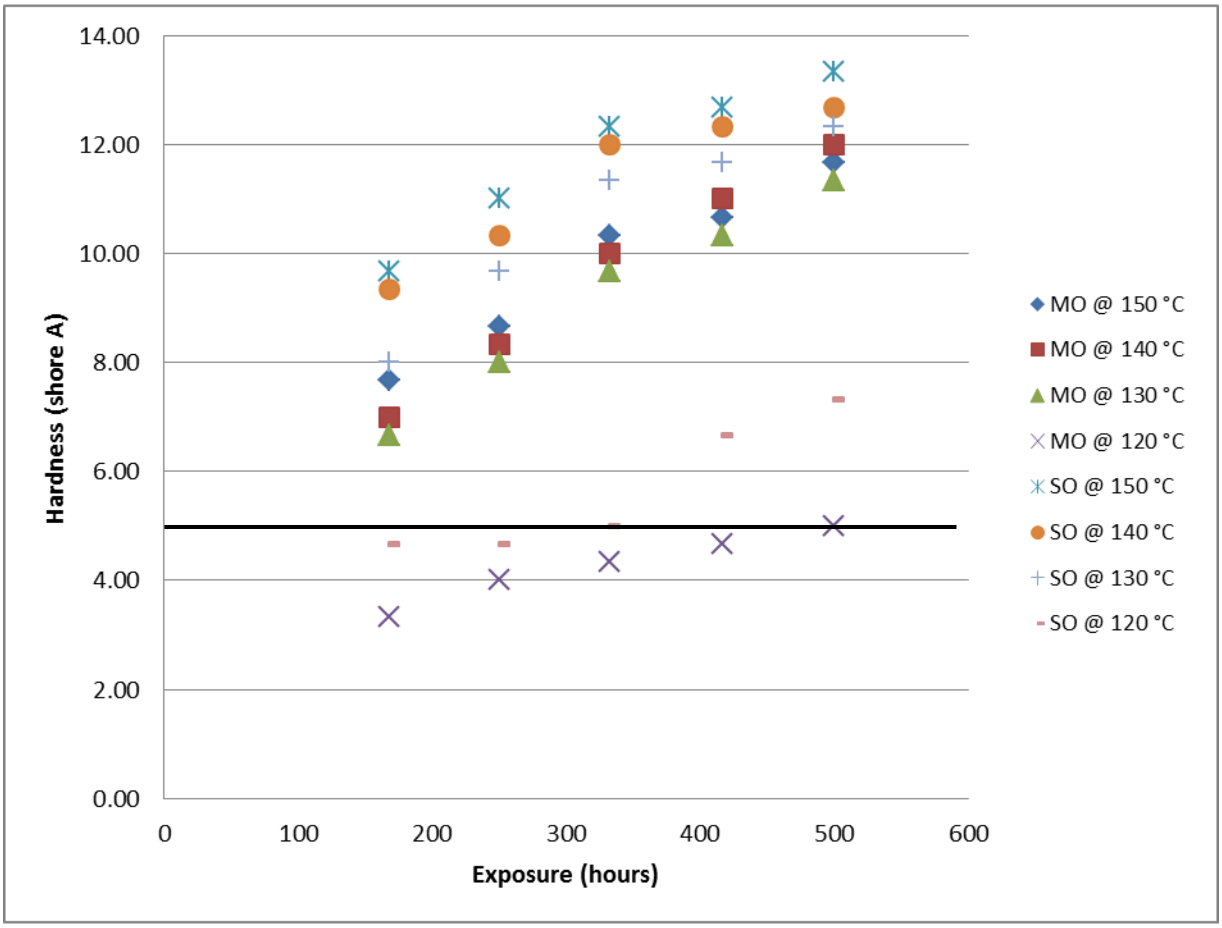


Figure 4.1: Effect of temperature and exposure on change in hardness of nitrile 321 immersed in oil

The trend shown in Figure 4.1 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. This shows that nitrile 321 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittlement which results in a harder product. This in turn puts the product out of specification according to the specifications required. The specification required is a change in hardness within the range -12 Shore A to 5 Shore A. The increased temperatures cause an increase in the change in hardness above the limits making it not fit for purpose for filtration in an automobile. Regarding mineral oil, the operating temperature for nitrile 321 for this application is 120 °C for exposure periods of 168 h to 500 h. As seen for synthetic oil, the operating temperature for nitrile 321 for this application is 120 °C for exposure periods of 168 h to 333 h.

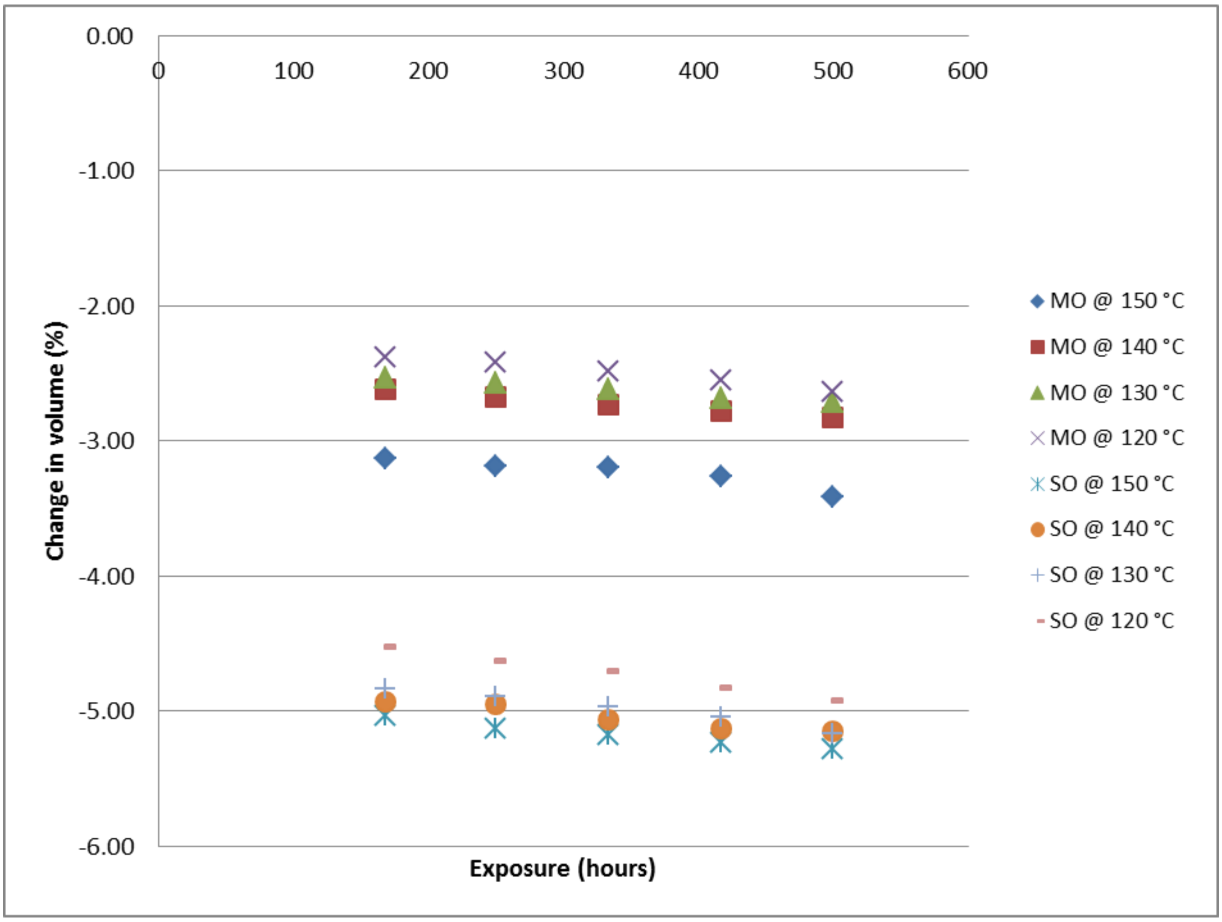


Figure 4.2: Effect of temperature and exposure on change in volume of nitrile 321 immersed in oil

The trend shown in Figure 4.2 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. The specification required is -8 % to 8 %. The degree of change in volume is minimal and is still within the specification for the required application which can be seen in the graph for mineral oil at temperatures between 120 °C and 150 °C and exposure periods between 168 h and 500 h and synthetic oil at temperatures between 120 °C and 150 °C and exposure periods between 168 h and 500 h.

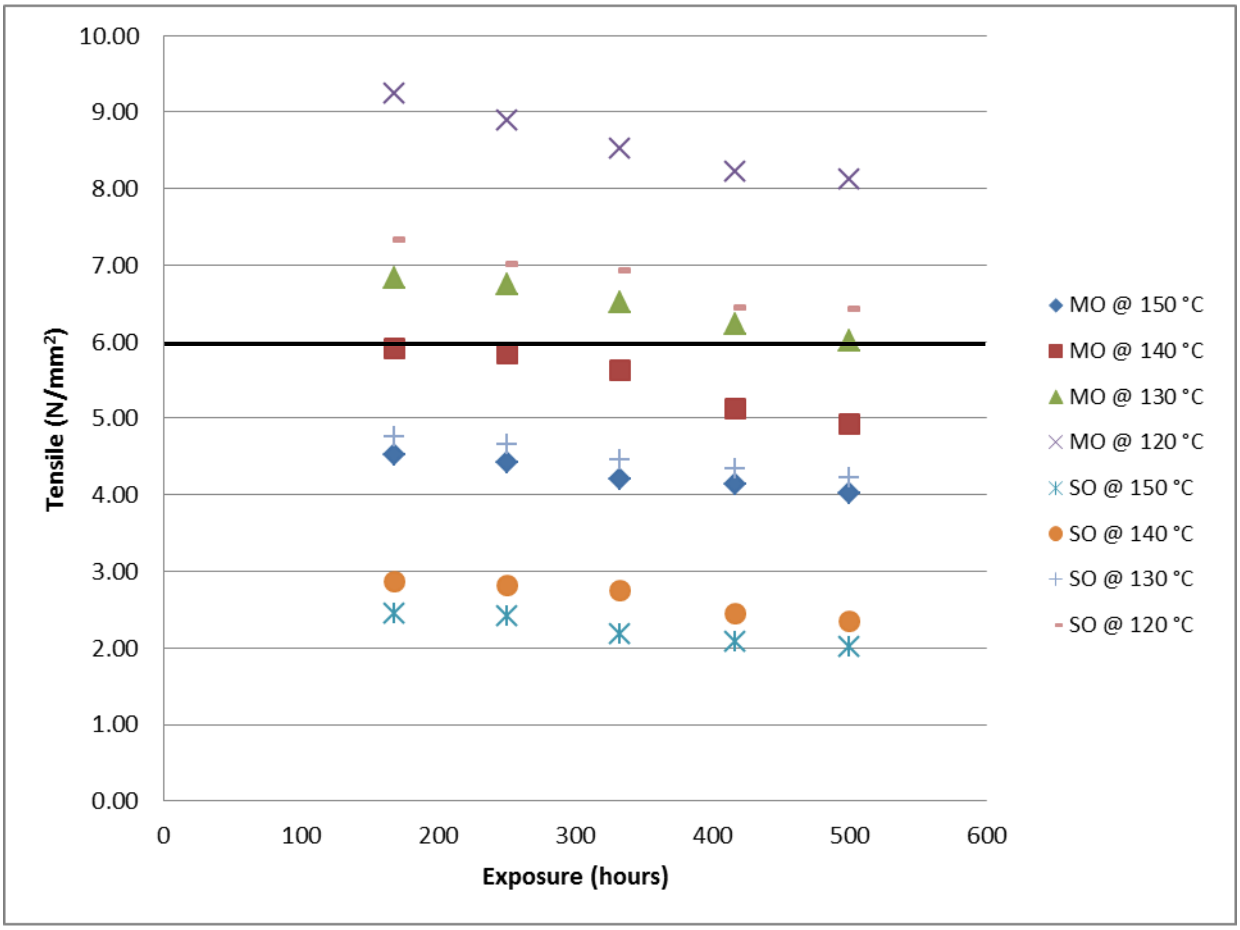


Figure 4.3: Effect of temperature and exposure on tensile strength of nitrile 321 immersed in oil

The trend shown in Figure 4.3 for mineral and synthetic oil illustrates a decrease in tensile strength as temperatures increase, and as exposure periods increase. This shows that nitrile 321 loses its strength as it is exposed to elevated temperatures. This may be due to the rubber embrittlement which results in the material being able to withstand diminishing stress while being stretched or pulled before failing or breaking. This in turn puts the product out of specification according to the specifications required. The specification required is a minimum of 6 N/mm^2. At temperatures 140 °C and 150 °C for 168 h to 500 h, the tensile strength is not within specification. At lower temperatures of 120 °C and 130 °C for 168 h to 500 h tensile strength is within specification for mineral oil and for synthetic oil. At temperatures between 130 °C and 150 °C for 168 h to 500 h the tensile strength is not within specification. At a lower temperature of 120 °C for 168 h to 500 h tensile strength is within specification. The significant impact that exposure periods have on NBR correspond with (Haroonabadi et al., 2018) as this study concludes that remarkable changes are caused by the thermal ageing process as seen in a study conducted at 100 °C for 7 days by applying varying sulphur curing systems. It also concludes that this trend could be explained by rubber properties such as tensile strength.

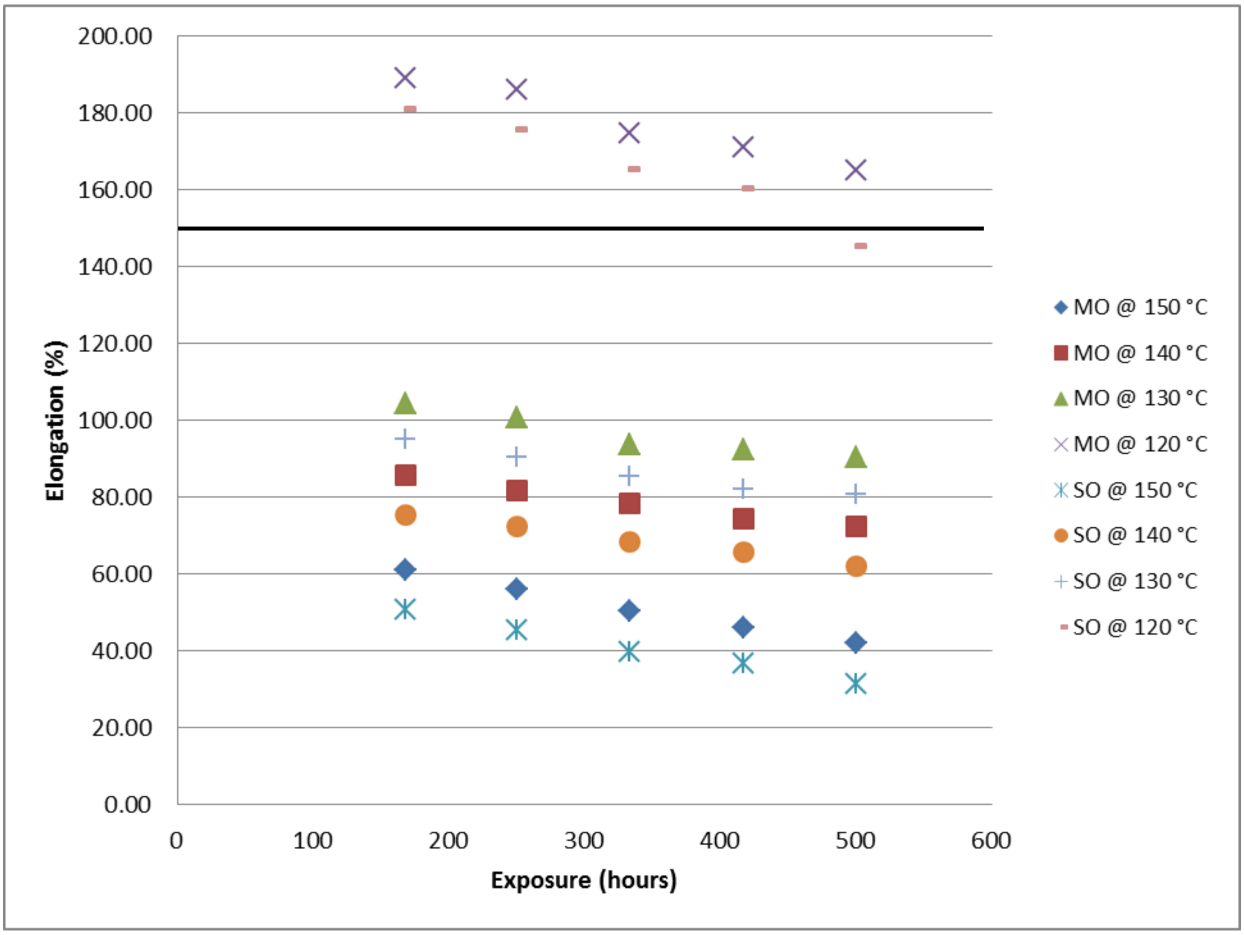


Figure 4.4: Effect of temperature and exposure on elongation of nitrile 321 immersed in oil

The trend shown Figure 4.4 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. This shows that nitrile 321 breaks more easily when exposed to elevated temperatures. This may be due to the rubber embrittlement which results in a harder product. This in turn puts the product out of specification for mineral oil and synthetic oil for temperatures that are greater than 130 °C. The specification required is a minimum of 150 % elongation. The increased temperatures result in a specification below 150 % making it not fit for purpose for automobile filtration application. As seen, the operating temperature for nitrile 321 for this application is 120 °C for exposure periods of 168 h to 500 h for mineral oil and exposure periods of 168 h to 417 h for synthetic oil.

4.1.2 Silicone 332

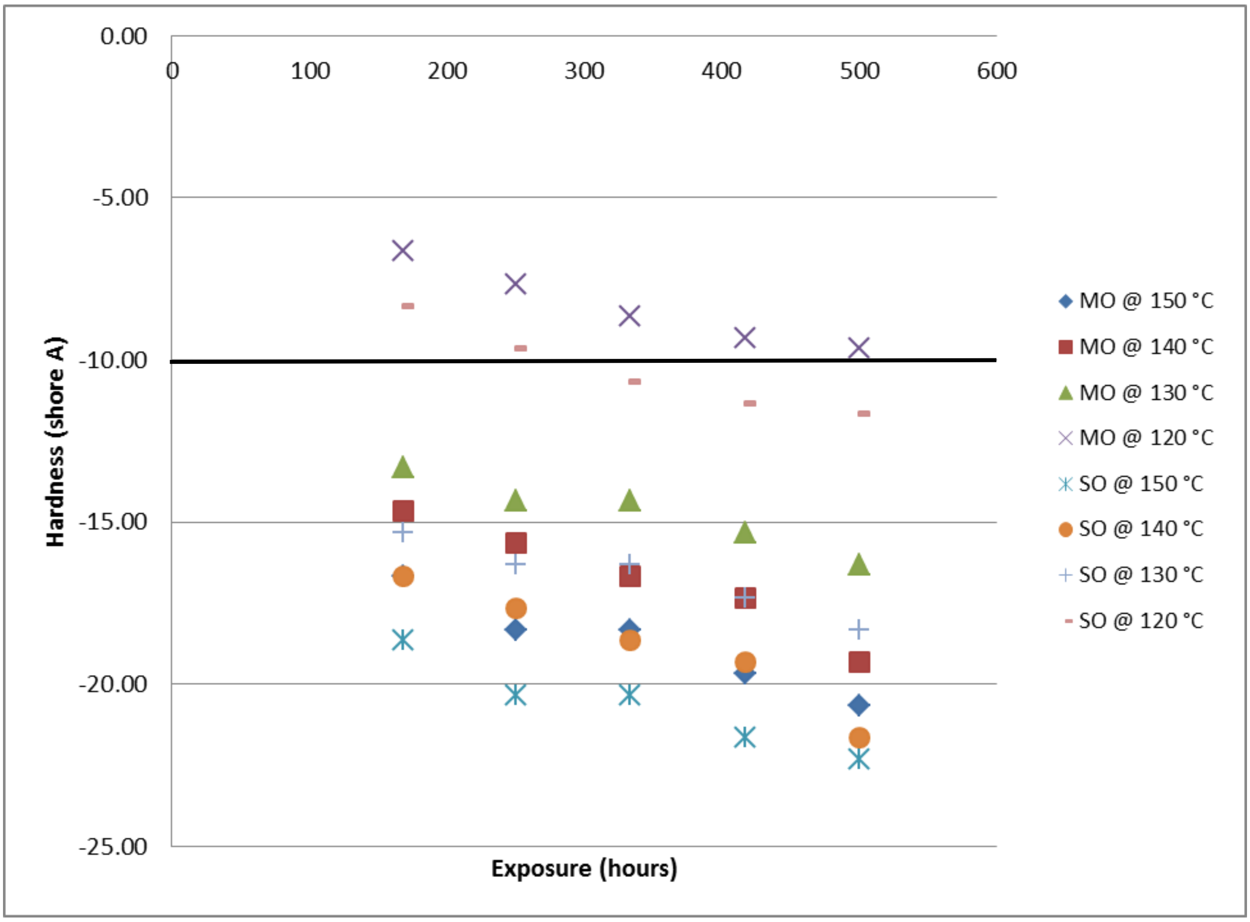


Figure 4.5: Effect of temperature and exposure on hardness of silicone rubber 332 immersed in oil

The trend shown in Figure 4.5 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. The trend of an increase in change in hardness concur with (Xishan et al 2017) as it makes mention that there is an increase in hardness of the silicone rubber when temperature cycling treatment occurs betewwen -25 °C and 70 °C. Kashi et al. (2018) adds to this by stating that hardness increased in the early stages of ageing when a study was condutced on silicone rubber to determine the effects of polyalkylene glycol at a temperature of 195 °C. This concludes that silicone 332 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittlement which results in a harder product. This in turn puts the product out of specification according to the specifications required. The specification required is -10 Shore A to 10 Shore A change in hardness. The increased temperatures cause an increase in the change in hardness above the limits making it not fit for purpose for the automobile filtration application. As seen, the operating temperature for Silicone 332 for this application is 120 °C for exposure periods of 168 h to 500 h for mineral oil and 168 h to 250 h for synthetic oil.

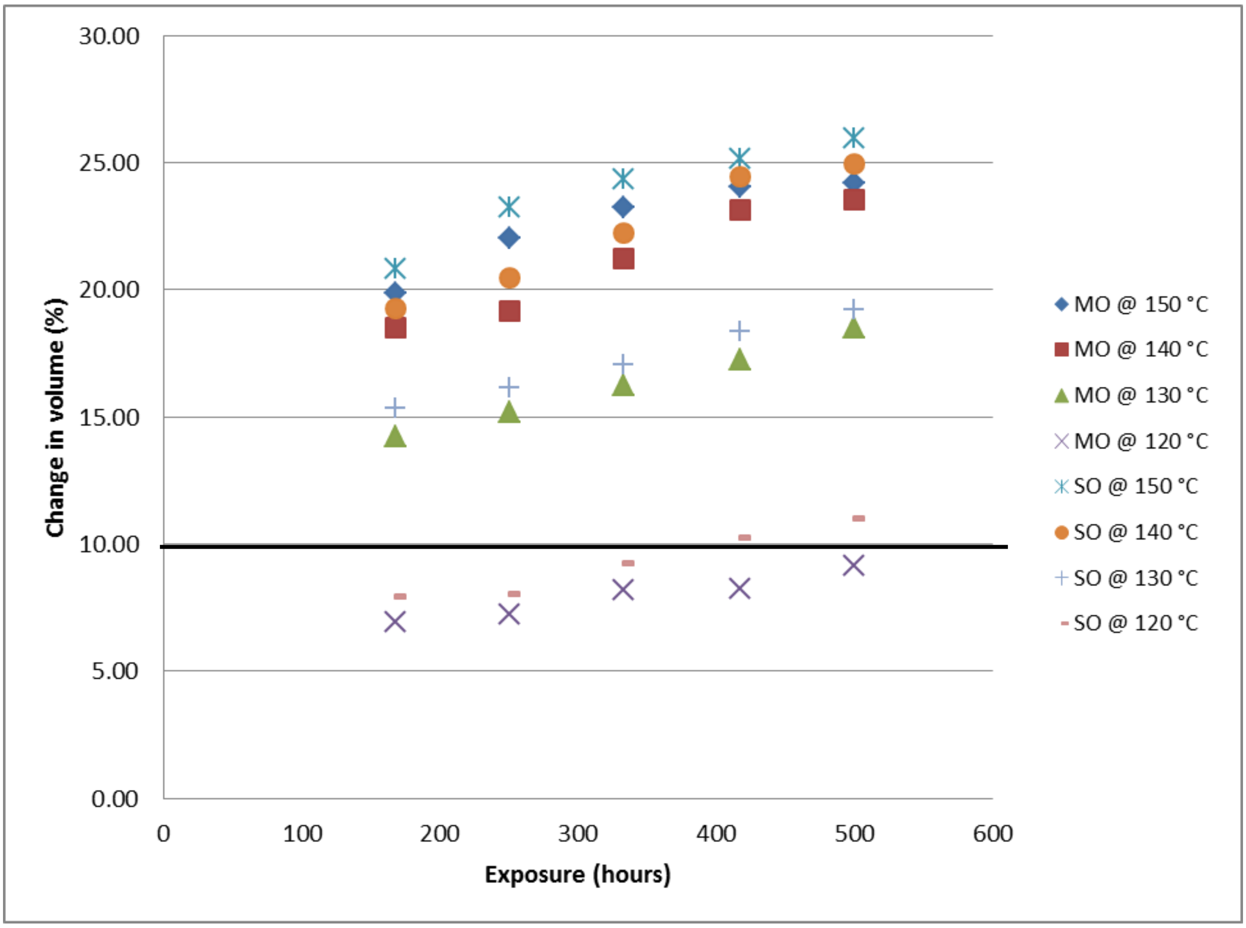


Figure 4.6: Effect of temperature and exposure on change in volume of silicone rubber 332 immersed in oil

The trend shown in Figure 4.6 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. This shows that silicone expands when exposed to increased temperatures and exposure periods. This may be due to the elasticity of the rubber. The specification required is -5 % to 10 %. The degrees of change in volume increases above the limit of 10 % therefore making it unsuitable at a temperature of 130 °C and above at 168 h to 500 h for mineral oil and at a temperature of 120 °C for 417 h to 500 h and temperatures of 130 °C and above at 168 h to 500 h for synthetic oil. The operating temperature for Silicone 332 for this application is 120 °C for exposure periods of 168 h to

333 h. The operating temperature for Silicone 332 for this application is 120 °C for exposure periods of 168 h to 500 h.

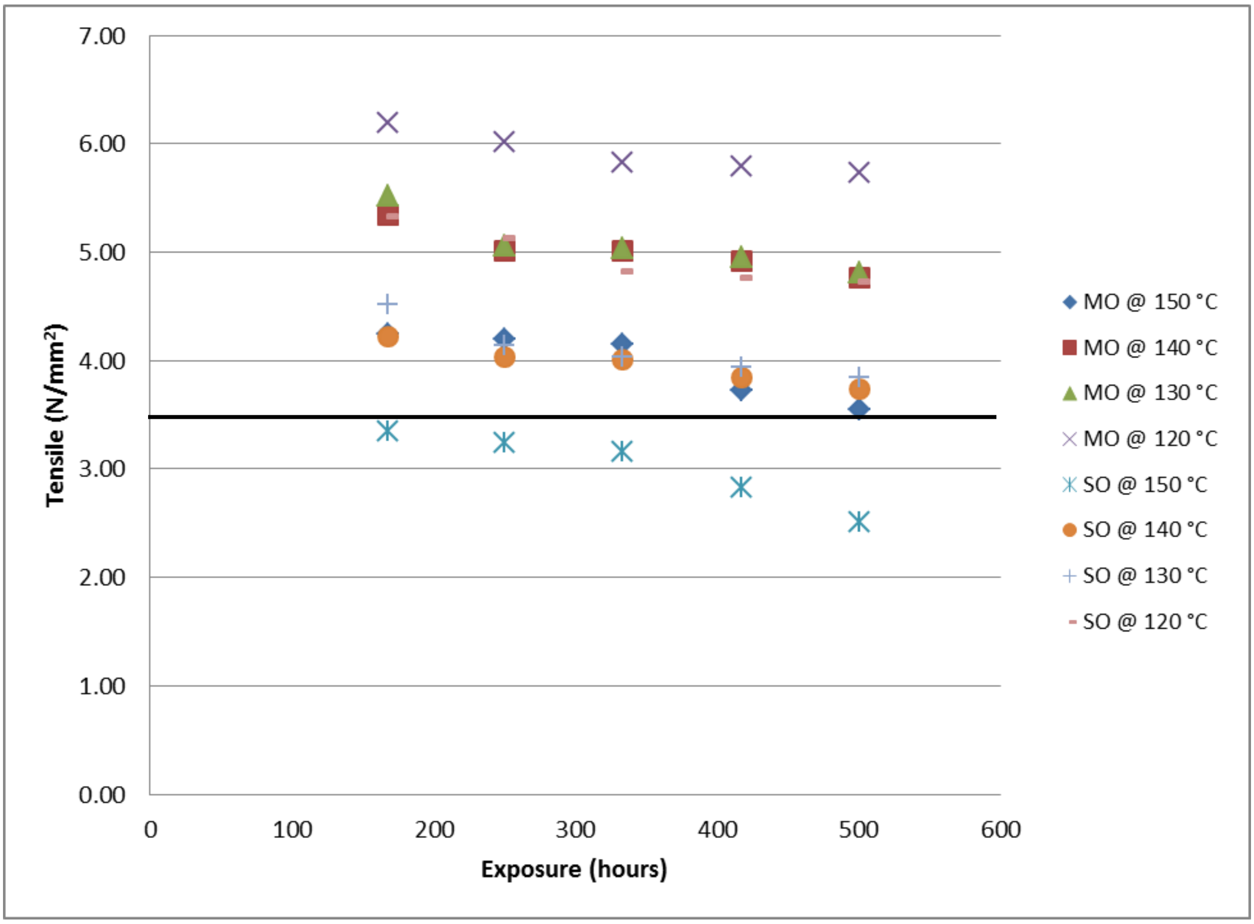


Figure 4.7: Effect of temperature and exposure on tensile strength of silicone rubber 332 immersed in oil

The trend shown in Figure 4.7 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase, and as exposure periods increase. Kashi et al. (2018) fully supports this result as when a study conducted involving an elevated temperature of 195 °C, tensile strength and elongation decreased from 7.4 MPa and 2250% in unaged silicone rubber to 1.5 MPa and 760% in 6 week aged silicone rubber, respectively. The specification required is a minimum 3.5 N/mm^2. All the values obtained were above 3.5 N/mm^2 which makes Silicone 332 within specification with regards to tensile strength for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil, and makes Silicone 332 within specification for temperatures between 120 °C and 140 °C for exposure periods between 168 h and 500 h and not within specification at a temperature of 150 °C for exposure periods between 168 h and 500 h for synthetic oil.

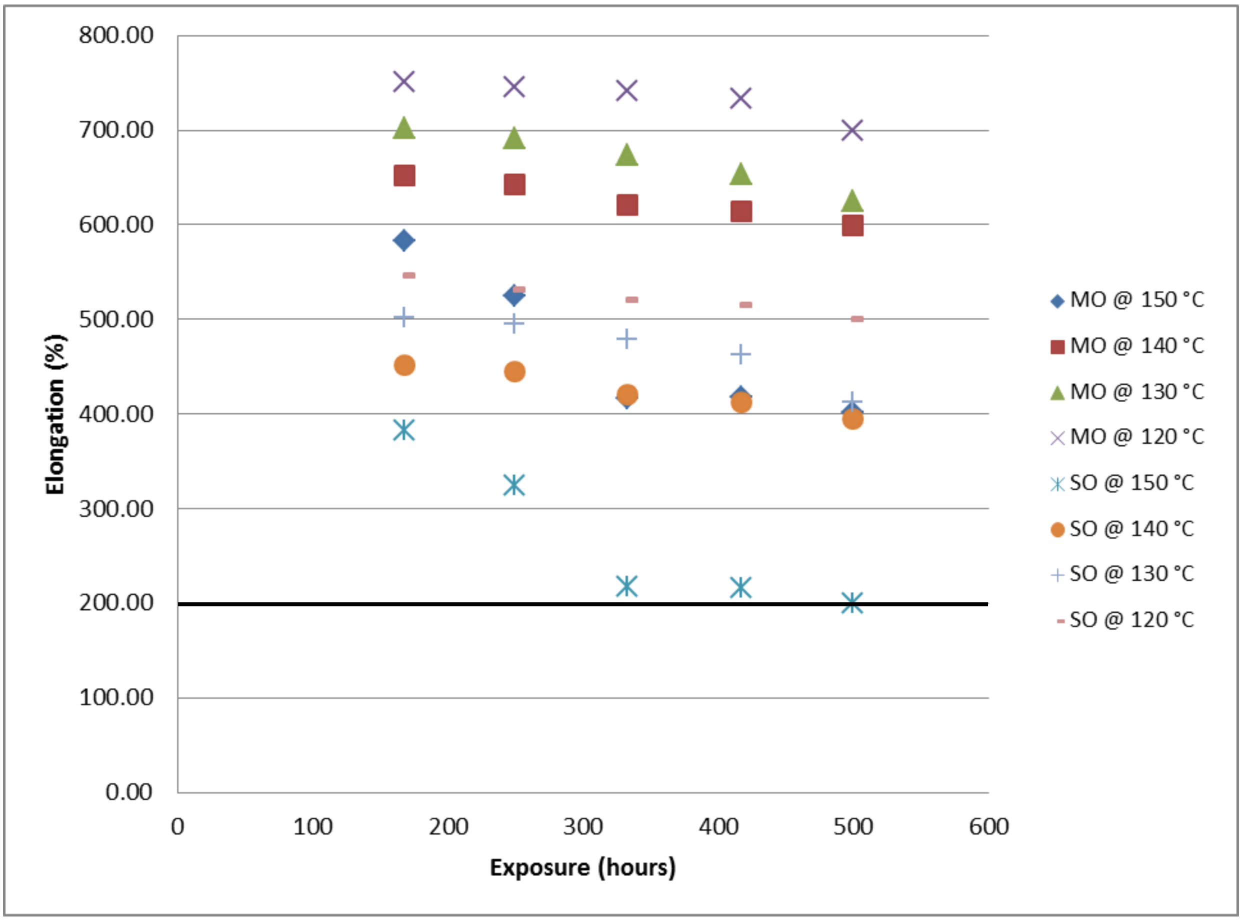


Figure 4.8: Effect of temperature and exposure on elongation of silicone rubber 332 immersed in oil

The trend shown in Figure 4.8 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. The specification required is a minimum of 200 %. All the values obtained were above 200 % which make silicone 332 within specification with regards to elongation for temperatures between 120 °C and 150 °C and exposure periods of 168 to 500 h for mineral oil. For synthetic oil all the values obtained were above 200 % which make silicone 332 within specification with regards to elongation for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h.

4.1.3 Nitrile 322

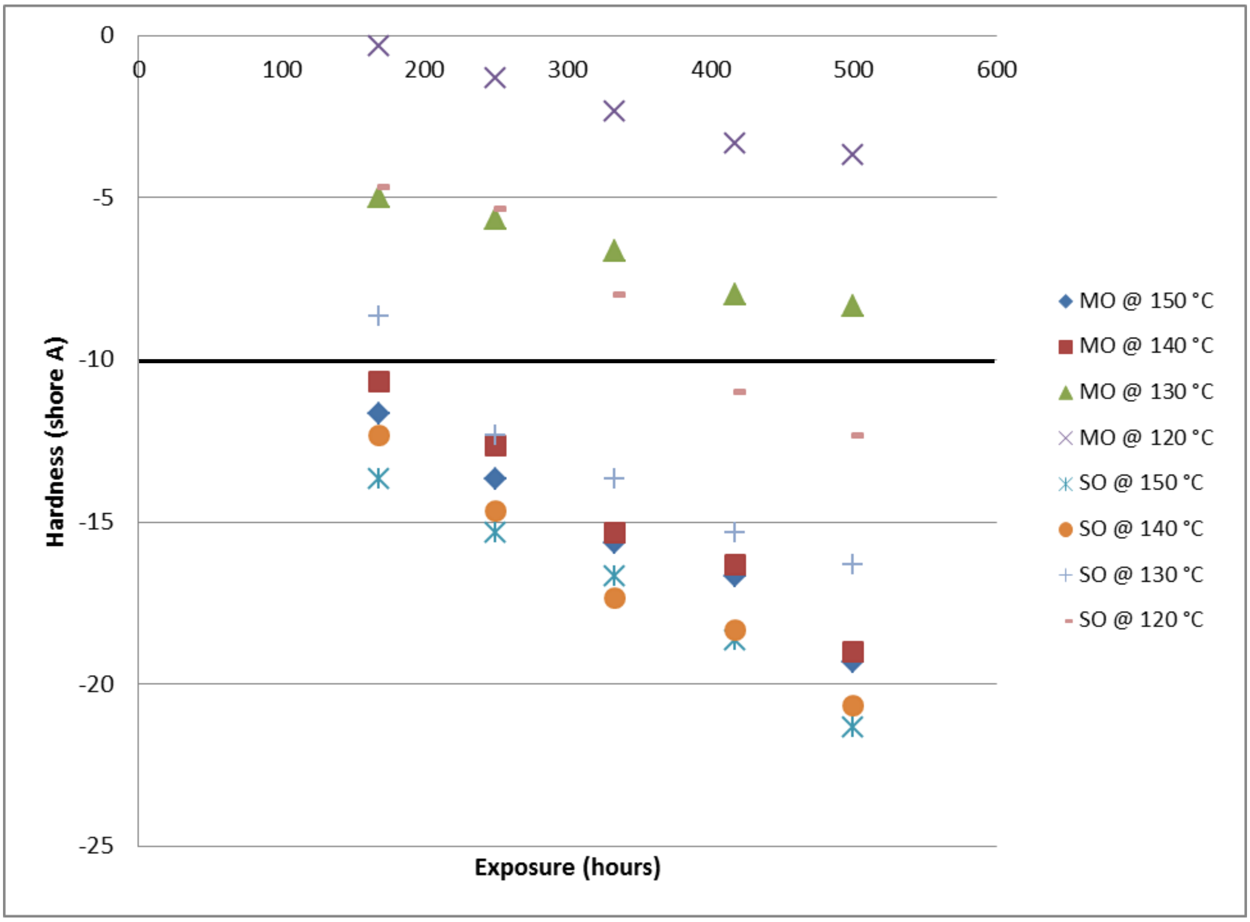


Figure 4.9: Effect of temperature and exposure on hardness of nitrile 322 immersed in oil

The trend shown in Figure 4.9 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. This shows that nitrile 322 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittlement which results in a harder product. This in turn puts the product out of specification. The specification required is -10 Shore A to 10 Shore A change in hardness. The increased temperatures cause an increase in the change in hardness above the limits making it not fit for purpose for automobile filtration application in terms of mineral oil. As seen the operating temperature for nitrile 322 for this application is 120 °C to 130 °C for exposure periods of 168 h to 500 h. Regarding synthetic oil, the operating temperature for nitrile 322 for this application is 130 °C at an exposure period of 168 h and 120 °C for exposure periods of 168 h to 333 h.

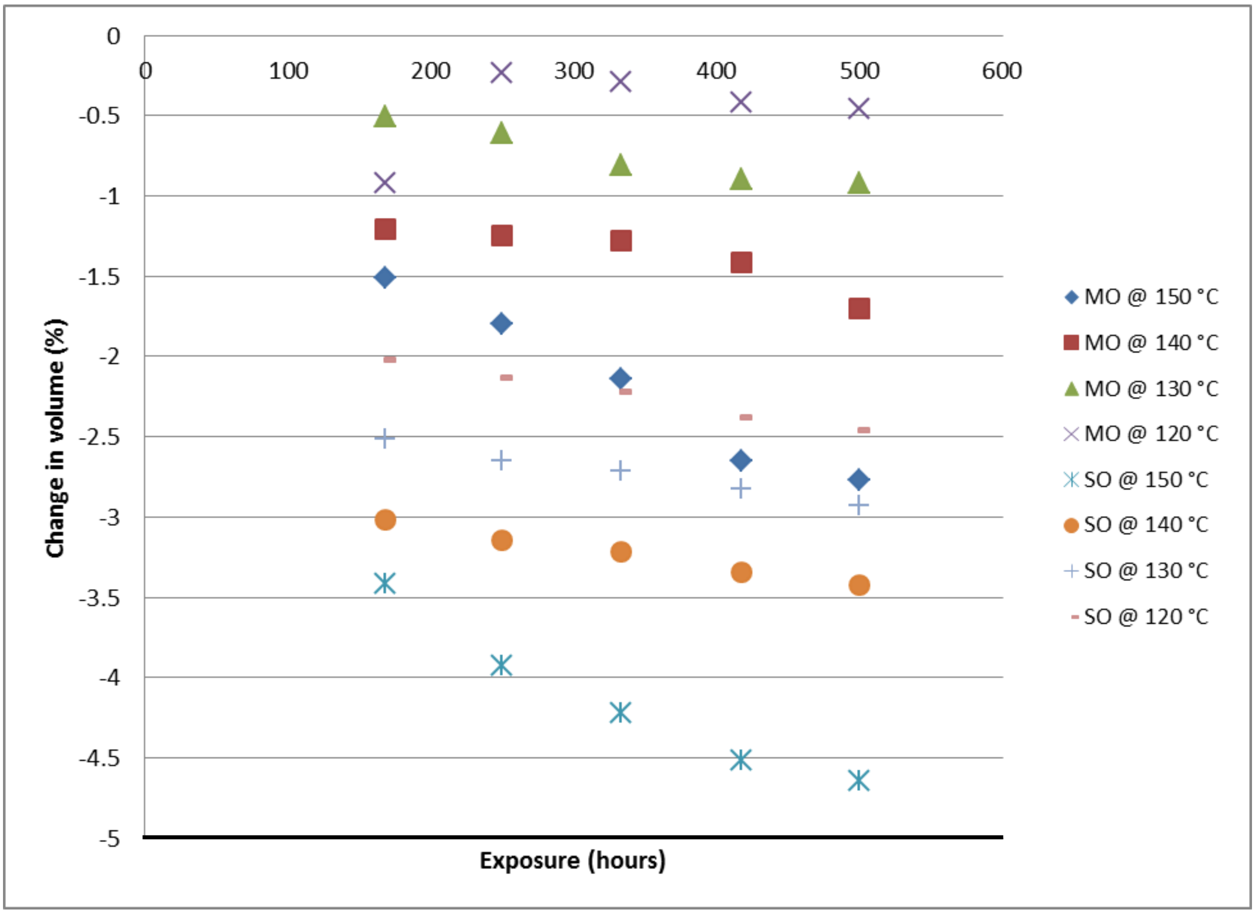


Figure 4.10: Effect of temperature and exposure on change in volume of nitrile 322 immersed in oil

The trend shown in Figure 4.10 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. The specification required is -5 % to 10 %. All the values obtained were within -5 % to 10 % which makes nitrile 322 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil and all the values obtained for synthetic oil were within -5 % to 10 % which makes nitrile 322 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h.

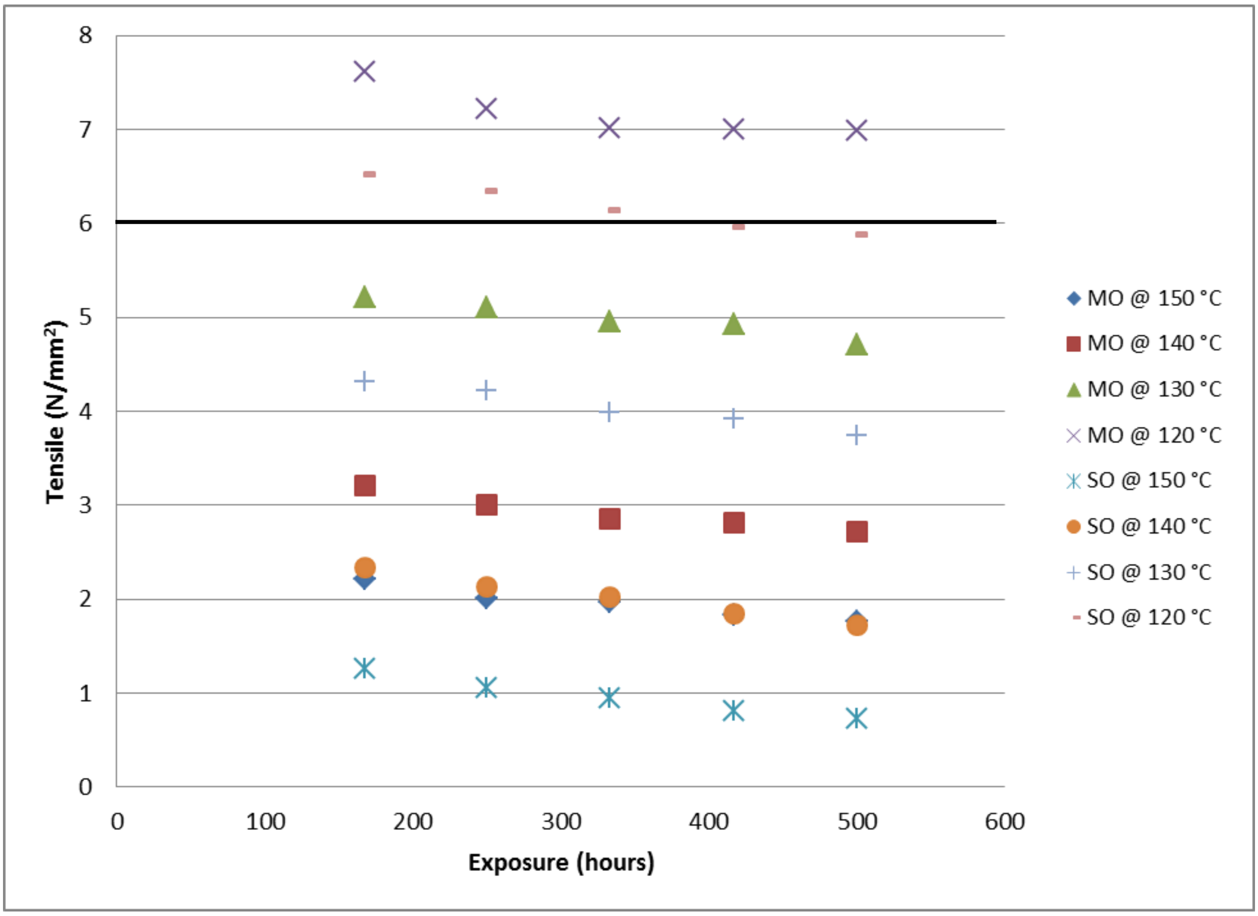


Figure 4.11: Effect of temperature and exposure on tensile strength of nitrile 322 immersed in oil

The trend shown in Figure 4.11 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase and as exposure periods increase. This shows that nitrile 322 loses its strength as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in the material being able to withstand diminishing stress while being stretched or pulled before failing or breaking. This in turn puts the product out of specification according to the specifications required. The specification required is a minimum of 6 N/mm^2. For mineral oil, at temperatures between 130 °C and 150 °C for 168 h to 500 h, the tensile strength is not within specification. At a lower temperature of 120 °C for 168 h to 500 h tensile strength is within specification making it fit for purpose for the automobile filtration application. For synthetic oil, at a temperature of 120 °C for 417 h to 500 h and temperatures between 130 °C and 150 °C for 168 h to 500 h, the tensile strength is not within specification, and at a lower temperature of 120 °C for 168 h to 333 h tensile strength is within specification making it fit for purpose for automobile filtration application.

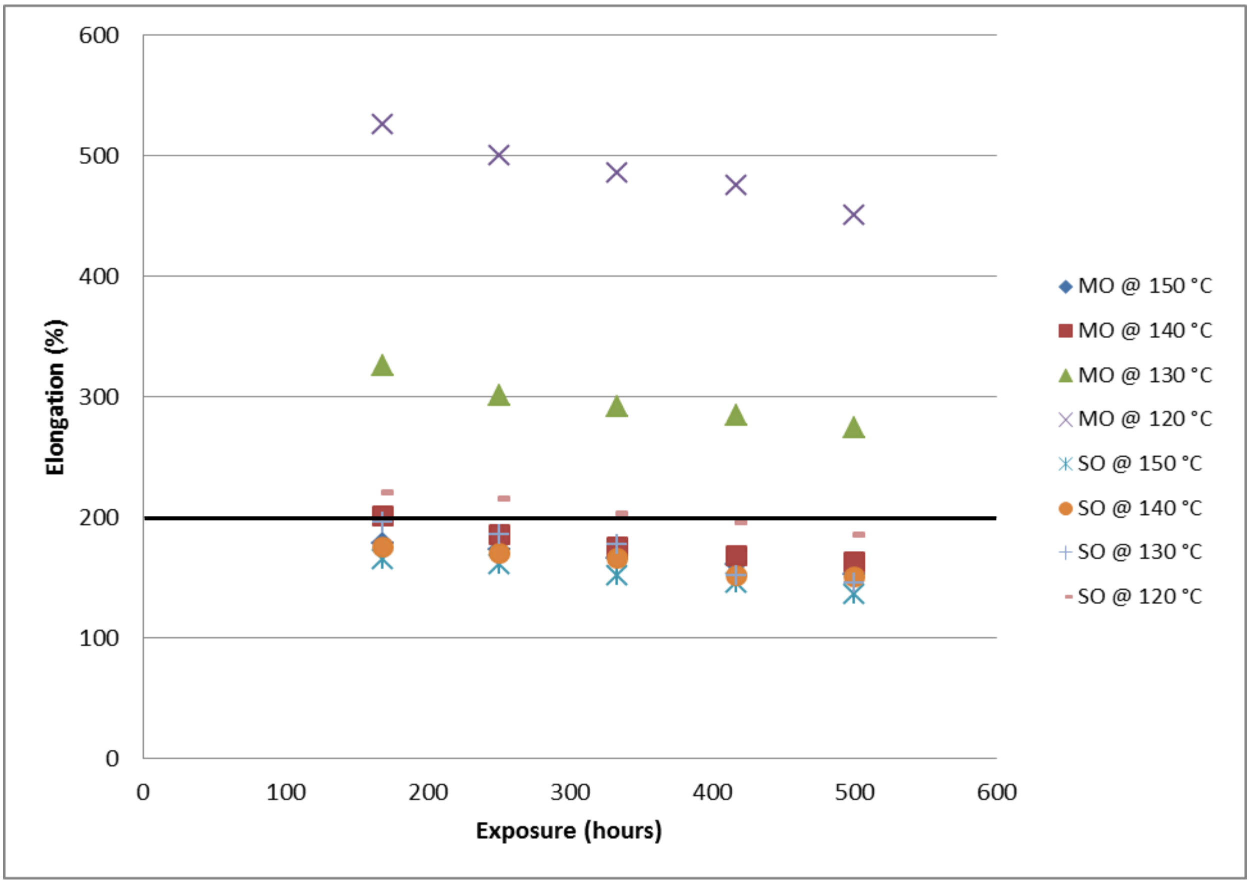


Figure 4.12: Effect of temperature and exposure on elongation of nitrile 322 immersed in oil

The trend shown in Figure 4.12 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. This shows that nitrile 322 breaks more easily when exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification. The specification required is a minimum of 200 % elongation. At a temperature of 150 °C, nitrile 322 is not within specification for 168 h to 500 h for mineral oil. The operating temperatures and exposure periods is a temperature of 140 °C at 168 h and temperatures between 120 °C and 130 °C for exposure periods between 168 h and 500 h for mineral oil. For synthetic oil, at a temperature of 120 °C for 417 h to 500 h and temperatures between 130 and 150 degrees Celsius, nitrile 322 is not within specification for 168 h to 500 h. The operating temperatures and exposure periods is a temperature of 120 °C for exposure periods between 168 h and 333 h.

4.1.4 Nitrile 333

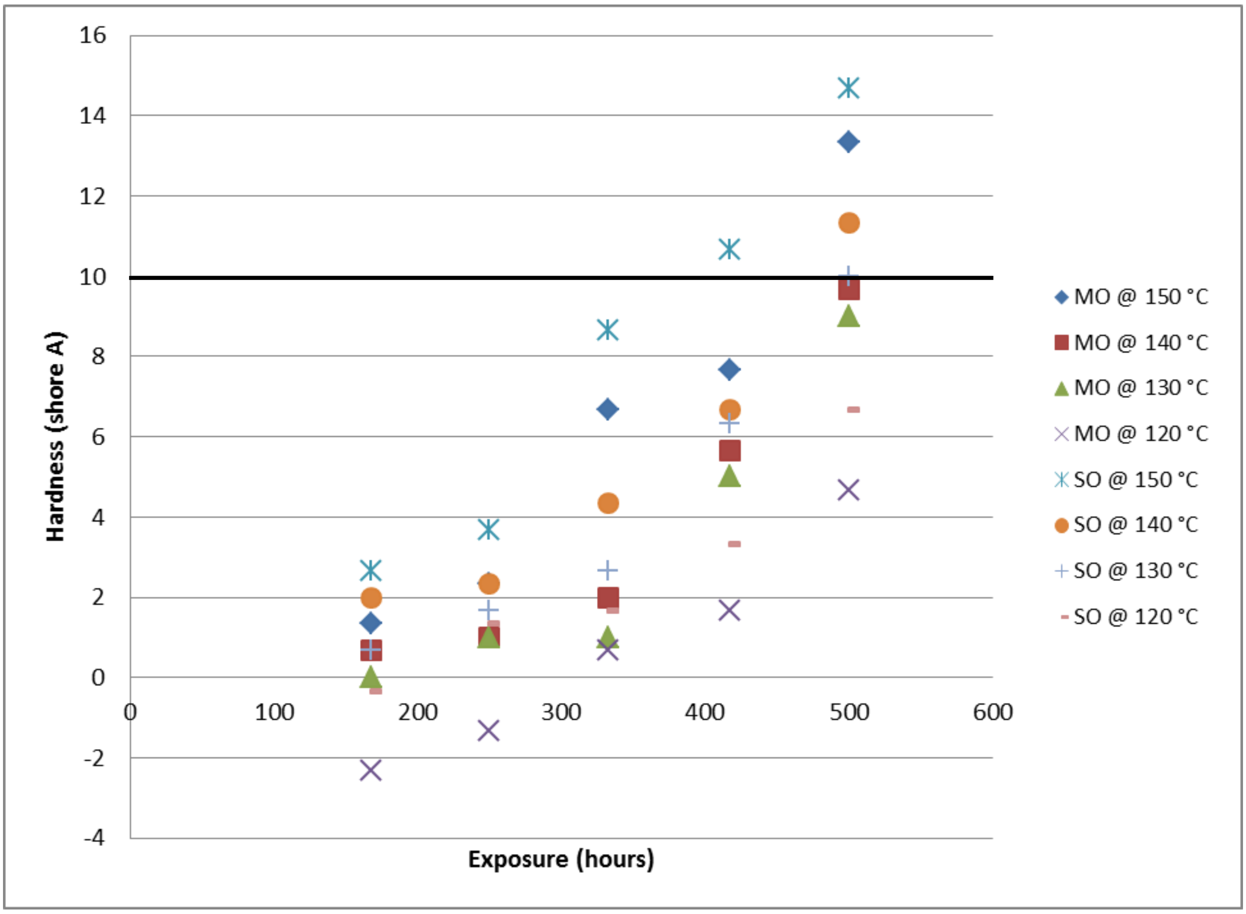


Figure 4.13: Effect of temperature and exposure on hardness of nitrile 333 immersed in oil

The trend shown in Figure 4.13 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. This shows that nitrile 333 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. The specification required is -10 Shore A to 10 Shore A change in hardness. The increased temperatures cause an increase in the change in hardness above the limits making it not fit for purpose for automobile filtration application. The acceptable operating temperature for nitrile 333 for this application is 120 °C to 140 °C for exposure periods of 168 h to 500 h and 150 °C at 168 h to 417 h for mineral oil. Nitrile 333 will not work at 150 °C at an exposure period of 500 h for mineral oil. The operating temperature for nitrile 333 for this application is 168 h to 333 h at 150 °C, 168 h to 417 h at 140 °C and 168 h to 500 h at 130 °C and 120 °C for synthetic oil.

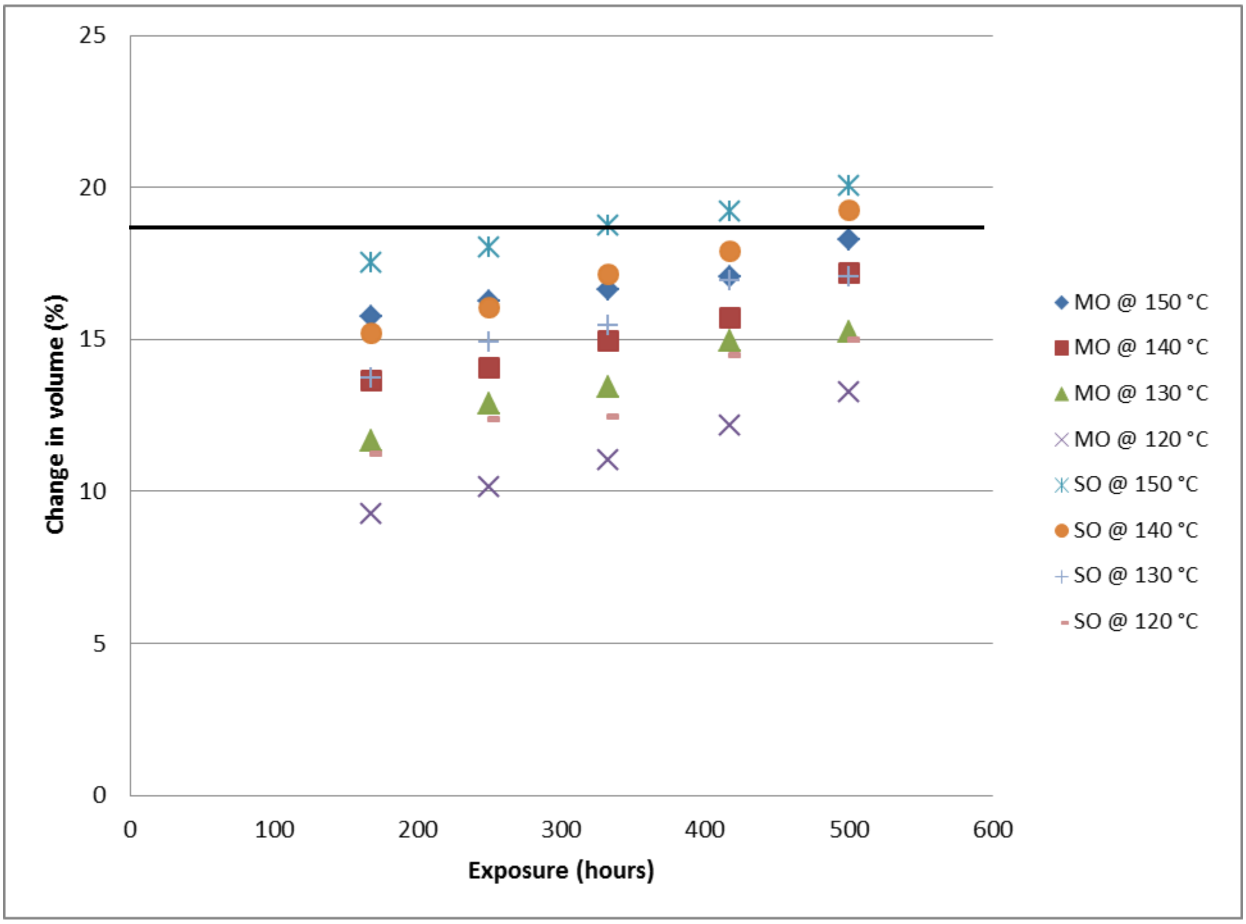


Figure 4.14: Effect of temperature and exposure on change in volume of nitrile 333 immersed in oil

The trend shown in Figure 4.14 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. This shows that nitrile 333 expands when exposed to increased temperatures and exposure periods. This may be due to the elasticity of the rubber. The specification required is 0 % to 18 % change in volume. The increased temperatures cause an increase in the change in volume above the limits for 150 °C at 500 h making it not fit for purpose for automobile filtration application for mineral oil. The operating temperature for nitrile 333 for this application is 120 °C to 140 °C for exposure periods of 168 h to 500 h and 150 °C at 168 h to 417 h for mineral oil. For synthetic oil, the degree of change in volume increases above the limit of 18 % therefore making it unsuitable at a temperature of 150 °C for 250 h to 500 h and a temperature of 140 °C for 500 h. As seen the operating temperature for nitrile 333 for this application is between 120 °C and 130 °C for exposure periods of 168 h to 500 h, 140 °C for 168 h to 417 h and a temperature of 150 °C for 168 h.

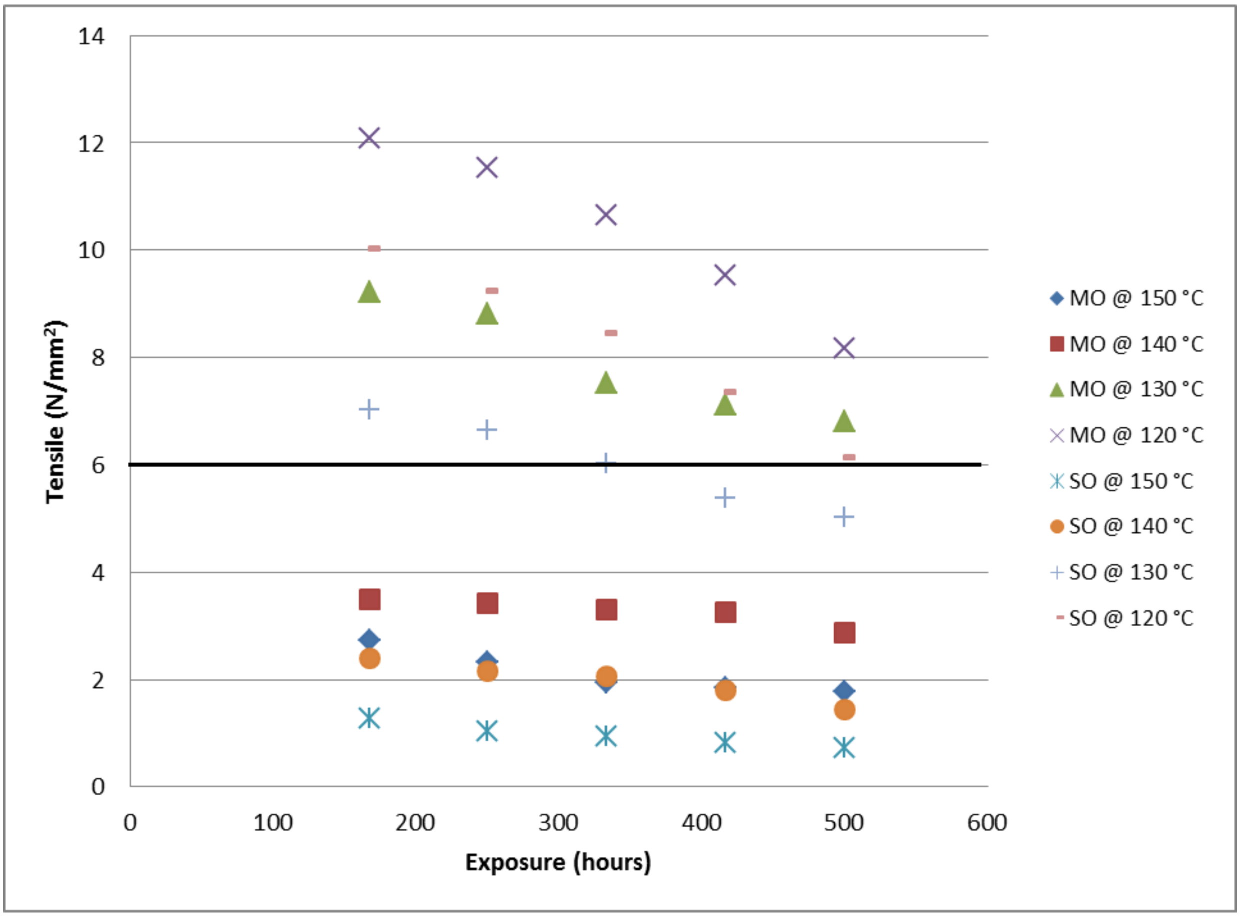


Figure 4.15: Effect of temperature and exposure on tensile strength of nitrile 333 immersed in oil

The trend shown in Figure 4.15 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase, and as exposure periods increase. This shows that nitrile 333 loses its strength as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in the material being able to withstand diminishing stress while being stretched or pulled before failing or breaking. This in turn puts the product out of specification according to the specifications required for temperatures at 140 °C to 150 °C for 168 h to 500 h for mineral oil and synthetic oil. The specification required is a minimum of 6 N/mm^2. For mineral oil, the operating temperature for nitrile 333 for this application is 120 °C to 130 °C for exposure periods of 168 h to 500 h. At a temperature of 130 °C for 417 h to 500 h and temperatures between 140 °C and 150 °C for 168 h to 500 h, the tensile strength is not within specification and at a lower temperature of 120 °C for 168 h to 333 h and at 130 °C for 168h to 333h, tensile strength is within specification making it fit for purpose for automobile filtration application for synthetic oil.

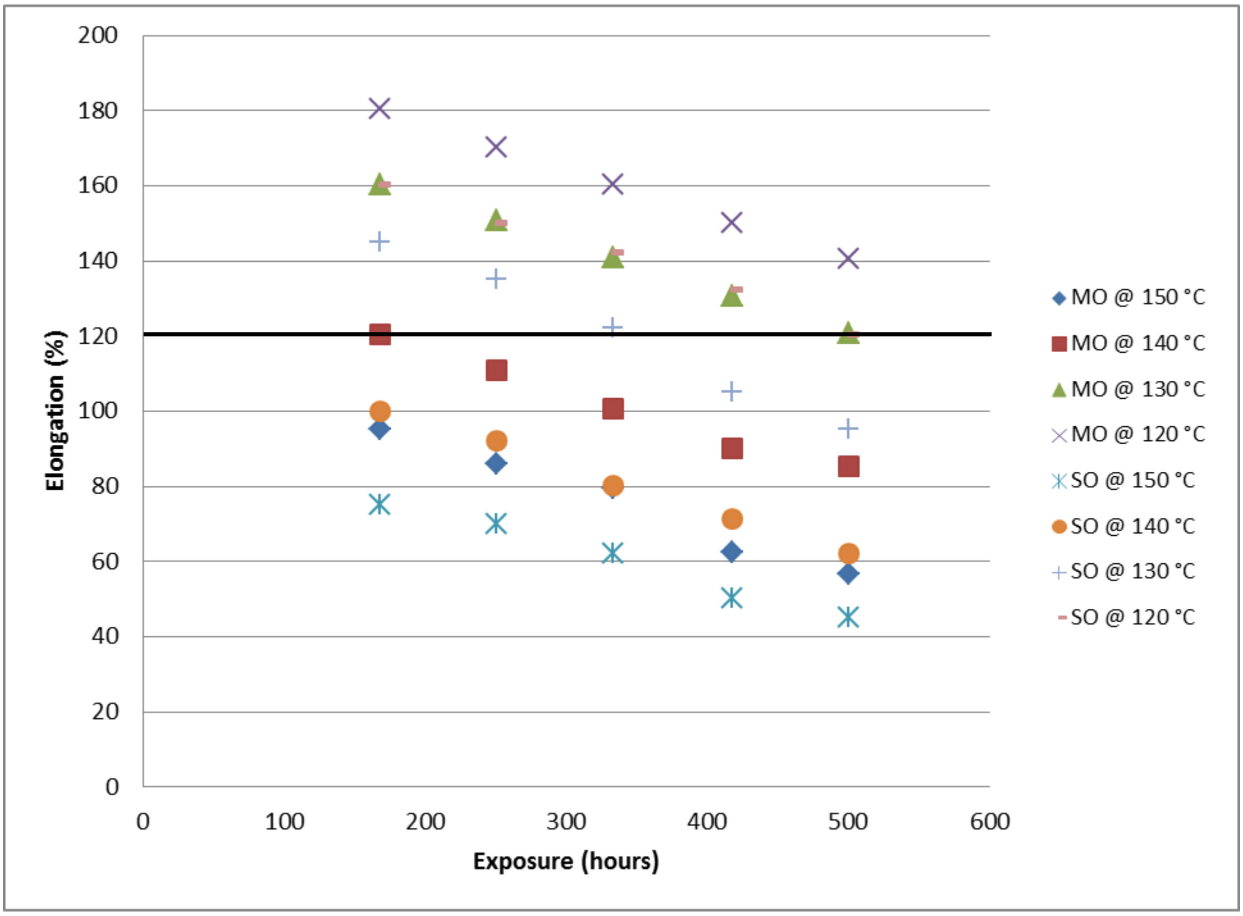


Figure 4.16: Effect of temperature and exposure on elongation of nitrile 333 immersed in oil

The trend shown in Figure 4.16 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. This shows that nitrile 333 breaks more easily when exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification for mineral oil according to the specifications required at a temperature of 150 °C for 168 h to 500 h and a temperature of 140 °C for 250 h to 500 h. The specification required is minimum 120 % elongation. The operating temperature for nitrile 333 for this application is 120 °C to 130 °C for exposure periods of 168 h to 500 h and 140 °C for 168 h. The specification required is a minimum of 200 % elongation. For synthetic oil, at temperatures between 140 °C and 150 °C for 168 h to 500 h and a temperature of 130 °C for 417 h to 500 h, nitrile 333 is not within specification. The operating temperatures and exposure periods is a temperature of 120 °C for exposure period between 168 h and 500 h and a temperature of 130 °C between exposure periods of 168 h and 333 h.

4.1.5 Polyacrylate 334

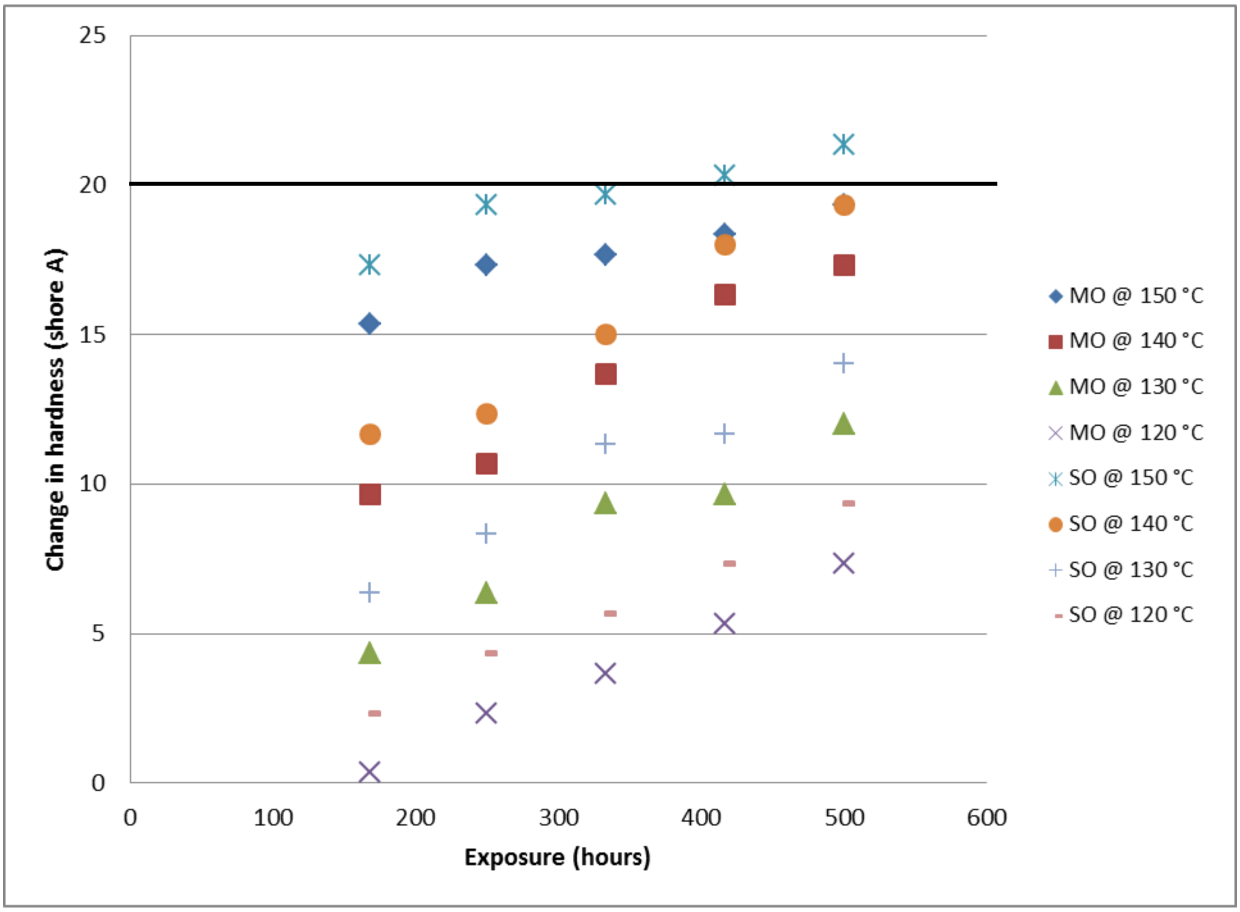


Figure 4.17: Effect of temperature and exposure on hardness of ACM 334 immersed in oil

The trend shown in Figure 4.17 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. The specification required was a maximum of 20 Shore A. All the values obtained were below 20 Shore A which makes ACM 334 within specification with regards to change in hardness for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil. This makes the oil filter best equipped to prevent leaks thereby reducing contaminants. The increased temperatures and extended service intervals cause an increase in the change in hardness above the limits making it not fit for purpose for automobile filtration application for specific temperature exposures and service intervals in synthetic oil. The operating temperature for polyacrylate 334 for this application is 168 h to 333 h at 150 °C and 168 h to 500 h for temperatures from 120 °C to 140 °C in synthetic oil.

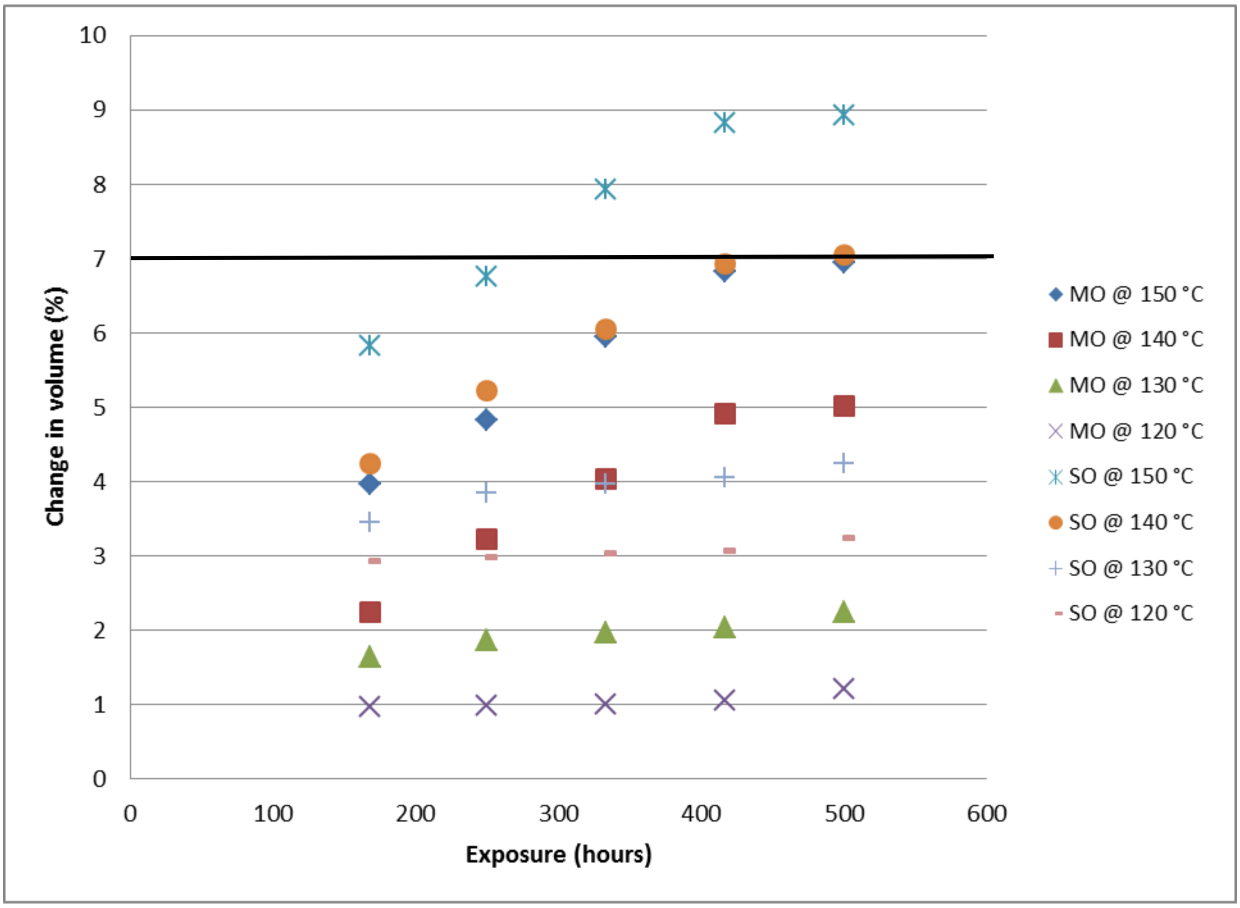


Figure 4.18: Effect of temperature and exposure on change in volume of ACM 334 immersed in oil

The trend shown in Figure 4.18 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. The specification required is -4 % to 7 %. All the values obtained for mineral oil were between -4 % and 7 % which makes ACM 334 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h. For synthetic oil, the degree of change in volume increases above the limit of 7 % therefore making it unsuitable at a temperature of 150 °C for 333 h to 500 h and a temperature of 140 °C for 500 h. As seen the operating temperature for ACM 334 for this application is 120 °C and 130 °C for exposure periods from 168 h to 500 h, 140 °C for 168 h to 417 h and a temperature of 150 °C for 168 h to 250 h.

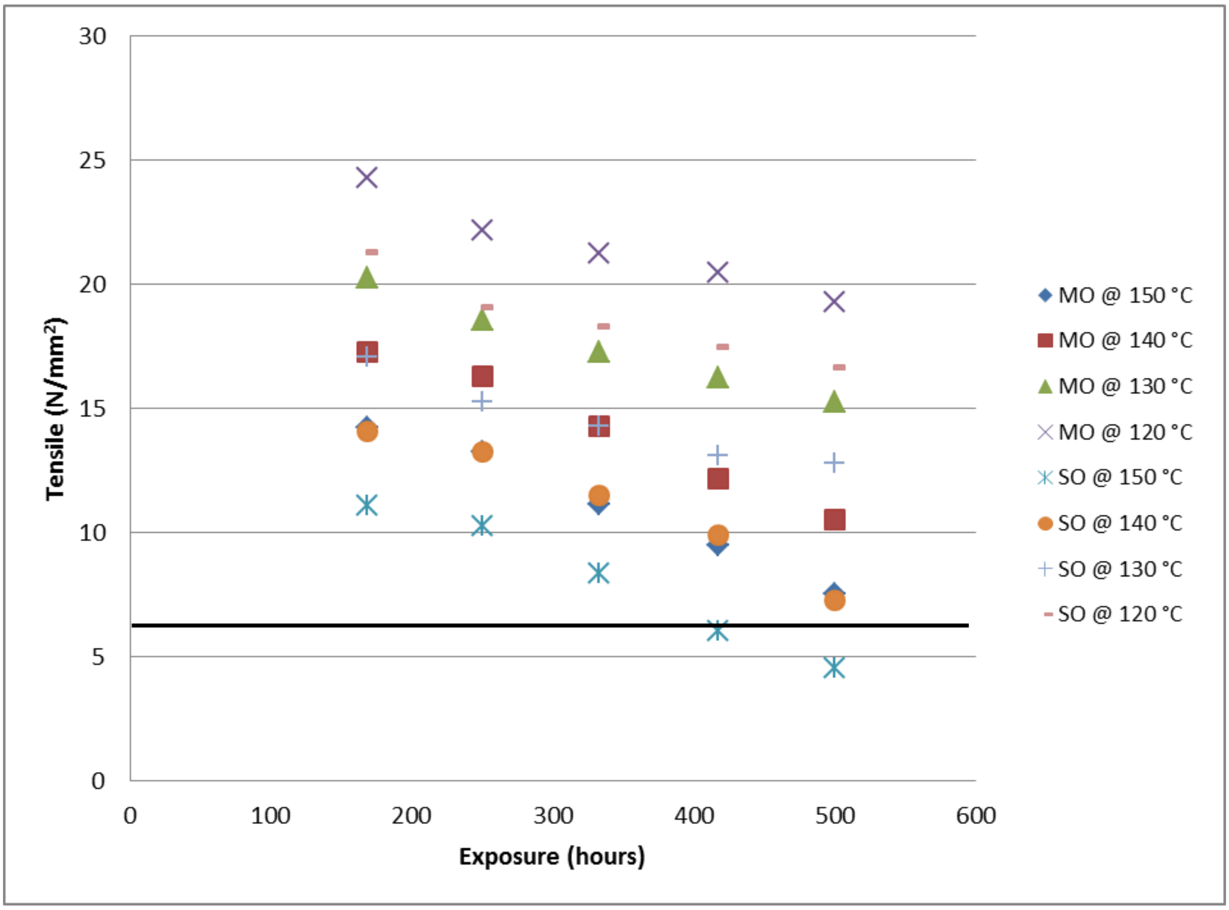


Figure 4.19: Effect of temperature and exposure on tensile strength of ACM 334 immersed in oil

The trend shown in Figure 4.19 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase, and as exposure periods increase. The specification required is a minimum of 6 N/mm^2. All the values obtained for mineral oil were above 6 N/mm^2 which makes ACM 334 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h. For synthetic oil, Figure 4.19 shows that ACM 334 loses its strength as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in the material being able to withstand diminishing stress while being stretched or pulled before failing or breaking. This in turn puts the product out of specification. At a temperature of 150 °C for 500 h, the tensile strength is not within specification while at lower temperatures of 120 °C to 140 °C for 168 h to 500 h and at 150 °C for 168 h to 417 h tensile strength is within specification making it fit for purpose for the automobile filtration application.

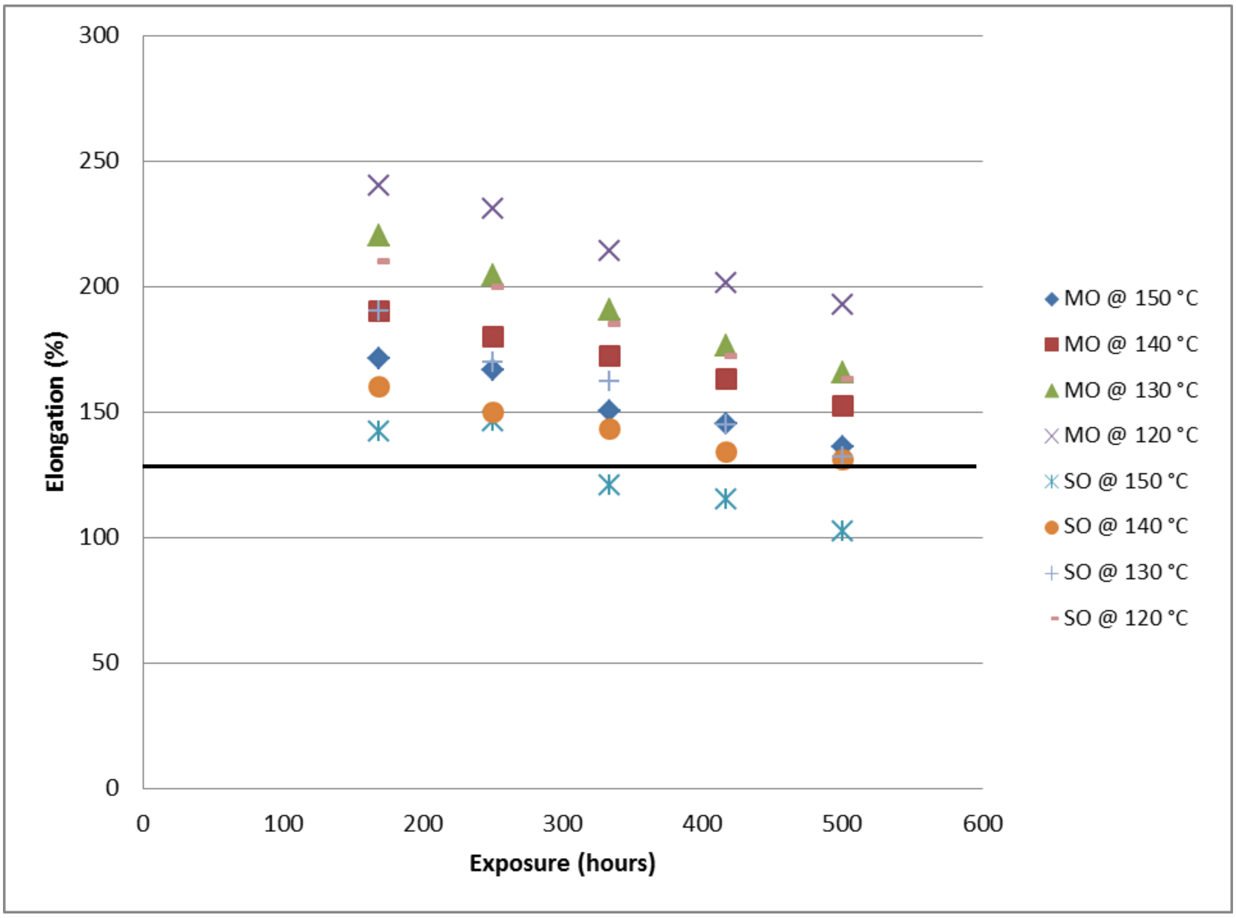


Figure 4.20: Effect of temperature and exposure on elongation of ACM 334 immersed in oil

The trend shown in Figure 4.20 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. The specification required is a minimum of 130 %. All the values obtained were above 130 % which makes ACM 334 within specification with regards to change in elongation for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil. The trend shown in Figure 4.20 for synthetic oil illustrates a decrease in change in elongation as temperatures increase and a decrease in elongation as exposure periods increase. This shows that ACM 334 breaks more easily when exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product for specific applications out of specification. At a temperature of 150 °C for 333 h to 500 h, ACM 334 is not within specification. The operating temperatures and exposure period are temperatures of 120 °C to 140 °C for exposure periods of between 168 h and 500 h and a temperature of 150 °C for exposure periods of 168 h and 250 h.

4.1.6 Viton 337

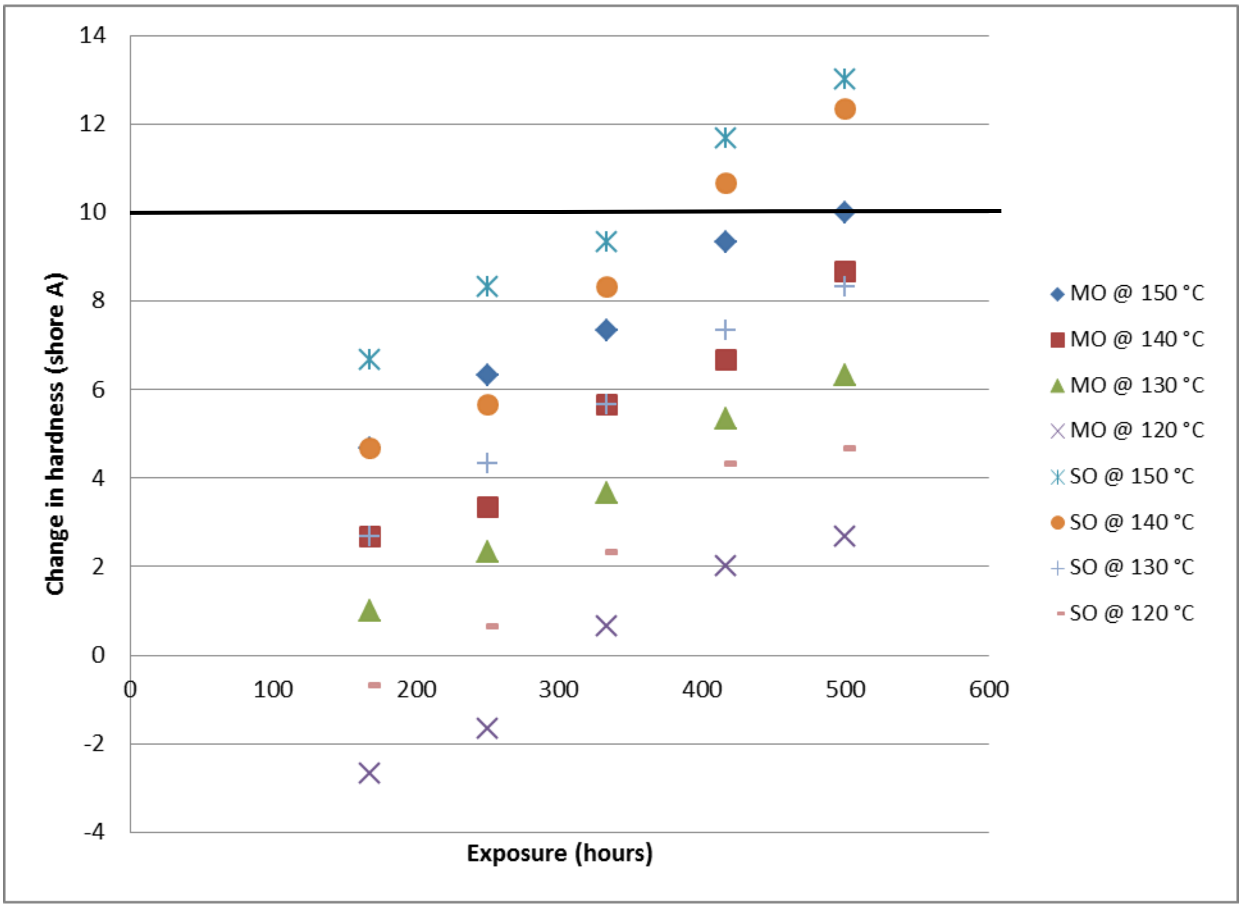


Figure 4.21: Effect of temperature and exposure on change in hardness of Viton 337 immersed in oil

The trend shown in Figure 4.21 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. The specification required is -5 Shore A to 10 Shore A. All the values obtained were between -5 Shore A and 10 Shore A for mineral oil which makes Viton 337 within specification with regard to change in hardness for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h. For synthetic oil, 4.21 shows that Viton 337 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification. The operating temperature for polyacrylate 334 for this application is 168 h to 333 h at 150 °C and 140 °C and 168 h to 500 h for temperatures from 120 °C to 130 °C.

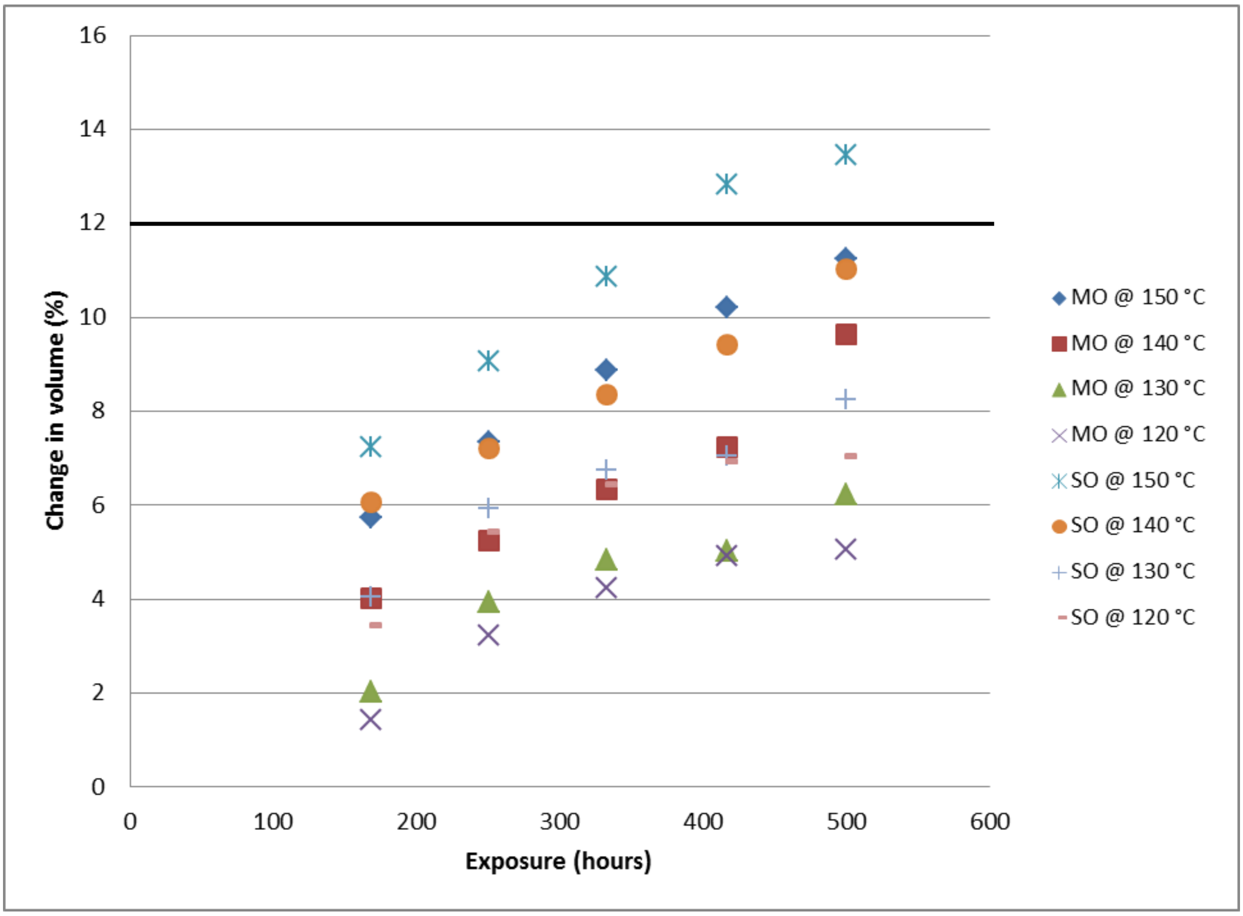


Figure 4.22: Effect of temperature and exposure on change in volume of Viton 337 immersed in oil

The trend shown in Figure 4.22 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. The specification required is -3 % to 12 %. All the values obtained were between -3 % and 12 % which makes Viton 337 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil. The trend shown in Figure 4.22 for synthetic oil shows that Viton expands when exposed to increased temperatures and exposure periods. This may be due to the elasticity of the rubber. The specification required is -3 % to 12 %. The degree of change in volume increases above the limit of 12 % therefore making it unsuitable at a temperature of 150 °C for 417 h to 500 h. As seen the operating temperature for Viton 337 for this application is 120 °C to 140 °C for exposure periods from 168 h to 500 h and 150 °C for 168 h to 333 h.

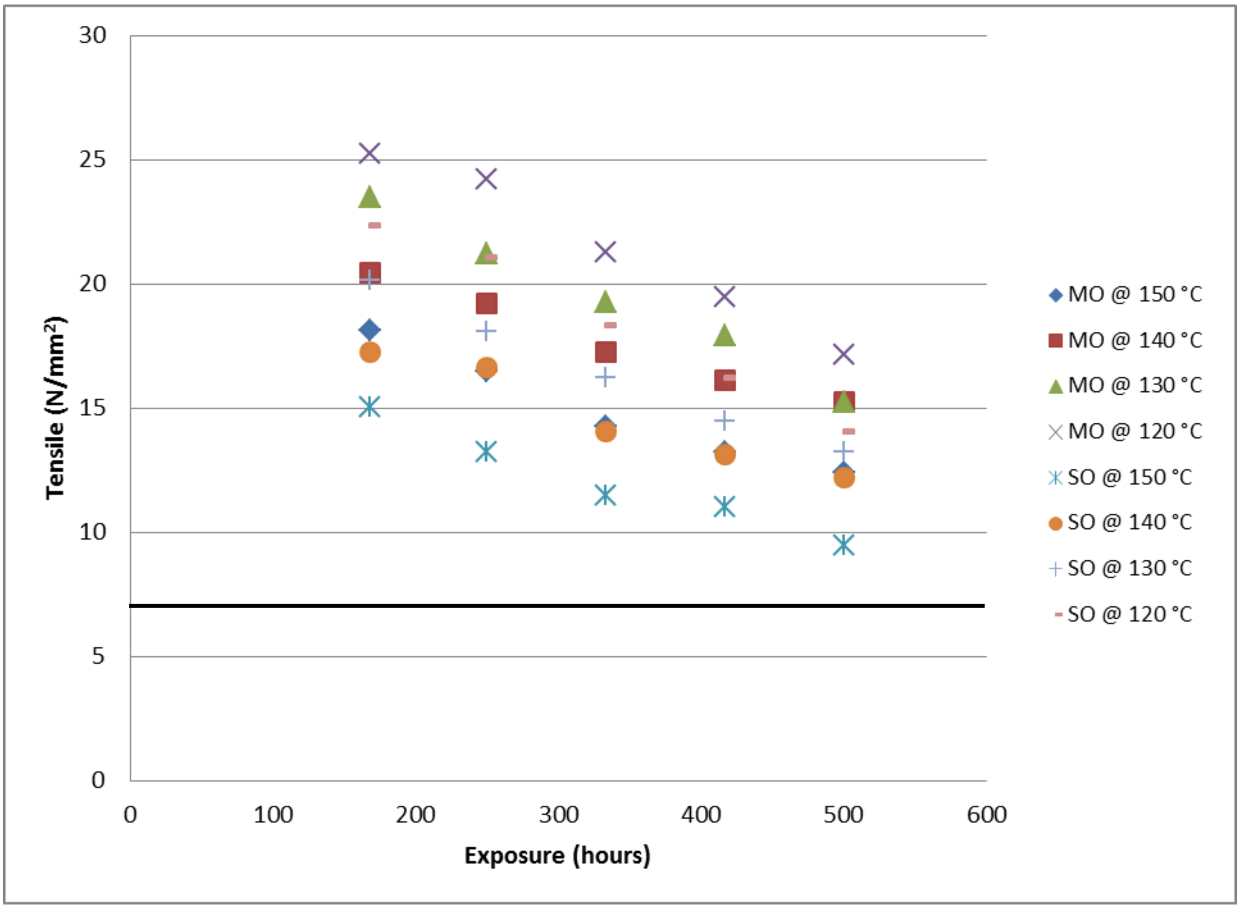


Figure 4.23: Effect of temperature and exposure on tensile strength of Viton 337 immersed in oil

The trend shown in Figure 4.23 for mineral oil and synthetic oil illustrates a decrease in tensile as temperatures increase, and as exposure periods increase. The specification required is a minimum of 7 N/mm^2. All the values obtained were above 7 N/mm^2 which makes Viton 337 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil and synthetic oil.

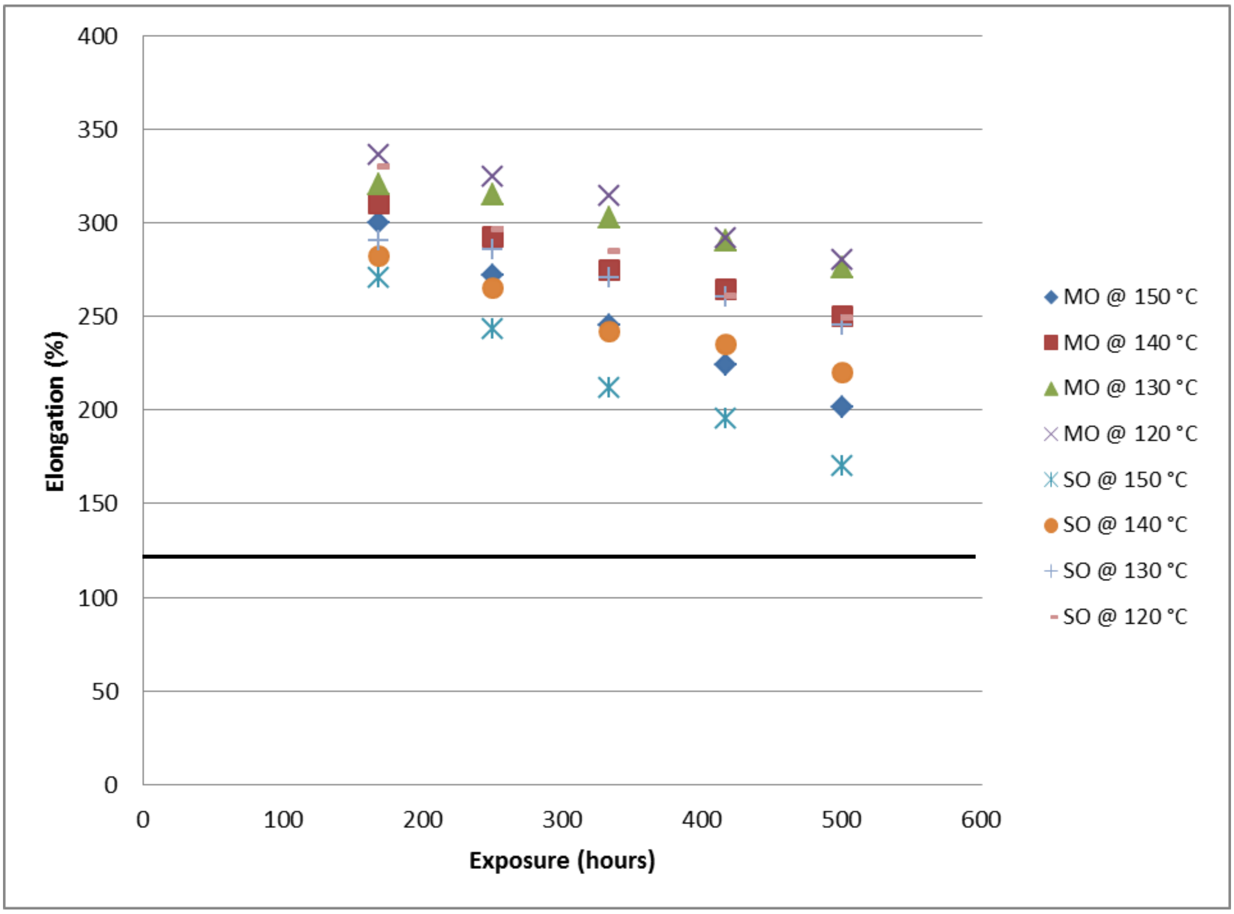


Figure 4.24: Effect of temperature and exposure on elongation of Viton 337 immersed in oil

The trend shown Figure 4.24 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. The specification required is a minimum of 120 %. All the values obtained were above 120 % which makes Viton 337 within specification with regards to change in elongation for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil and for synthetic oil.

4.1.7 HNBR 338

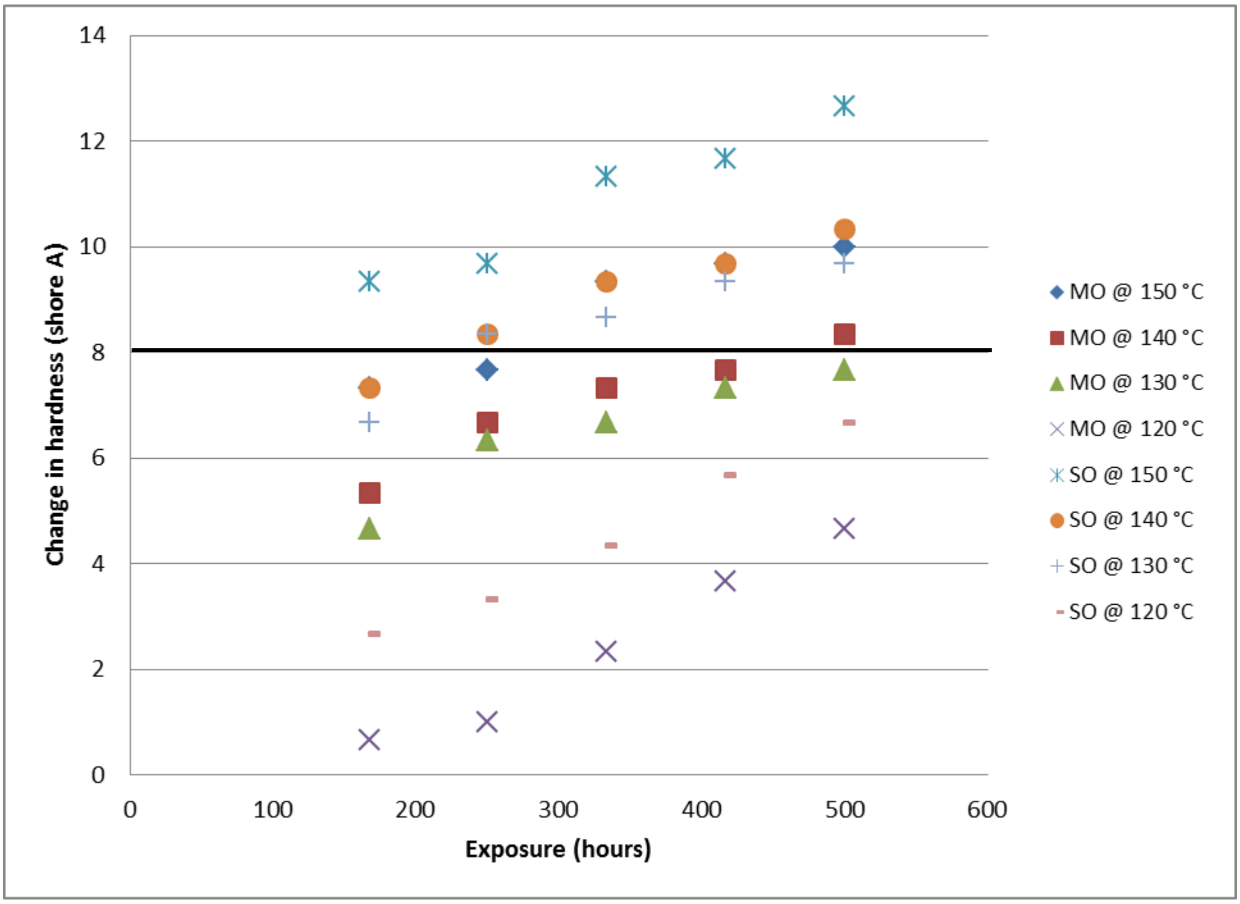


Figure 4.25: Effect of temperature and exposure on change in hardness of HNBR 338 immersed in oil

The trend shown in Figure 4.25 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. This shows that HNBR 338 rubber gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. The harder seal can break resulting in contaminants entering the filter. This in turn puts the product out of specification. The specification required is -8 Shore A to 8 Shore A change in hardness. The increased temperatures and extended service intervals cause an increase in the change in hardness above the limits making it not fit for purpose for automobile filtration application for specific temperature exposures and service intervals. The operating temperature for HNBR 338 for this application is 168 h to 500 h at 120 °C and 130 °C and 168 h to 417 h at a temperature of 140 °C and 168 h to 250 h at a temperature of 150 °C for mineral oil. The operating temperature for synthetic oil HNBR 338 for this application is 168 h to 500 h at 120 °C and 168 h at 130 °C and 140 °C.

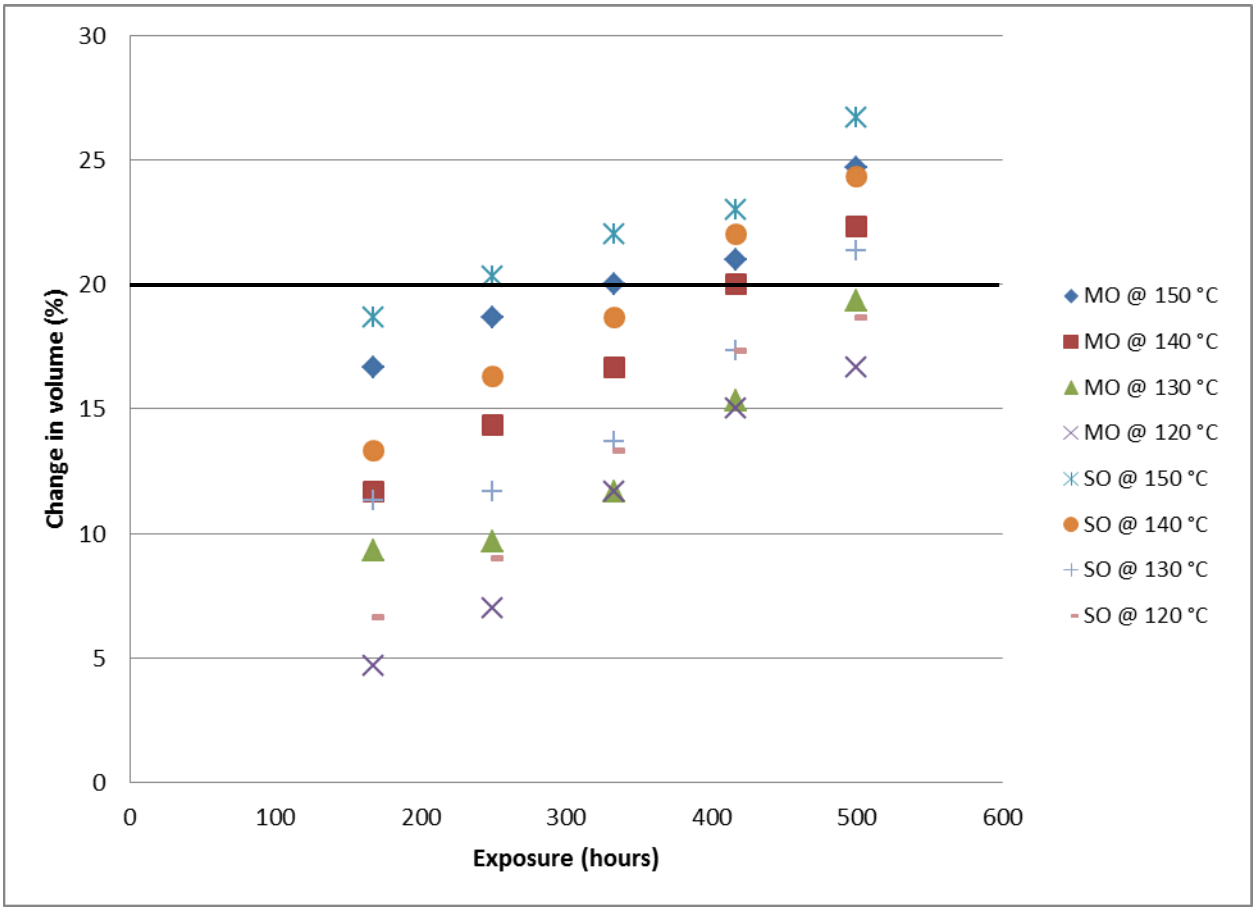


Figure 4.26: Effect of temperature and exposure on change in volume of HNBR 338 immersed in oil

The trend shown in Figure 4.26 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. This shows that HNBR 338 rubber expands when exposed to increased temperatures and exposure periods. This may be due to the elasticity of the rubber. The specification required is -3 % to 20 %. The degree of change in volume increases above the limit of 20 % therefore making it unsuitable at a temperature of 150 °C for 333 h to 500 h and 140 °C for 500 h for mineral oil. For mineral oil the operating temperature for HNBR 338 for this application is 120 °C to 130 °C at exposure periods from 168 h to 500 h, 140 °C for 168 h to 333 h and 150 °C for 168 h to 250 h. For synthetic oil the operating temperature for HNBR 338 for this application is 140 °C for exposure periods from 168 h to 333 h, 130 °C for 168 h to 417 h and 120 °C for 168 h to 500 h.

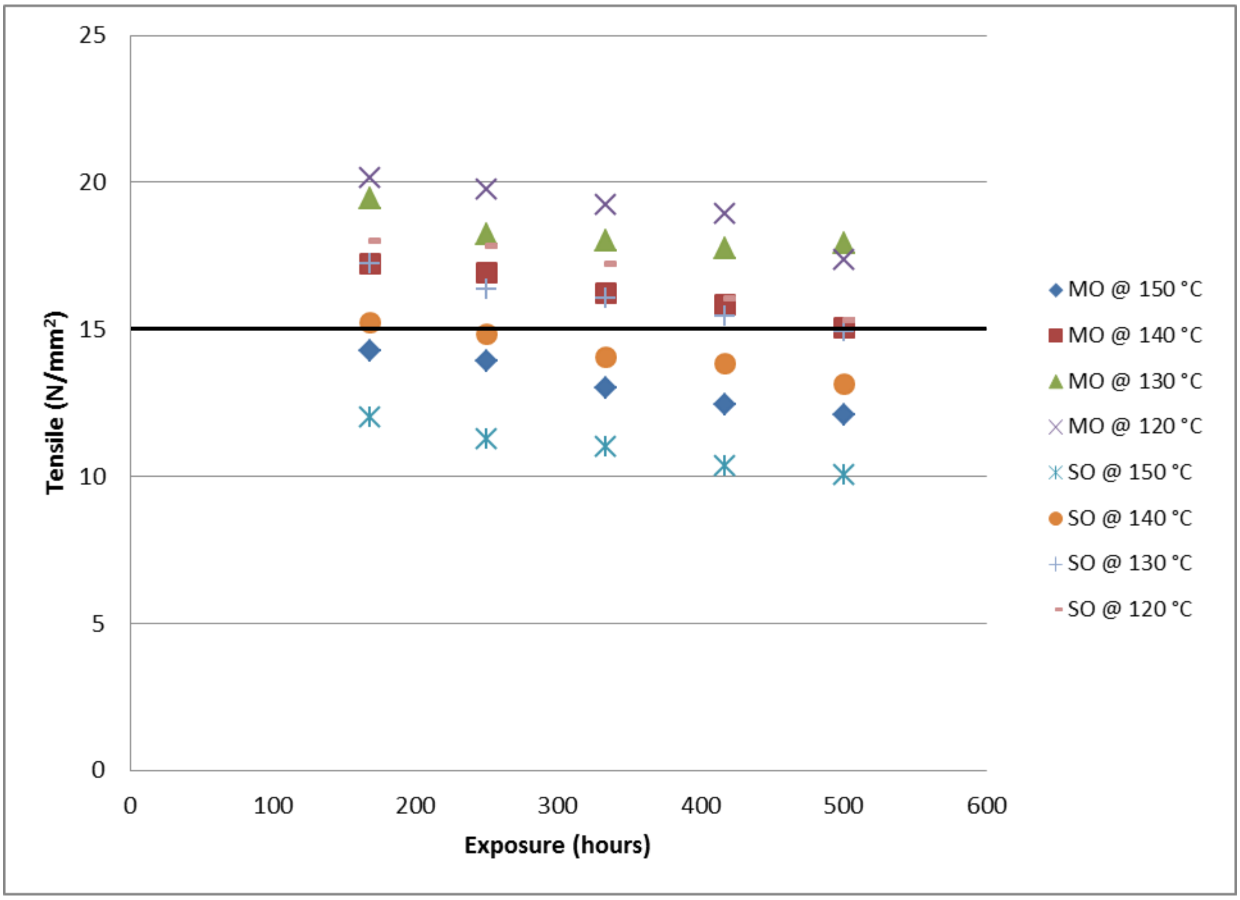


Figure 4.27: Effect of temperature and exposure on tensile strength of HNBR 338 immersed in oil

The trend shown in Figure 4.27 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase and as exposure periods increase. This shows that HNBR 338 rubber loses its strength as it is exposed to elevated temperatures. This may be due to the rubber embrittlement which results in the material being able withstand diminishing stress while being stretched or pulled before failing or breaking. The tensile strength increase and embrittlment of HNBR as exposure time increases concur with (Alcock et al., 2020) as this study involved exposing HNBR to hot air at 150 degrees Celsius for about 12 weeks with different degrees of carbon black content and it was concluded that with increased exposure time, tensile stiffness increased and samples became more brittle. Lou et al. (2017) adds to this whereby a study conducted on the degredation behaviours on HNBR under compression and free state in oil envioremnets at increasing temperatures concluded that the fracture of compressed samples become more predominant with an increased exposure time. This in turn puts the product out of specification. The specification required is a minimum of 15 N/mm^2. For mineral oil, at a temperature of 150 °C for 168 h to 500 h, the tensile strength is not within specification and at lower temperatures and service intervals of 120 °C and 140 °C for 168 h to 500 h, tensile strength is within specification making it fit for purpose for automobile filtration application. For synthetic oil, at a temperature of 150 °C for 168 h to 500 h, 140 °C for 250 h to 500 h and 130 °C for 500 h, the tensile strength is not within specification, and at lower temperatures and service intervals of 120 °C for 168 h to 500 h 130 °C for 168 h to 417 h and 140 °C for 168 h, tensile strength is within specification making it fit for purpose for automobile filtration application.

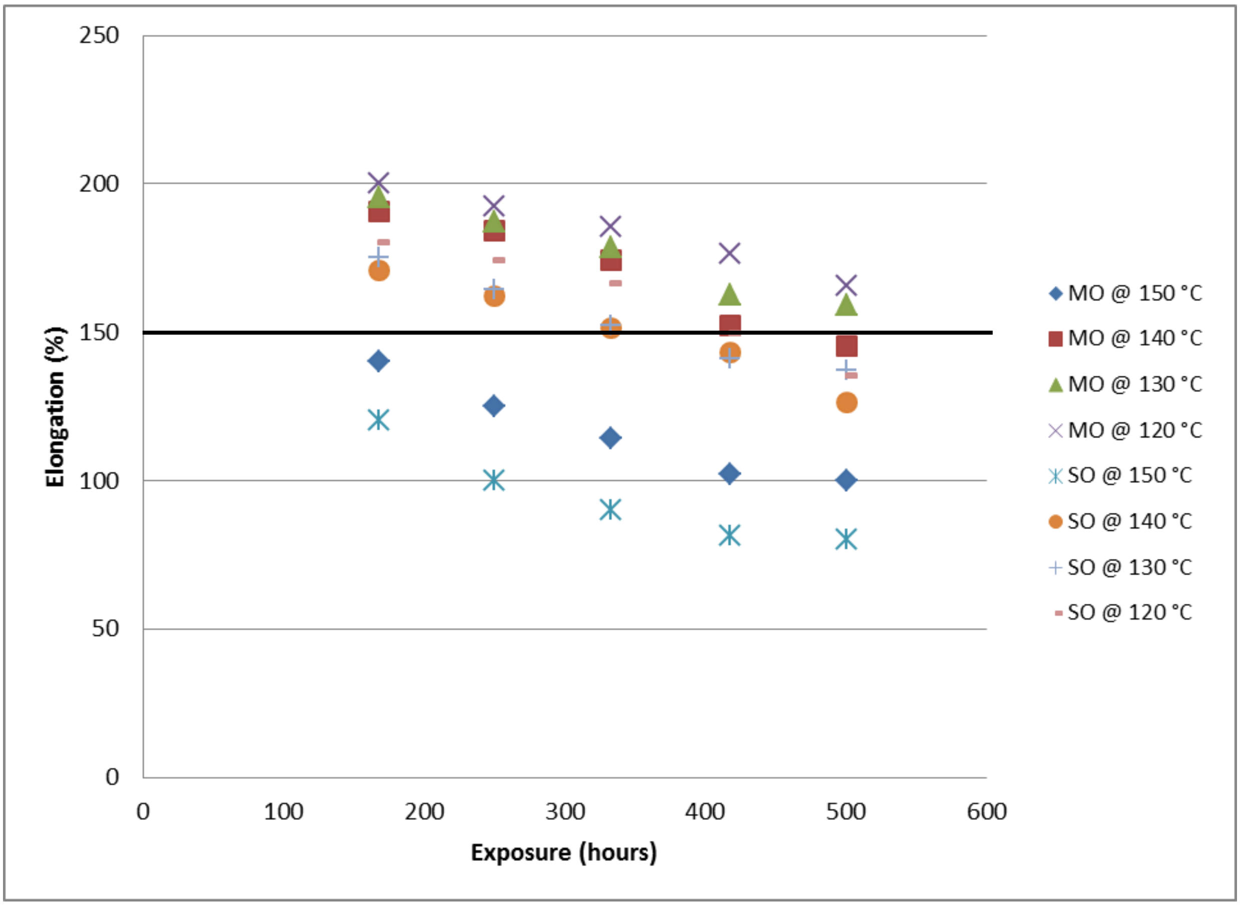


Figure 4.28: Effect of temperature and exposure effect on elongation of HNBR 338 immersed in oil

The trend shown in Figure 4.28 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. This shows that HNBR 338 breaks more easily when exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification for mineral oil according to the specifications required at a temperature of 150 °C for 168 h to 500 h and a temperature of 140 °C for 500 h. The specification required is a minimum of 150 % elongation. As seen the operating temperature for HNBR 338 for this application is 120 °C to 130 °C for exposure periods from 168 h to 500 h and 140 °C for 168 h to 417 h for mineral oil. For synthetic oil, the product is out of specification at a temperature of 150 °C for 168 h to 500 and a temperature of 140 °C, 130 °C and 120 °C for 417 h to 500 h. The specification required is a minimum of 150 % elongation. As seen the operating temperature for HNBR 338 is 120 °C to 140 °C for exposure periods from 168 h to 333 h.

4.1.8 AEM 336

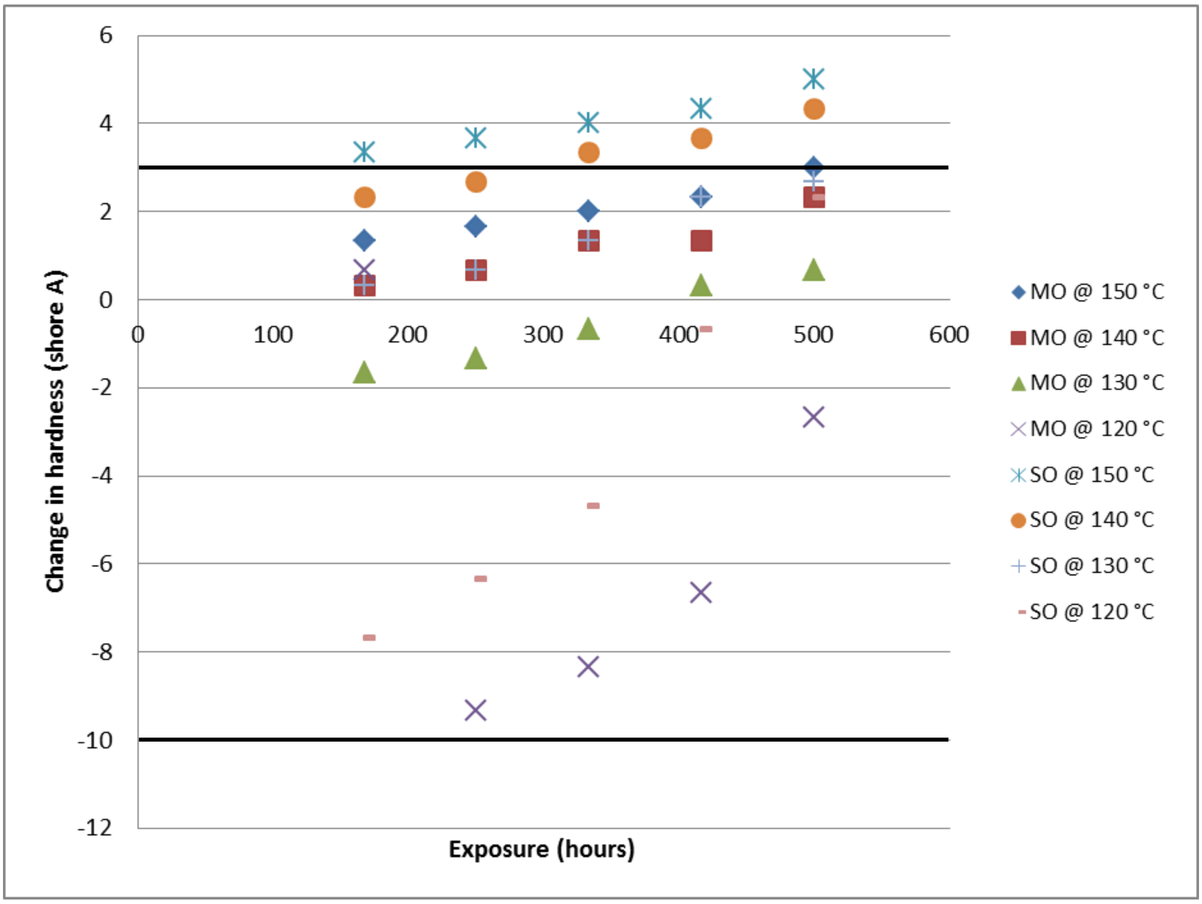


Figure 4.29: Effect of temperature and exposure on change in hardness of AEM 336 immersed in oil

The trend shown in Figure 4.29 for mineral oil and synthetic oil illustrates an increase in change in hardness as temperatures increase, and as exposure periods increase. The specification required is -10 Shore A to 3 Shore A. All the values obtained for mineral oil were between -10 Shore A and 3 Shore A which makes AEM 336 within specification with regards to change in hardness for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil. The trend for synthetic oil in Figure 4.29 shows that AEM 336 gets harder as it is exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification. The increased temperatures and extended service intervals cause an increase in the change in hardness above the limits making it not fit for purpose for automobile filtration application at for specific temperature exposures and service intervals. The operating temperature for AEM 336 for this application is 168 h to 250 h at 140 °C, 168 h to 500 h at a temperature of 130 °C and 168 h to 500 h at a temperature of 120 °C.

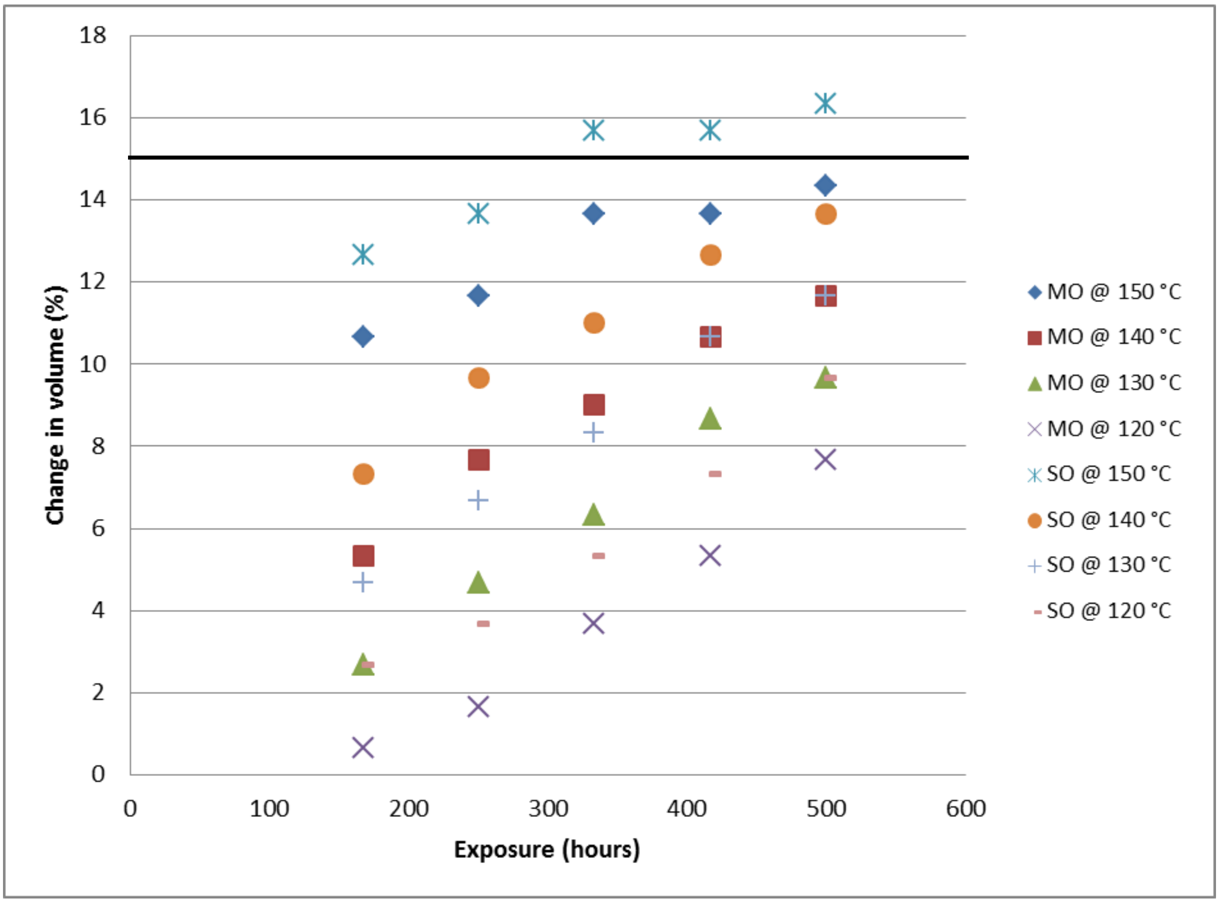


Figure 4.30: Effect of temperature and exposure on change in volume of AEM 336 immersed in oil

The trend shown in Figure 4.30 for mineral oil and synthetic oil illustrates an increase in change in volume as temperatures increase, and as exposure periods increase. The specification required is -3 % to 15 %. All the values for mineral oil obtained were between -3 % and 15 % which makes AEM 336 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h. The trend shown in Figure 4.30 for synthetic oil shows that AEM expands when exposed to increased temperatures and exposure periods. This may be due to the elasticity of the rubber. The specification required is -3 % to 15 %. The degree of change in volume increases above the limit of 15 % therefore making it unsuitable at a temperature of 150 °C for 333 h to 500 h. The operating temperature for AEM 336 for this application is 120 °C to 140 °C for exposure periods from 168 h to 500 h and 150 °C for 168 h to 250 h for synthetic oil.

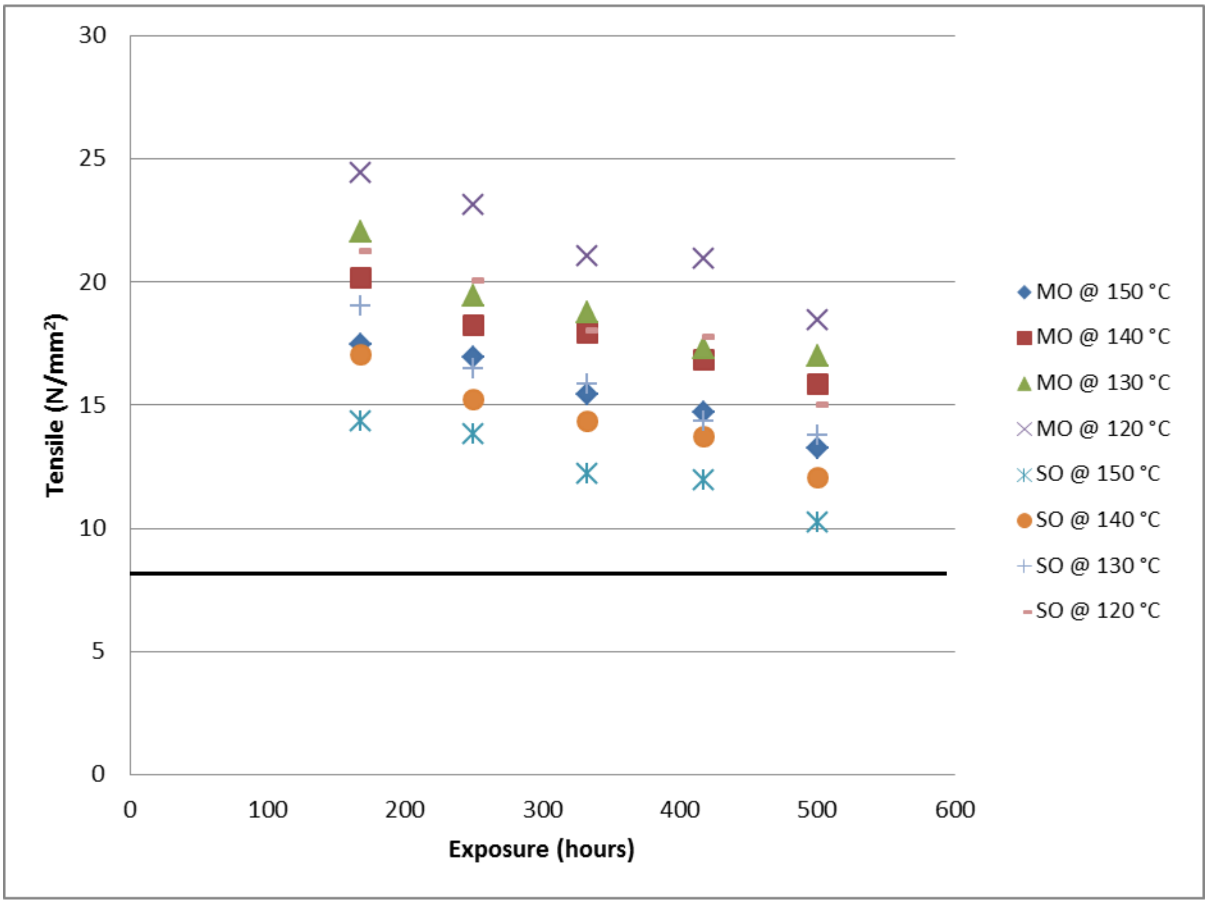


Figure 4.31: Effect of temperature and exposure on tensile strength of AEM 336 immersed in oil

The trend shown in Figure 4.31 for mineral oil and synthetic oil illustrates a decrease in tensile strength as temperatures increase, and as exposure periods increase. The specification required is a minimum of 8 N/mm^2. All the values obtained were above 8 N/mm^2 which makes AEM 336 within specification with regards to change in volume for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h for mineral oil and for synthetic oil.

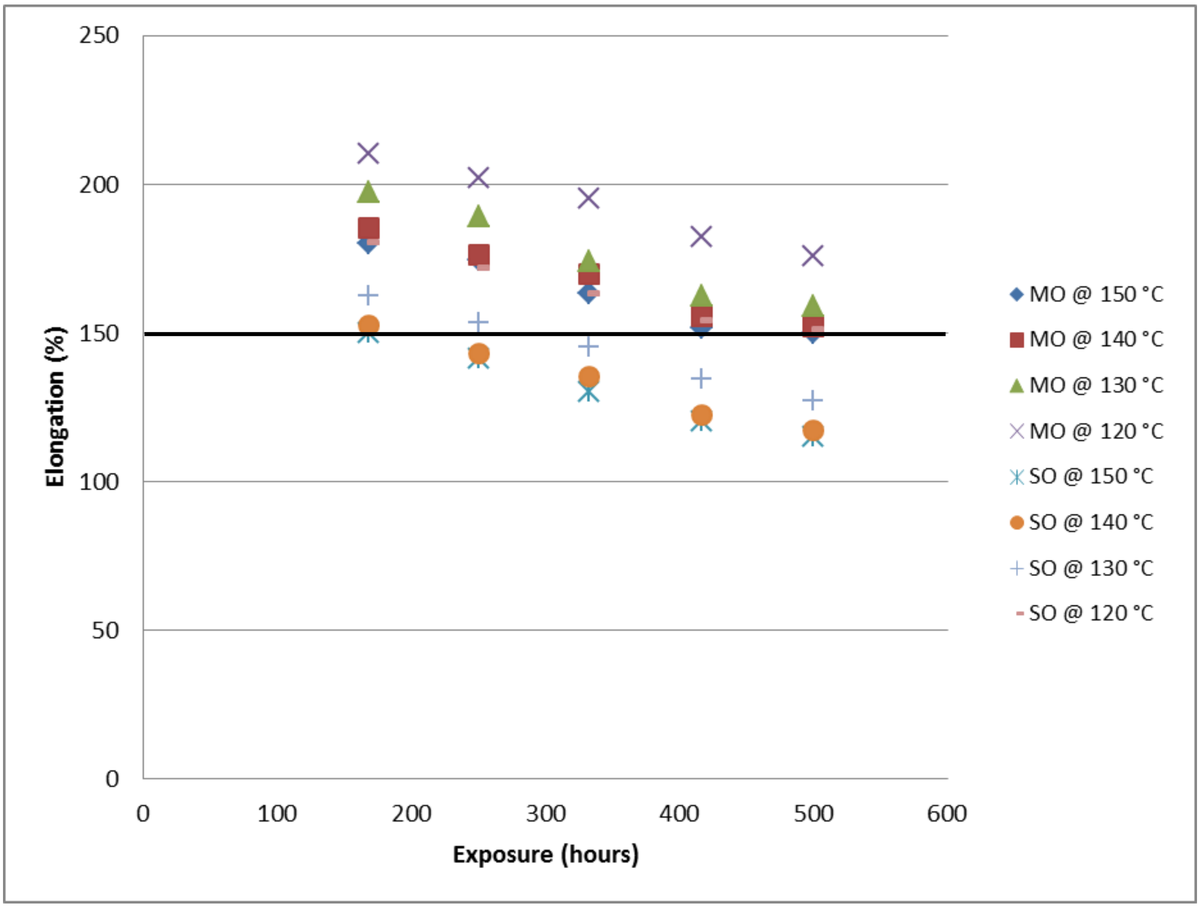


Figure 4.32: Effect of temperature and exposure on elongation of AEM 336 immersed in oil

The trend shown in Figure 4.32 for mineral oil and synthetic oil illustrates a decrease in change in elongation as temperatures increase, and as exposure periods increase. The specification required is a minimum of 150 %. All the values obtained for mineral oil were above 150 % which makes AEM 336 within specification with regards to change in elongation for temperatures between 120 °C and 150 °C and exposure periods of 168 h to 500 h. The trend shown in Figure 4.32 for synthetic oil shows that AEM 336 breaks 5more easily when exposed to elevated temperatures. This may be due to the rubber embrittling which results in a harder product. This in turn puts the product out of specification according to the specifications required at a temperature of 150 °C for 250 h to 500 h, a temperature of 140 °C for 250 h to 500 h and a temperature of 130 °C for 333 h to 500 h. As seen the operating temperature for AEM 336 for this application is 120 °C for exposure periods from 168 h to 500 h, 130 °C for 168 h to 250 h and 140 °C to 150 °C for 168 h.

4.2 Summary of results and discussion and summary of results and discussion related to literature

The trend of increase of hardness and change in volume and decrease of tensile strength and elongation as temperature and exposure periods increase is typical of the literature (Kim et al. 2007) regarding lifetime prediction of rubber gaskets for fuel cells because of acid aging characteristics. Sparks and Chase (2015), emphasises the effect that emissions have on the environment which is in line with the filter company as emissions lead to putting specifications in place which the filter company has to adhere to, leading down all the way to a rubber seal and how long it is in use for. Scraba (2019) makes reference to how an oil filter is key to an engine of a car which corresponds with the filter company as one of the vital checks is the contaminant build up on filters. Filters are tested for dirt holding capacity to assure customers via laboratory reports that the filter is able to withstand a certain amount of dirt. The reference in this literature of cold weather is brought to attention. This study does not cover the effects of cold weather on the rubber seals but it is interesting to conduct a study on this to gain a better understanding in order to critique the literature. It is stated again in (Youngk 2000), that irregular changes of an oil filter can lead to wear and tear of the engine. In many literature studies, this key fact is mentioned which shows the relevance of conducting this study. Sealing Technology (2004) mentions that a car can catch on fire if the rubber gasket fails. This can't be verified as a study on this has not been done and it is not very common to hear of such fires caused. The results make mention of a rubber seal becoming brittle if exposed to the incorrect environment and irregular oil filter changes can be one of those incorrect environments, which is service intervals therefore (Naskar Group n.d) is another valid reference when stating how important it is to change an oil filter. Brown (2002), makes mention of high temperatures and overdue service intervals, which are clearly key aspects in the results.

4.3 Results relevance to an oil filter

A hardness level above specification can cause the rubber to become brittle, thereby causing it to break and allowing contaminants through to the filter which could lead to engine break down. A change in volume can cause a rubber to either swell or shrink. If the rubber seal shrinks below specification, there will be room for leakage of contaminants into the filter thereby causing clogging, leading to a blocked oil filter which could lead to damage of an engine. If elongation results are not within specification, the rubber could break if it cannot be stretched enough and if tensile strength is not within specification, the rubber could not have enough strength in it and when pulled, it could break. These engine failure possibilities relate to literatures of (Scraba 2019), (Naskar Group n.d), (Youngk 2000) and further studies

Summary tables

Table 4.1: Hardness

	120	130	140	150
Nitrile 321	MO ≤ 500 h, SO ≤ 417 h	MO -, SO -	MO -, SO -	MO - SO -
Silicone 332	MO ≤ 500 h, SO ≤ 250 h	MO -, SO -	MO -, SO -	MO -, SO -
Nitrile 322	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 500 h, SO ≤ 168 h	MO = 500, SO -	MO -, SO -
Nitrile 333	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h	MO ≤ 417 h, SO ≤ 333 h
ACM 334	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 333 h
Viton 337	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 500 h, SO ≤ 333 h
HNBR 338	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 168 h	MO ≤ 417 h, SO ≤ 168 h	MO ≤ 168 h, SO -
AEM/Vamac 336	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO -

Table 4.2: Change in volume

	120	130	140	150
Nitrile 321	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h
Silicone 332	MO ≤ 500 h, SO ≤ 333 h	MO -, SO -	MO -, SO -	MO -, SO -
Nitrile 322	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h
Nitrile 333	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h	MO ≤ 417 h, SO ≤ 168 h
ACM 334	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h	MO ≤ 500 h, SO ≤ 250 h
Viton 337	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 333 h
HNBR 338	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h	MO ≤ 417 h, SO ≤ 333 h	MO ≤ 333 h, SO ≤ 168 h
AEM/Vamac 336	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 250 h

Table 4.3: Tensile strength

	120	130	140	150
Nitrile 321	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO -	MO -, SO -	MO -, SO -
Silicone 332	MO ≤ 500 h, SO	MO ≤ 500 h, SO	MO ≤ 500 h, SO	MO ≤ 500 h, SO

	≤ 500 h	≤ 500 h	≤ 500 h	-
Nitrile 322	MO ≤ 500 h, SO ≤ 333 h	MO -, SO -	MO -, SO -	MO -, SO -
Nitrile 333	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 333 h	MO -, SO -	MO -, SO -
ACM 334	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h
Viton 337	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h
HNBR 338	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 417 h	MO ≤ 500 h, SO ≤ 168 h	MO -, SO -
AEM/Vamac 336	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h

Table 4.4: Elongation

	120	130	140	150
Nitrile 321	MO ≤ 500 h, SO ≤ 417 h	MO -, SO -	MO -, SO -	MO -, SO -
Silicone 332	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h
Nitrile 322	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 500 h, SO-	MO ≤ 168 h, SO -	MO -, SO -
Nitrile 333	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 168 h, SO -	MO -, SO -
ACM 334	MO ≤ 500 h, SO	MO ≤ 500 h, SO	MO ≤ 500 h, SO	MO ≤ 500 h, SO

	≤ 500 h	≤ 500 h	≤ 500 h	≤ 250 h
Viton 337	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 500 h
HNBR 338	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 500 h, SO ≤ 333 h	MO ≤ 417 h, SO ≤ 333 h	MO -, SO -
AEM/Vamac 336	MO ≤ 500 h, SO ≤ 500 h	MO ≤ 500 h, SO ≤ 250 h	MO ≤ 500 h, SO ≤ 168 h	MO ≤ 500 h, SO ≤ 168 h

Chapter 5: DOE

5.1 Introduction

The purpose of using DOE is to determine if the data produced is significant and to determine model equations for each variable i.e. change in hardness, change in volume, tensile strength and elongation. This will be plotted against actual data to determine predicted verse actual plot to determine how accurate data is. This has been conducted for mineral oil and not synthetic oil as synthetic oil has the same trends as mineral oil but more degrading. The outcome will be the same.

5.1.1 Model terms for submersion in mineral oil

Power calculations are performed using response type "Continuous" and parameters where Delta = 2 and Sigma = 1. Power is evaluated over the -1 to +1 coded factor space. Standard errors should be similar to each other in a balanced design. Lower standard errors are better. The ideal VIF value is 1.0. VIFs above 10 are cause for concern. VIFs above 100 are cause for alarm, indicating coefficients are poorly estimated due to multicollinearity. The Ideal R_i^2 is 0.0. High R_i^2 means terms are correlated with each other, possibly leading to poor models.

Table 5.1: Model term evaluation

Term	Standard Error*	VIF	R_i^2	Power
A	0.3536	1	0.0000	68.1 %
B	0.3536	1	0.0000	68.1 %
C	0.3536	1	0.0000	68.1 %
AB	0.5000	1	0.0000	40.8 %
AC	0.5000	1	0.0000	40.8 %
BC	0.5000	1	0.0000	40.8 %
A^2	0.4873	1.00588	0.0058	93.8 %
B^2	0.4873	1.00588	0.0058	93.8 %
C^2	0.4873	1.00588	0.0058	93.8 %

- For a standard deviation of 1.

The model determined from data in table 5.1 for prediction of materials clearly indicates that the coefficients are correctly estimated as the VIFs are all below 10. The R_i^2 values obtained are 0 for term A which is material, B which is temperature, C which is time, AB, AC and BC. The R_i^2 values obtained are 0.0058 for A^2, B^2 and C^2. These values show that the model is not poor as the values are 0 and close to 0.

5.2 Analysis of model terms for materials submerged in mineral oil

5.2.1 ANOVA for quadratic model for hardness results for submersion in mineral oil

The ANOVA table assists in detecting the chosen effects together with their coefficients. Table 5.2 shows the ANOVA outputs for hardness results for nitrile 321, ACM 334 and Viton 337 (refer to Table A.1 for raw data).

Table 5.2: Response 1 hardness mineral oil

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	382.66	4	95.67	33.53	< 0.0001	Significant
A-Materials	31.32	1	31.32	10.98	0.0062	
B-Temp	196.68	1	196.68	68.93	< 0.0001	
C-Time	57.84	1	57.84	20.27	0.0007	
A^2	96.82	1	96.82	33.93	< 0.0001	
Residual	34.24	12	2.85			
Lack of Fit	34.24	8	4.28			
Pure Error	0.0000	4	0.0000			
Cor Total	416.90	16				

The Model F-value of 33.53 implies the model is significant. There is only a 0.01 % chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C, A^2 are significant model terms which means that temperature and time can be correlated to materials. Values greater than 0.1000 indicate the model terms are not significant.

Model:

$$Hardness = 11.09 - 1.98A + 4.96B + 2.69C - 4.78A^2$$

The model meets the objectives as all terms are significant as all p-values are less than 0.05.

5.2.2 ANOVA for quadratic model for change in volume results for submersion in mineral oil

Table 5.3: Response 2 change in volume mineral oil

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	190.90	4	47.73	28.58	< 0.0001	significant
A-Materials	153.56	1	153.56	91.97	< 0.0001	
B-Temp	20.03	1	20.03	12.00	0.0047	
C-Time	7.86	1	7.86	4.71	0.0508	
A^2	9.45	1	9.45	5.66	0.0348	
Residual	20.04	12	1.67			
Lack of Fit	20.04	8	2.50			
Pure Error	0.0000	4	0.0000			
Cor Total	210.94	16				

The Model F-value of 28.58 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. Therefor C is significant because although C is greater than 0.0500, it is less than 0.1000.

Model:

Volume = -13.11972 + 4.38125M + 0.105500TE + 0.005971T – 1.49347M

5.2.3 ANOVA for quadratic model for tensile strength results for submersion in mineral oil

Table 5.4: Response 3 strength mineral oil

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	535.23	4	133.81	56.96	< 0.0001	significant
A-Materials	289.20	1	289.20	123.12	< 0.0001	
B-Temp	136.87	1	136.87	58.27	< 0.0001	
C-Time	46.80	1	46.80	19.92	0.0008	
A^2	62.36	1	62.36	26.55	0.0002	
Residual	28.19	12	2.35			

Lack of Fit	28.19	8	3.52			
Pure Error	0.0000	4	0.0000			
Cor Total	563.42	16				

The Model F-value of 56.96 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C, A^2 are significant model terms.

Model:

Tensile strength = 15.99 + 6.01A – 4.14B – 2.42C – 3.84A2

5.2.4 ANOVA for quadratic model for tensile strength results for submersion in mineral oil

Table 5.5: Response 4 elongation mineral oil

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	83648.54	4	20912.14	101.35	< 0.0001	significant
A-Materials	67813.24	1	67813.24	328.65	< 0.0001	
B-Temp	12728.90	1	12728.90	61.69	< 0.0001	
C-Time	2740.96	1	2740.96	13.28	0.0034	
A^2	365.45	1	365.45	1.77	0.2080	
Residual	2476.05	12	206.34			
Lack of Fit	2476.05	8	309.51			
Pure Error	0.0000	4	0.0000			
Cor Total	86124.59	16				

The Model F-value of 101.35 implies the model is significant. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C is significant model terms. Values greater than 0.1000 indicate the model terms are not significant. In this scenario A^2 is not significant.

Model:

*Elongation = 183.11 + 92.07A – 39.89 -18.51C +9.29*A^2

5.3 Fit statistics determination of R^2 value for materials submerged in mineral oil

These results are based on nitrile 321 represented as -1, ACM 334 represented as 0 and Viton 334 represented as 1.

5.3.1 Determination of R^2 for hardness results for submersion in mineral oil

Table 5.6: Hardness R2 results mineral oil

Std. Dev.	1.69	**R^2**	0.9179
Mean	8.84	**Adjusted R^2**	0.8905
C.V. %	19.10	**Predicted R^2**	0.7966
		Adeq Precision	21.1394

The Predicted R^2 of 0.7966 is in reasonable agreement with the Adjusted R^2 of 0.8905; i.e. the difference is less than 0.2. Adequate Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The model ratio of 21.139 indicates an adequate signal. This model can be used to navigate the design space.

5.3.2 Determination of R^2 for change in volume results for submersion in mineral oil

Table 5.7: Change in volume R2 results mineral oil

Std. Dev.	1.29	**R^2**	0.9050
Mean	2.41	**Adjusted R^2**	0.8734
C.V. %	53.52	**Predicted R^2**	0.7592
		Adeq Precision	17.0207

The Predicted R^2 of 0.7592 is in reasonable agreement with the Adjusted R^2 of 0.8734; i.e. the difference is less than 0.2. The model ratio of 17.021 indicates an adequate signal. This model can be used to navigate the design space.

5.3.3 Determination of R^2 for tensile strength results for submersion in mineral oil

Table 5.8: Tensile strength R2 results mineral oil

Std. Dev.	1.53	**R^2**	0.9500
Mean	14.19	**Adjusted R^2**	0.9333
C.V. %	10.80	**Predicted R^2**	0.8744
		Adeq Precision	24.7126

The Predicted R^2 of 0.8744 is in reasonable agreement with the Adjusted R^2 of 0.9333; i.e. the difference is less than 0.2. The model ratio of 24.713 indicates an adequate signal. This model can be used to navigate the design space.

5.3.4 Determination of R^2 for tensile strength results for submersion in mineral oil

Table 5.9: Tensile strength R2 results mineral oil

Std. Dev.	14.36	**R^2**	0.9713
Mean	187.48	**Adjusted R^2**	0.9617
C.V. %	7.66	**Predicted R^2**	0.9271
		Adeq Precision	33.8778

The Predicted R^2 of 0.9271 is in reasonable agreement with the Adjusted R^2 of 0.9617; i.e. the difference is less than 0.2. The model ratio of 33.878 indicates an adequate signal. This model can be used to navigate the design space.

5.4 Coefficient estimates for materials submerged in mineral oil

These results are based on nitrile 321 represented as -1, ACM 334 represented as 0 and Viton 334 represented as 1. The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multi-colinearity, the higher the VIF the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable. Table 5.10, 5.11, 5.12 and 5.13 indicate that the factors are orthogonal.

Table 5.10: Coefficients in terms of coded factors for hardness mineral oil

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	11.09	1	0.5631	9.87	12.32	
A-Materials	-1.98	1	0.5972	-3.28	-0.6775	1.0000
B-Temp	4.96	1	0.5972	3.66	6.26	1.0000
C-Time	2.69	1	0.5972	1.39	3.99	1.0000
A^2	-4.78	1	0.8208	-6.57	-2.99	1.0000

Table 5.11: Coefficients in terms of coded factors for change in volume mineral oil

Factor	Coefficient	df	Standard	95% CI	95% CI	VIF

	Estimate		Error	Low	High	
Intercept	3.12	1	0.4307	2.18	4.06	
A-Materials	4.38	1	0.4568	3.39	5.38	1.0000
B-Temp	1.58	1	0.4568	0.5871	2.58	1.0000
C-Time	0.9912	1	0.4568	-0.0041	1.99	1.0000
A^2	-1.49	1	0.6279	-2.86	-0.1255	1.0000

Table 5.12: Coefficients in terms of coded factors for tensile strength mineral oil

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	15.99	1	0.5109	14.88	17.11	
A-Materials	6.01	1	0.5419	4.83	7.19	1.0000
B-Temp	-4.14	1	0.5419	-5.32	-2.96	1.0000
C-Time	-2.42	1	0.5419	-3.60	-1.24	1.0000
A^2	-3.84	1	0.7447	-5.46	-2.21	1.0000

Table 5.13: Coefficients in terms of coded factors for elongation mineral oil

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	183.11	1	4.79	172.68	193.54	
A-Materials	92.07	1	5.08	81.00	103.13	1.0000
B-Temp	-39.89	1	5.08	-50.95	-28.82	1.0000
C-Time	-18.51	1	5.08	-29.58	-7.44	1.0000
A^2	9.29	1	6.98	-5.92	24.50	1.0000

5.5 Coded equations and actual equations for materials submerged in mineral oil

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

The equations in terms of coded factors for mineral oil are as follows:

$$Hardness = 11.09 - 1.98A + 4.96B + 2.69C - 4.78A^2$$ **Equation 5.1**

$$Volume = 3.12 + 4.38A + 1.58 + 0.9912C - 1.49A^2$$ **Equation 5.2**

$$Tensile\ strength = 15.99 + 6.01A - 4.14B - 2.42C - 3.84A2$$ **Equation 5.3**

$$Elongation = 183.11 + 92.07A - 39.89 - 18.51C + 9.29A^2$$ **Equation 5.4**

Equation 5.1, 5.2, 5.3 and 5.4 may possibly be used to make estimations about the coded factors.

Final equations are as follows:

$$Hardness = -38.94230 - 1.97875M + 0.330556TE + 0.016197T - 4.78134M^2 \quad \textbf{Equation 5.5}$$

$$Volume = -13.11972 + 4.38125M + 0.105500TE + 0.005971T - 1.49347M \quad \textbf{Equation 5.6}$$

$$Tensile\ strength = 58.08511 + 6.01250M - 0.275750TE - 0.014571T - 3.83722M^2 \quad \textbf{Equation 5.7}$$

$$Elongation = 579.35398 + 92.06875M - 2.65925TE - 0.111506T + 9.28903M^2 \quad \textbf{Equation 5.8}$$

Equation 5.5 and 5.6, 5.7 and 5.8 may possibly be used to make estimations about the actual factors.

Sample calculations: (Table A.5)

$$Hardness = -38.94230 - 1.97875(0) + 0.330556(150) + 0.016197(334) - 4.78134(0)^2 = 16.0509$$

Actual raw data = 17.6667

$$Hardness = -38.94230 - 1.97875(0) + 0.330556(120) + 0.016197(250) - 4.78134(0)^2 = 4.77367$$

Actual raw data = 2.33333

$$Hardness = -38.94230 - 1.97875(0) + 0.330556(150) + 0.016197(250) - 4.78134(0)^2 = 14.69035$$

Actual raw data = 17.3333

$$Hardness = -38.94230 - 1.97875(0) + 0.330556(130) + 0.016197(250) - 4.78134(0)^2 = 8.07923$$

Actual raw data = 6.33333

$$Hardness = -38.94230 - 1.97875(0) + 0.330556(140) + 0.016197(500) - 4.78134(0)^2 = 15.43404$$

Actual raw data = 17.3333

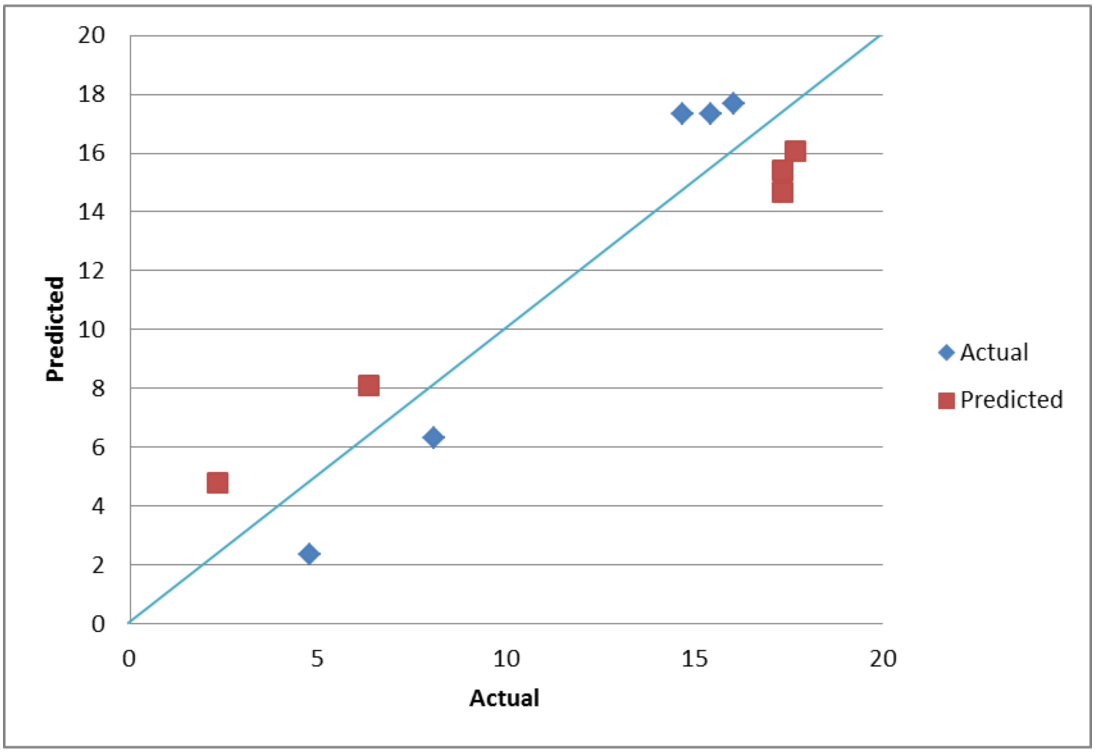


Figure 5.1: Predicted verses actual plot for hardness mineral oil

The rest of the DOE parameters are shown in Appendix E.

The coefficients were adjusted by removing the insignificant factors that did not produce an R^2 that was close to 99%. The R^2 shows that the trends are significant.

Chapter 6: Conclusions

Based on DOE results, the following conclusions have been made due to validation of lab testing. The laboratory hours were converted to km by using an average speed of a car as 60 km/h.

6.1 Nitrile 321

When nitrile 321 is exposed to mineral oil, its overall operating condition is 120 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C for a maximum of 20 000 km. This indicates that synthetic oil is a stronger fluid as it degrades nitrile 321 more rapidly than mineral oil.

6.2 Silicone 332

When Silicone 332 is exposed to mineral oil, its overall operating condition is 120 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C for a maximum of 15 000 km. This indicates that synthetic oil is a stronger fluid as it degrades silicone 332 more rapidly than mineral oil.

6.3 Nilrile 322

When nitrile 322 is exposed to mineral oil, its overall operating condition is 120 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C for a maximum of 20 000 km. This indicates that synthetic oil is a stronger fluid as it degrades nitrile 332 more rapidly than mineral oil.

6.4 Nitrile 333

When nitrile 333 is exposed to mineral oil, its overall operating condition is 120 °C and 130 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C for a maximum of 30 000 km and 130 °C for a maximum service interval of 20 000 km. This indicates that synthetic oil is a stronger fluid as it degrades nitrile 333 more rapidly than mineral oil.

6.5 ACM 334

When ACM 334 is exposed to mineral oil, its overall operating condition is 120 °C to 150 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C to 130 °C for a maximum of 30 000 km, 140 °C for a maximum service interval of 20 000 km's and 150 °C for a maximum service interval of 15 000 km. This indicates that synthetic oil is a stronger fluid as it degrades ACM 334 more rapidly than mineral oil.

6.6 Viton 337

When Viton 337 is exposed to mineral oil, its overall operating condition is 120 °C to 150 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C to 130 °C for a maximum of 30 000 km, 140 °C for a maximum service interval of 20 000 km and 150 °C for a maximum of 20 000 km. This indicates that synthetic oil is a stronger fluid as it degrades Viton 337 more rapidly than mineral oil.

6.7 HNBR 338

When HNBR 338 is exposed to mineral oil, its overall operating condition is 120 °C to 130 °C for a maximum service interval of 30 000 km and 140 °C for a maximum service interval of 20 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C for a maximum of 20 000 km, 130 °C for a maximum service interval of 10 000 km, 140 °C for a maximum service interval of 10 000 km. This indicates that synthetic oil is a stronger fluid as it degrades HNBR 338 more rapidly than mineral oil.

6.8 AEM 336

When AEM 336 is exposed to mineral oil, its overall operating condition is 120 °C to 150 °C for a maximum service interval of 30 000 km and when exposed to synthetic oil, the overall operating condition is 120 °C to 130 °C for a maximum of 30 000 km and 140 °C for a maximum service interval of 10 000 km. This indicates that synthetic oil is a stronger fluid as it degrades AEM 336 more rapidly than mineral oil.

Overall summary:

This work has eliminated the process of using FTIR as the DOE will be able to identify which material to use for which requirement. The work has also identified the best rubber grades that generally suitable in all areas. This can be used to mass buy and thereby reduce costs. Synthetic oil was tested as certain cars use this type of oil and that is why it is relevant to the selection of rubber.

Chapter 7: Recommendations

1. ACM/Viton to be used across all filters if cost effective.

2. Synthetic oil DOE to be conducted if doctorate pursued on the same subject matter.

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Appendices

Appendix A: Hardness results

Table A 1: Nitrile 321 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
1	Nitrile 321	Mineral Oil	150	168	8	7	8	7.67
2	Nitrile 321	Mineral Oil	150	250	9	8	9	8.67
3	Nitrile 321	Mineral Oil	150	333	10	11	10	10.33
4	Nitrile 321	Mineral Oil	150	417	11	11	10	10.67
5	Nitrile 321	Mineral Oil	150	500	12	12	11	11.67
6	Nitrile 321	Mineral Oil	140	168	7	7	7	7.00
7	Nitrile 321	Mineral Oil	140	250	9	8	8	8.33
8	Nitrile 321	Mineral Oil	140	333	10	10	10	10.00
9	Nitrile 321	Mineral Oil	140	417	11	11	11	11.00
10	Nitrile 321	Mineral Oil	140	500	12	12	12	12.00
11	Nitrile 321	Mineral Oil	130	168	7	7	6	6.67
12	Nitrile 321	Mineral Oil	130	250	8	8	8	8.00
13	Nitrile 321	Mineral Oil	130	333	10	9	10	9.67
14	Nitrile 321	Mineral Oil	130	417	10	10	11	10.33
15	Nitrile 321	Mineral Oil	130	500	11	11	12	11.33
16	Nitrile 321	Mineral Oil	120	168	4	3	3	3.33
17	Nitrile 321	Mineral Oil	120	250	4	4	4	4.00
18	Nitrile 321	Mineral Oil	120	333	4	4	5	4.33
19	Nitrile 321	Mineral Oil	120	417	4	5	5	4.67
20	Nitrile 321	Mineral Oil	120	500	5	5	5	5.00

Table A 2: Silicone 332 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
21	Silicone 332	Mineral Oil	150	168	-17	-17	-16	-16.67
22	Silicone 332	Mineral Oil	150	250	-18	-18	-19	-18.33
23	Silicone 332	Mineral Oil	150	333	-18	-18	-19	-18.33
24	Silicone 332	Mineral Oil	150	417	-20	-20	-19	-19.67
25	Silicone 332	Mineral Oil	150	500	-21	-20	-21	-20.67
26	Silicone 332	Mineral Oil	140	168	-14	-15	-15	-14.67
27	Silicone 332	Mineral Oil	140	250	-16	-15	-16	-15.67
28	Silicone 332	Mineral Oil	140	333	-17	-16	-17	-16.67
29	Silicone 332	Mineral Oil	140	417	-18	-17	-17	-17.33
30	Silicone 332	Mineral Oil	140	500	-20	-19	-19	-19.33
31	Silicone 332	Mineral Oil	130	168	-13	-13	-14	-13.33
32	Silicone 332	Mineral Oil	130	250	-14	-15	-14	-14.33
33	Silicone 332	Mineral Oil	130	333	-14	-14	-15	-14.33
34	Silicone 332	Mineral Oil	130	417	-15	-16	-15	-15.33
35	Silicone 332	Mineral Oil	130	500	-17	-16	-16	-16.33
36	Silicone 332	Mineral Oil	120	168	-7	-6	-7	-6.67
37	Silicone 332	Mineral Oil	120	250	-8	-8	-7	-7.67
38	Silicone 332	Mineral Oil	120	333	-9	-8	-9	-8.67
39	Silicone 332	Mineral Oil	120	417	-10	-9	-9	-9.33
40	Silicone 332	Mineral Oil	120	500	-10	-9	-10	-9.67

Table A 3: Nitrile 322 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
41	Nitrile 322	Mineral Oil	150	168	-12	-11	-12	-11.667
42	Nitrile 322	Mineral Oil	150	250	-14	-13	-14	-13.667
43	Nitrile 322	Mineral Oil	150	333	-16	-15	-16	-15.667
44	Nitrile 322	Mineral Oil	150	417	-17	-16	-17	-16.667
45	Nitrile 322	Mineral Oil	150	500	-19	-19	-20	-19.333
46	Nitrile 322	Mineral Oil	140	168	-10	-11	-11	-10.667
47	Nitrile 322	Mineral Oil	140	250	-13	-13	-12	-12.667
48	Nitrile 322	Mineral Oil	140	333	-15	-16	-15	-15.333
49	Nitrile 322	Mineral Oil	140	417	-16	-16	-17	-16.333
50	Nitrile 322	Mineral Oil	140	500	-19	-19	-19	-19
51	Nitrile 322	Mineral Oil	130	168	-4	-5	-6	-5
52	Nitrile 322	Mineral Oil	130	250	-6	-6	-5	-5.6667
53	Nitrile 322	Mineral Oil	130	333	-7	-6	-7	-6.6667
54	Nitrile 322	Mineral Oil	130	417	-8	-8	-8	-8
55	Nitrile 322	Mineral Oil	130	500	-9	-8	-8	-8.3333
56	Nitrile 322	Mineral Oil	120	168	0	0	-1	-0.3333
57	Nitrile 322	Mineral Oil	120	250	-1	-1	-2	-1.3333
58	Nitrile 322	Mineral Oil	120	333	-2	-2	-3	-2.3333
59	Nitrile 322	Mineral Oil	120	417	-4	-3	-3	-3.3333
60	Nitrile 322	Mineral Oil	120	500	-4	-4	-3	-3.6667

Table A 4: Nitrile 322 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
61	Nitrile 333	Mineral Oil	150	168	1	1	2	1.33333
62	Nitrile 333	Mineral Oil	150	250	2	2	3	2.33333
63	Nitrile 333	Mineral Oil	150	333	7	7	6	6.66667
64	Nitrile 333	Mineral Oil	150	417	8	8	7	7.66667
65	Nitrile 333	Mineral Oil	150	500	14	13	13	13.3333
66	Nitrile 333	Mineral Oil	140	168	0	1	1	0.66667
67	Nitrile 333	Mineral Oil	140	250	1	1	1	1
68	Nitrile 333	Mineral Oil	140	333	2	2	2	2
69	Nitrile 333	Mineral Oil	140	417	5	6	6	5.66667
70	Nitrile 333	Mineral Oil	140	500	10	9	10	9.66667
71	Nitrile 333	Mineral Oil	130	168	-1	0	0	-0.3333
72	Nitrile 333	Mineral Oil	130	250	1	0	1	0.66667
73	Nitrile 333	Mineral Oil	130	333	1	2	1	1.33333
74	Nitrile 333	Mineral Oil	130	417	4	5	5	4.66667
75	Nitrile 333	Mineral Oil	130	500	10	10	9	9.66667
76	Nitrile 333	Mineral Oil	120	168	-3	-2	-2	-2.3333
77	Nitrile 333	Mineral Oil	120	250	-1	-2	-1	-1.3333
78	Nitrile 333	Mineral Oil	120	333	0	1	1	0.66667
79	Nitrile 333	Mineral Oil	120	417	1	2	2	1.66667
80	Nitrile 333	Mineral Oil	120	500	5	4	5	4.66667

Table A 5: ACM 334 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
81	ACM 334	Mineral Oil	150	168	15	15	16	15.3333
82	ACM 334	Mineral Oil	150	250	17	18	17	17.3333
83	ACM 334	Mineral Oil	150	333	17	18	18	17.6667
84	ACM 334	Mineral Oil	150	417	18	18	19	18.3333
85	ACM 334	Mineral Oil	150	500	19	20	19	19.3333
86	ACM 334	Mineral Oil	140	168	10	10	9	9.66667
87	ACM 334	Mineral Oil	140	250	11	11	10	10.6667
88	ACM 334	Mineral Oil	140	333	14	13	14	13.6667
89	ACM 334	Mineral Oil	140	417	16	16	17	16.3333
90	ACM 334	Mineral Oil	140	500	17	18	17	17.3333
91	ACM 334	Mineral Oil	130	168	4	4	5	4.33333
92	ACM 334	Mineral Oil	130	250	6	6	7	6.33333
93	ACM 334	Mineral Oil	130	333	9	9	10	9.33333
94	ACM 334	Mineral Oil	130	417	10	10	9	9.66667
95	ACM 334	Mineral Oil	130	500	12	12	12	12
96	ACM 334	Mineral Oil	120	168	0	0	1	0.33333
97	ACM 334	Mineral Oil	120	250	2	2	3	2.33333
98	ACM 334	Mineral Oil	120	333	4	4	3	3.66667
99	ACM 334	Mineral Oil	120	417	5	5	6	5.33333
100	ACM 334	Mineral Oil	120	500	7	7	8	7.33333

Table A 6:Viton 337 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
101	Viton 337	Mineral Oil	150	168	5	4	5	4.66667
102	Viton 337	Mineral Oil	150	250	6	6	7	6.33333
103	Viton 337	Mineral Oil	150	333	7	7	8	7.33333
104	Viton 337	Mineral Oil	150	417	9	10	9	9.33333
105	Viton 337	Mineral Oil	150	500	10	10	10	10
106	Viton 337	Mineral Oil	140	168	3	2	3	2.66667
107	Viton 337	Mineral Oil	140	250	4	3	3	3.33333
108	Viton 337	Mineral Oil	140	333	6	5	6	5.66667
109	Viton 337	Mineral Oil	140	417	7	6	7	6.66667
110	Viton 337	Mineral Oil	140	500	9	8	9	8.66667
111	Viton 337	Mineral Oil	130	168	1	1	1	1
112	Viton 337	Mineral Oil	130	250	2	3	2	2.33333
113	Viton 337	Mineral Oil	130	333	4	4	3	3.66667
114	Viton 337	Mineral Oil	130	417	5	6	5	5.33333
115	Viton 337	Mineral Oil	130	500	6	7	6	6.33333
116	Viton 337	Mineral Oil	120	168	-2	-3	-3	-2.6667
117	Viton 337	Mineral Oil	120	250	-1	-2	-2	-1.6667
118	Viton 337	Mineral Oil	120	333	0	1	1	0.66667
119	Viton 337	Mineral Oil	120	417	2	2	2	2
120	Viton 337	Mineral Oil	120	500	3	2	3	2.66667

Table A 7: Viton 337 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
121	HNBR 338	Mineral Oil	150	168	7	8	7	7.33333
122	HNBR 338	Mineral Oil	150	250	8	8	7	7.66667
123	HNBR 338	Mineral Oil	150	333	9	9	10	9.33333
124	HNBR 338	Mineral Oil	150	417	10	10	9	9.66667
125	HNBR 338	Mineral Oil	150	500	10	10	10	10
126	HNBR 338	Mineral Oil	140	168	6	5	5	5.33333
127	HNBR 338	Mineral Oil	140	250	7	7	6	6.66667
128	HNBR 338	Mineral Oil	140	333	8	7	7	7.33333
129	HNBR 338	Mineral Oil	140	417	8	7	8	7.66667
130	HNBR 338	Mineral Oil	140	500	8	9	8	8.33333
131	HNBR 338	Mineral Oil	130	168	5	4	5	4.66667
132	HNBR 338	Mineral Oil	130	250	6	6	7	6.33333
133	HNBR 338	Mineral Oil	130	333	7	7	6	6.66667
134	HNBR 338	Mineral Oil	130	417	8	7	7	7.33333
135	HNBR 338	Mineral Oil	130	500	8	7	8	7.66667
136	HNBR 338	Mineral Oil	120	168	0	1	1	0.66667
137	HNBR 338	Mineral Oil	120	250	1	1	1	1
138	HNBR 338	Mineral Oil	120	333	2	3	2	2.33333
139	HNBR 338	Mineral Oil	120	417	4	4	3	3.66667
140	HNBR 338	Mineral Oil	120	500	5	4	5	4.66667

Table A 8: AEM/Vamac 336 hardness results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
141	AEM/Vamac 336	Mineral Oil	150	168	2	1	1	1.33333
142	AEM/Vamac 336	Mineral Oil	150	250	1	2	2	1.66667
143	AEM/Vamac 336	Mineral Oil	150	333	2	2	2	2
144	AEM/Vamac 336	Mineral Oil	150	417	3	2	2	2.33333
145	AEM/Vamac 336	Mineral Oil	150	500	3	3	3	3
146	AEM/Vamac 336	Mineral Oil	140	168	0	1	0	0.33333
147	AEM/Vamac 336	Mineral Oil	140	250	0	1	1	0.66667
148	AEM/Vamac 336	Mineral Oil	140	333	1	2	1	1.33333
149	AEM/Vamac 336	Mineral Oil	140	417	2	1	1	1.33333
150	AEM/Vamac 336	Mineral Oil	140	500	2	2	3	2.33333
151	AEM/Vamac 336	Mineral Oil	130	168	-2	-1	-2	-1.6667
152	AEM/Vamac 336	Mineral Oil	130	250	-2	-1	-1	-1.3333
153	AEM/Vamac 336	Mineral Oil	130	333	-1	-1	0	-0.6667
154	AEM/Vamac 336	Mineral Oil	130	417	0	1	0	0.33333
155	AEM/Vamac 336	Mineral Oil	130	500	1	1	0	0.66667
156	AEM/Vamac 336	Mineral Oil	120	168	-9	-9	-10	-9.3333
157	AEM/Vamac 336	Mineral Oil	120	250	-8	-8	-9	-8.3333
158	AEM/Vamac 336	Mineral Oil	120	333	-6	-7	-7	-6.6667
159	AEM/Vamac 336	Mineral Oil	120	417	-2	-3	-3	-2.6667
160	AEM/Vamac 336	Mineral Oil	120	500	0	0	1	0.33333

Table A 9: Nitrile 321 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
161	Nitrile 321	Synthetic Oil	150	168	9	10	10	9.67
162	Nitrile 321	Synthetic Oil	150	250	11	11	11	11.00
163	Nitrile 321	Synthetic Oil	150	333	13	12	12	12.33
164	Nitrile 321	Synthetic Oil	150	417	13	12	13	12.67
165	Nitrile 321	Synthetic Oil	150	500	14	13	13	13.33
166	Nitrile 321	Synthetic Oil	140	168	9	10	9	9.33
167	Nitrile 321	Synthetic Oil	140	250	10	11	10	10.33
168	Nitrile 321	Synthetic Oil	140	333	12	12	12	12.00
169	Nitrile 321	Synthetic Oil	140	417	13	12	12	12.33
170	Nitrile 321	Synthetic Oil	140	500	12	12	14	12.67
171	Nitrile 321	Synthetic Oil	130	168	9	8	7	8.00
172	Nitrile 321	Synthetic Oil	130	250	9	10	10	9.67
173	Nitrile 321	Synthetic Oil	130	333	11	12	11	11.33
174	Nitrile 321	Synthetic Oil	130	417	11	11	13	11.67
175	Nitrile 321	Synthetic Oil	130	500	13	12	12	12.33
176	Nitrile 321	Synthetic Oil	120	168	4	5	5	4.67
177	Nitrile 321	Synthetic Oil	120	250	4	5	5	4.67
178	Nitrile 321	Synthetic Oil	120	333	5	5	5	5.00
179	Nitrile 321	Synthetic Oil	120	417	7	6	7	6.67
180	Nitrile 321	Synthetic Oil	120	500	8	7	7	7.33

Table A 10: Silicone 332 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
181	Silicone 332	Synthetic Oil	150	168	-19	-18	-19	-18.67
182	Silicone 332	Synthetic Oil	150	250	-20	-20	-21	-20.33
183	Silicone 332	Synthetic Oil	150	333	-20	-21	-20	-20.33
184	Silicone 332	Synthetic Oil	150	417	-22	-21	-22	-21.67
185	Silicone 332	Synthetic Oil	150	500	-23	-22	-22	-22.33
186	Silicone 332	Synthetic Oil	140	168	-16	-17	-17	-16.67
187	Silicone 332	Synthetic Oil	140	250	-18	-17	-18	-17.67
188	Silicone 332	Synthetic Oil	140	333	-19	-19	-18	-18.67
189	Silicone 332	Synthetic Oil	140	417	-20	-19	-19	-19.33
190	Silicone 332	Synthetic Oil	140	500	-22	-22	-21	-21.67
191	Silicon 332	Synthetic Oil	130	168	-15	-16	-15	-15.33
192	Silicon 332	Synthetic Oil	130	250	-16	-17	-16	-16.33
193	Silicon 332	Synthetic Oil	130	333	-16	-16	-17	-16.33
194	Silicon 332	Synthetic Oil	130	417	-17	-18	-17	-17.33
195	Silicon 332	Synthetic Oil	130	500	-18	-18	-19	-18.33
196	Silicon 332	Synthetic Oil	120	168	-9	-7	-9	-8.33
197	Silicon 332	Synthetic Oil	120	250	-10	-10	-9	-9.67
198	Silicon 332	Synthetic Oil	120	333	-11	-11	-10	-10.67
199	Silicon 332	Synthetic Oil	120	417	-11	-12	-11	-11.33
200	Silicon 332	Synthetic Oil	120	500	-12	-11	-12	-11.67

Table A 11: Nitrile 322 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
201	Nitrile 322	Synthetic Oil	150	168	-14	-14	-13	-13.667
202	Nitrile 322	Synthetic Oil	150	250	-15	-15	-16	-15.333
203	Nitrile 322	Synthetic Oil	150	333	-17	-17	-16	-16.667
204	Nitrile 322	Synthetic Oil	150	417	-19	-19	-18	-18.667
205	Nitrile 322	Synthetic Oil	150	500	-21	-21	-22	-21.333
206	Nitrile 322	Synthetic Oil	140	168	-12	-13	-12	-12.333
207	Nitrile 322	Synthetic Oil	140	250	-15	-15	-14	-14.667
208	Nitrile 322	Synthetic Oil	140	333	-18	-17	-17	-17.333
209	Nitrile 322	Synthetic Oil	140	417	-18	-18	-19	-18.333
210	Nitrile 322	Synthetic Oil	140	500	-21	-20	-21	-20.667
211	Nitrile 322	Synthetic Oil	130	168	-8	-8	-10	-8.6667
212	Nitrile 322	Synthetic Oil	130	250	-12	-13	-12	-12.333
213	Nitrile 322	Synthetic Oil	130	333	-14	-13	-14	-13.667
214	Nitrile 322	Synthetic Oil	130	417	-15	-15	-16	-15.333
215	Nitrile 322	Synthetic Oil	130	500	-16	-16	-17	-16.333
216	Nitrile 322	Synthetic Oil	120	168	-4	-5	-5	-4.6667
217	Nitrile 322	Synthetic Oil	120	250	-5	-5	-6	-5.3333
218	Nitrile 322	Synthetic Oil	120	333	-7	-8	-9	-8
219	Nitrile 322	Synthetic Oil	120	417	-10	-11	-12	-11
220	Nitrile 322	Synthetic Oil	120	500	-12	-12	-13	-12.333

Table A 12: Nitrile 333 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
221	Nitrile 333	Synthetic Oil	150	168	3	2	3	2.66667
222	Nitrile 333	Synthetic Oil	150	250	4	3	4	3.66667
223	Nitrile 333	Synthetic Oil	150	333	9	8	9	8.66667
224	Nitrile 333	Synthetic Oil	150	417	10	10	12	10.6667
225	Nitrile 333	Synthetic Oil	150	500	15	14	15	14.6667
226	Nitrile 333	Synthetic Oil	140	168	2	2	2	2
227	Nitrile 333	Synthetic Oil	140	250	2	2	3	2.33333
228	Nitrile 333	Synthetic Oil	140	333	4	5	4	4.33333
229	Nitrile 333	Synthetic Oil	140	417	7	7	6	6.66667
230	Nitrile 333	Synthetic Oil	140	500	12	10	12	11.3333
231	Nitrile 333	Synthetic Oil	130	168	1	0	1	0.66667
232	Nitrile 333	Synthetic Oil	130	250	1	2	2	1.66667
233	Nitrile 333	Synthetic Oil	130	333	3	3	2	2.66667
234	Nitrile 333	Synthetic Oil	130	417	6	6	7	6.33333
235	Nitrile 333	Synthetic Oil	130	500	10	10	10	10
236	Nitrile 333	Synthetic Oil	120	168	-1	0	0	-0.3333
237	Nitrile 333	Synthetic Oil	120	250	2	1	1	1.33333
238	Nitrile 333	Synthetic Oil	120	333	2	2	1	1.66667
239	Nitrile 333	Synthetic Oil	120	417	3	3	4	3.33333
240	Nitrile 333	Synthetic Oil	120	500	7	6	7	6.66667

Table A 13: ACM 334 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
241	ACM 334	Synthetic Oil	150	168	17	17	18	17.3333
242	ACM 334	Synthetic Oil	150	250	20	19	19	19.3333
243	ACM 334	Synthetic Oil	150	333	19	20	20	19.6667
244	ACM 334	Synthetic Oil	150	417	21	20	20	20.3333
245	ACM 334	Synthetic Oil	150	500	22	21	21	21.3333
246	ACM 334	Synthetic Oil	140	168	12	11	12	11.6667
247	ACM 334	Synthetic Oil	140	250	12	13	12	12.3333
248	ACM 334	Synthetic Oil	140	333	16	14	15	15
249	ACM 334	Synthetic Oil	140	417	18	17	19	18
250	ACM 334	Synthetic Oil	140	500	19	20	19	19.3333
251	ACM 334	Synthetic Oil	130	168	6	7	6	6.33333
252	ACM 334	Synthetic Oil	130	250	8	9	8	8.33333
253	ACM 334	Synthetic Oil	130	333	11	12	11	11.3333
254	ACM 334	Synthetic Oil	130	417	11	12	12	11.6667
255	ACM 334	Synthetic Oil	130	500	14	14	14	14
256	ACM 334	Synthetic Oil	120	168	3	2	2	2.33333
257	ACM 334	Synthetic Oil	120	250	4	5	4	4.33333
258	ACM 334	Synthetic Oil	120	333	6	5	6	5.66667
259	ACM 334	Synthetic Oil	120	417	7	8	7	7.33333
260	ACM 334	Synthetic Oil	120	500	9	10	9	9.33333

Table A 14: Viton 337 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
261	Viton 337	Synthetic Oil	150	168	7	7	6	6.66667
262	Viton 337	Synthetic Oil	150	250	8	9	8	8.33333
263	Viton 337	Synthetic Oil	150	333	9	10	9	9.33333
264	Viton 337	Synthetic Oil	150	417	12	11	12	11.6667
265	Viton 337	Synthetic Oil	150	500	12	13	14	13
266	Viton 337	Synthetic Oil	140	168	5	5	4	4.66667
267	Viton 337	Synthetic Oil	140	250	6	6	5	5.66667
268	Viton 337	Synthetic Oil	140	333	8	9	8	8.33333
269	Viton 337	Synthetic Oil	140	417	10	11	11	10.6667
270	Viton 337	Synthetic Oil	140	500	12	12	13	12.3333
271	Viton 337	Synthetic Oil	130	168	3	3	2	2.66667
272	Viton 337	Synthetic Oil	130	250	4	5	4	4.33333
273	Viton 337	Synthetic Oil	130	333	6	5	6	5.66667
274	Viton 337	Synthetic Oil	130	417	7	8	7	7.33333
275	Viton 337	Synthetic Oil	130	500	8	8	9	8.33333
276	Viton 337	Synthetic Oil	120	168	-1	0	-1	-0.6667
277	Viton 337	Synthetic Oil	120	250	1	0	1	0.66667
278	Viton 337	Synthetic Oil	120	333	2	3	2	2.33333
279	Viton 337	Synthetic Oil	120	417	4	5	4	4.33333
280	Viton 337	Synthetic Oil	120	500	5	4	5	4.66667

Table A 15: HNBR 338 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
281	HNBR 338	Synthetic Oil	150	168	9	10	9	9.33333
282	HNBR 338	Synthetic Oil	150	250	10	10	9	9.66667
283	HNBR 338	Synthetic Oil	150	333	11	12	11	11.3333
284	HNBR 338	Synthetic Oil	150	417	11	12	12	11.6667
285	HNBR 338	Synthetic Oil	150	500	12	13	13	12.6667
286	HNBR 338	Synthetic Oil	140	168	7	7	8	7.33333
287	HNBR 338	Synthetic Oil	140	250	9	9	7	8.33333
288	HNBR 338	Synthetic Oil	140	333	10	9	9	9.33333
289	HNBR 338	Synthetic Oil	140	417	10	10	9	9.66667
290	HNBR 338	Synthetic Oil	140	500	10	11	10	10.3333
291	HNBR 338	Synthetic Oil	130	168	7	6	7	6.66667
292	HNBR 338	Synthetic Oil	130	250	8	8	9	8.33333
293	HNBR 338	Synthetic Oil	130	333	9	9	8	8.66667
294	HNBR 338	Synthetic Oil	130	417	10	9	9	9.33333
295	HNBR 338	Synthetic Oil	130	500	9	10	10	9.66667
296	HNBR 338	Synthetic Oil	120	168	2	3	3	2.66667
297	HNBR 338	Synthetic Oil	120	250	3	3	4	3.33333
298	HNBR 338	Synthetic Oil	120	333	4	5	4	4.33333
299	HNBR 338	Synthetic Oil	120	417	6	5	6	5.66667
300	HNBR 338	Synthetic Oil	120	500	7	6	7	6.66667

Table A 16: AEM 336 hardness results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
301	AEM/Vamac 336	Synthetic Oil	150	168	4	3	3	3.33333
302	AEM/Vamac 336	Synthetic Oil	150	250	3	4	4	3.66667
303	AEM/Vamac 336	Synthetic Oil	150	333	4	4	4	4
304	AEM/Vamac 336	Synthetic Oil	150	417	4	5	4	4.33333
305	AEM/Vamac 336	Synthetic Oil	150	500	5	5	5	5
306	AEM/Vamac 336	Synthetic Oil	140	168	2	2	3	2.33333
307	AEM/Vamac 336	Synthetic Oil	140	250	3	3	2	2.66667
308	AEM/Vamac 336	Synthetic Oil	140	333	3	4	3	3.33333
309	AEM/Vamac 336	Synthetic Oil	140	417	4	3	4	3.66667
310	AEM/Vamac 336	Synthetic Oil	140	500	4	5	4	4.33333
311	AEM/Vamac 336	Synthetic Oil	130	168	0	1	0	0.33333
312	AEM/Vamac 336	Synthetic Oil	130	250	0	1	1	0.66667
313	AEM/Vamac 336	Synthetic Oil	130	333	1	2	1	1.33333
314	AEM/Vamac 336	Synthetic Oil	130	417	2	3	2	2.33333
315	AEM/Vamac 336	Synthetic Oil	130	500	2	3	3	2.66667
316	AEM/Vamac 336	Synthetic Oil	120	168	-7	-7	-9	-7.6667
317	AEM/Vamac 336	Synthetic Oil	120	250	-6	-7	-6	-6.3333
318	AEM/Vamac 336	Synthetic Oil	120	333	-4	-5	-5	-4.6667
319	AEM/Vamac 336	Synthetic Oil	120	417	0	-1	-1	-0.6667
320	AEM/Vamac 336	Synthetic Oil	120	500	2	2	3	2.33333

Appendix B: Change in volume results

Table B 1: Nitrile 321 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
1	Nitrile 321	Mineral Oil	150	168	-3.13	-3.14	-3.12	-3.13
2	Nitrile 321	Mineral Oil	150	250	-3.19	-3.18	-3.18	-3.18
3	Nitrile 321	Mineral Oil	150	333	-3.21	-3.2	-3.19	-3.20
4	Nitrile 321	Mineral Oil	150	417	-3.26	-3.27	-3.26	-3.26
5	Nitrile 321	Mineral Oil	150	500	-3.4	-3.42	-3.43	-3.42
6	Nitrile 321	Mineral Oil	140	168	-2.6	-2.62	-2.64	-2.62
7	Nitrile 321	Mineral Oil	140	250	-2.67	-2.69	-2.68	-2.68
8	Nitrile 321	Mineral Oil	140	333	-2.72	-2.74	-2.73	-2.73
9	Nitrile 321	Mineral Oil	140	417	-2.79	-2.78	-2.76	-2.78
10	Nitrile 321	Mineral Oil	140	500	-2.82	-2.84	-2.83	-2.83
11	Nitrile 321	Mineral Oil	130	168	-2.54	-2.52	-2.53	-2.53
12	Nitrile 321	Mineral Oil	130	250	-2.56	-2.57	-2.57	-2.57
13	Nitrile 321	Mineral Oil	130	333	-2.62	-2.62	-2.63	-2.62
14	Nitrile 321	Mineral Oil	130	417	-2.69	-2.68	-2.69	-2.69
15	Nitrile 321	Mineral Oil	130	500	-2.72	-2.71	-2.71	-2.71
16	Nitrile 321	Mineral Oil	120	168	-2.39	-2.37	-2.38	-2.38
17	Nitrile 321	Mineral Oil	120	250	-2.42	-2.43	-2.42	-2.42
18	Nitrile 321	Mineral Oil	120	333	-2.49	-2.47	-2.49	-2.48
19	Nitrile 321	Mineral Oil	120	417	-2.56	-2.54	-2.56	-2.55
20	Nitrile 321	Mineral Oil	120	500	-2.62	-2.65	-2.65	-2.64

Table B 2: Silicone 332 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
21	Silicone 332	Mineral Oil	150	168	19.87	19.85	19.86	19.86
22	Silicone 332	Mineral Oil	150	250	22.07	22	22.01	22.03
23	Silicone 332	Mineral Oil	150	333	23.33	23.21	23.23	23.26
24	Silicone 332	Mineral Oil	150	417	24.04	24.01	24.02	24.02
25	Silicone 332	Mineral Oil	150	500	24.23	24.19	24.19	24.20
26	Silicone 332	Mineral Oil	140	168	18.52	18.5	18.51	18.51
27	Silicone 332	Mineral Oil	140	250	19.21	19.17	19.18	19.19
28	Silicone 332	Mineral Oil	140	333	21.23	21.2	21.21	21.21
29	Silicone 332	Mineral Oil	140	417	23.12	23.1	23.14	23.12
30	Silicone 332	Mineral Oil	140	500	23.56	23.51	23.51	23.53
31	Silicon 332	Mineral Oil	130	168	14.23	14.2	14.23	14.22
32	Silicon 332	Mineral Oil	130	250	15.12	15.21	15.19	15.17
33	Silicon 332	Mineral Oil	130	333	16.23	16.21	16.22	16.22
34	Silicon 332	Mineral Oil	130	417	17.24	17.31	17.26	17.27
35	Silicon 332	Mineral Oil	130	500	18.52	18.5	18.45	18.49
36	Silicon 332	Mineral Oil	120	168	6.98	6.94	6.92	6.95
37	Silicon 332	Mineral Oil	120	250	7.23	7.24	7.26	7.24
38	Silicon 332	Mineral Oil	120	333	8.15	8.17	8.18	8.17
39	Silicon 332	Mineral Oil	120	417	8.21	8.22	8.22	8.22
40	Silicon 332	Mineral Oil	120	500	9.12	9.13	9.13	9.13

Table B 3: Nitrile 322 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	∆ Hardness (Shore A)			Avg
41	Nitrile 322	Mineral Oil	150	168	-1.52	-1.51	-1.49	-1.5067
42	Nitrile 322	Mineral Oil	150	250	-1.82	-1.78	-1.79	-1.7967
43	Nitrile 322	Mineral Oil	150	333	-2.12	-2.14	-2.16	-2.14
44	Nitrile 322	Mineral Oil	150	417	-2.62	-2.64	-2.7	-2.6533
45	Nitrile 322	Mineral Oil	150	500	-2.76	-2.74	-2.8	-2.7667
46	Nitrile 322	Mineral Oil	140	168	-1.2	-1.22	-1.21	-1.21
47	Nitrile 322	Mineral Oil	140	250	-1.24	-1.26	-1.24	-1.2467
48	Nitrile 322	Mineral Oil	140	333	-1.26	-1.27	-1.3	-1.2767
49	Nitrile 322	Mineral Oil	140	417	-1.42	-1.44	-1.39	-1.4167
50	Nitrile 322	Mineral Oil	140	500	-1.71	-1.68	-1.72	-1.7033
51	Nitrile 322	Mineral Oil	130	168	-0.52	-0.51	-0.49	-0.5067
52	Nitrile 322	Mineral Oil	130	250	-0.62	-0.62	-0.58	-0.6067
53	Nitrile 322	Mineral Oil	130	333	-0.82	-0.79	-0.82	-0.81
54	Nitrile 322	Mineral Oil	130	417	-0.91	-0.89	-0.88	-0.8933
55	Nitrile 322	Mineral Oil	130	500	-0.92	-0.94	-0.89	-0.9167
56	Nitrile 322	Mineral Oil	120	168	-0.21	-0.25	-0.25	-0.2367
57	Nitrile 322	Mineral Oil	120	250	-0.34	-0.32	-0.2	-0.2867
58	Nitrile 322	Mineral Oil	120	333	-0.41	-0.42	-0.42	-0.4167
59	Nitrile 322	Mineral Oil	120	417	-0.45	-0.46	-0.46	-0.4567
60	Nitrile 322	Mineral Oil	120	500	-0.51	-0.52	-0.53	-0.52

Table B 4: Nitrile 322 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
61	Nitrile 333	Mineral Oil	150	168	15.71	15.74	15.76	15.7367
62	Nitrile 333	Mineral Oil	150	250	16.28	16.24	16.2	16.24
63	Nitrile 333	Mineral Oil	150	333	16.63	16.64	16.65	16.64
64	Nitrile 333	Mineral Oil	150	417	17.04	17.06	17.05	17.05
65	Nitrile 333	Mineral Oil	150	500	18.27	18.29	18.27	18.2767
66	Nitrile 333	Mineral Oil	140	168	13.65	13.62	13.64	13.6367
67	Nitrile 333	Mineral Oil	140	250	14.02	14.05	14.07	14.0467
68	Nitrile 333	Mineral Oil	140	333	14.98	14.92	14.95	14.95
69	Nitrile 333	Mineral Oil	140	417	15.72	15.71	15.76	15.73
70	Nitrile 333	Mineral Oil	140	500	17.23	17.17	17.19	17.1967
71	Nitrile 333	Mineral Oil	130	168	11.67	11.62	11.65	11.6467
72	Nitrile 333	Mineral Oil	130	250	12.92	12.9	12.88	12.9
73	Nitrile 333	Mineral Oil	130	333	13.45	13.42	13.41	13.4267
74	Nitrile 333	Mineral Oil	130	417	14.92	14.92	14.96	14.9333
75	Nitrile 333	Mineral Oil	130	500	15.23	15.26	15.24	15.2433
76	Nitrile 333	Mineral Oil	120	168	9.23	9.26	9.27	9.25333
77	Nitrile 333	Mineral Oil	120	250	10.14	10.16	10.17	10.1567
78	Nitrile 333	Mineral Oil	120	333	11.02	11.04	11.06	11.04
79	Nitrile 333	Mineral Oil	120	417	12.14	12.16	12.17	12.1567
80	Nitrile 333	Mineral Oil	120	500	13.23	13.26	13.27	13.2533

Table B 5: ACM 334 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	∆ Hardness (Shore A)			Avg
81	ACM 334	Mineral Oil	150	168	3.95	3.97	3.96	3.96
82	ACM 334	Mineral Oil	150	250	4.84	4.83	4.82	4.83
83	ACM 334	Mineral Oil	150	333	5.96	5.94	5.93	5.94333
84	ACM 334	Mineral Oil	150	417	6.83	6.81	6.82	6.82
85	ACM 334	Mineral Oil	150	500	6.94	6.94	6.96	6.94667
86	ACM 334	Mineral Oil	140	168	2.26	2.25	2.24	2.25
87	ACM 334	Mineral Oil	140	250	3.21	3.22	3.23	3.22
88	ACM 334	Mineral Oil	140	333	4.02	4.03	4.04	4.03
89	ACM 334	Mineral Oil	140	417	4.92	4.91	4.9	4.91
90	ACM 334	Mineral Oil	140	500	5.01	5.02	5.04	5.02333
91	ACM 334	Mineral Oil	130	168	1.62	1.63	1.65	1.63333
92	ACM 334	Mineral Oil	130	250	1.87	1.86	1.87	1.86667
93	ACM 334	Mineral Oil	130	333	1.95	1.97	1.96	1.96
94	ACM 334	Mineral Oil	130	417	2.03	2.04	2.01	2.02667
95	ACM 334	Mineral Oil	130	500	2.23	2.24	2.25	2.24
96	ACM 334	Mineral Oil	120	168	0.95	0.97	0.96	0.96
97	ACM 334	Mineral Oil	120	250	0.99	0.99	0.98	0.98667
98	ACM 334	Mineral Oil	120	333	1.02	1.01	1	1.01
99	ACM 334	Mineral Oil	120	417	1.07	1.04	1.06	1.05667
100	ACM 334	Mineral Oil	120	500	1.21	1.19	1.2	1.2

Table B 6: Viton 337 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
101	Viton 337	Mineral Oil	150	168	5.72	5.73	5.72	5.72333
102	Viton 337	Mineral Oil	150	250	7.36	7.35	7.35	7.35333
103	Viton 337	Mineral Oil	150	333	8.89	8.87	8.86	8.87333
104	Viton 337	Mineral Oil	150	417	10.24	10.21	10.2	10.2167
105	Viton 337	Mineral Oil	150	500	11.23	11.26	11.25	11.2467
106	Viton 337	Mineral Oil	140	168	4.01	4.02	4.05	4.02667
107	Viton 337	Mineral Oil	140	250	5.24	5.25	5.25	5.24667
108	Viton 337	Mineral Oil	140	333	6.32	6.34	6.34	6.33333
109	Viton 337	Mineral Oil	140	417	7.24	7.26	7.25	7.25
110	Viton 337	Mineral Oil	140	500	9.62	9.63	9.65	9.63333
111	Viton 337	Mineral Oil	130	168	2.01	2.03	2.04	2.02667
112	Viton 337	Mineral Oil	130	250	3.93	3.94	3.95	3.94
113	Viton 337	Mineral Oil	130	333	4.86	4.85	4.82	4.84333
114	Viton 337	Mineral Oil	130	417	5.02	5.01	5.03	5.02
115	Viton 337	Mineral Oil	130	500	6.21	6.22	6.22	6.21667
116	Viton 337	Mineral Oil	120	168	1.42	1.39	1.44	1.41667
117	Viton 337	Mineral Oil	120	250	3.21	3.24	3.24	3.23
118	Viton 337	Mineral Oil	120	333	4.25	4.21	4.23	4.23
119	Viton 337	Mineral Oil	120	417	4.96	4.92	4.92	4.93333
120	Viton 337	Mineral Oil	120	500	5.02	5.03	5.05	5.03333

Table B 7: Viton 337 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
121	HNBR 338	Mineral Oil	150	168	17	16	17	16.6667
122	HNBR 338	Mineral Oil	150	250	19	18	19	18.6667
123	HNBR 338	Mineral Oil	150	333	19	20	21	20
124	HNBR 338	Mineral Oil	150	417	21	20	22	21
125	HNBR 338	Mineral Oil	150	500	25	24	25	24.6667
126	HNBR 338	Mineral Oil	140	168	12	11	12	11.6667
127	HNBR 338	Mineral Oil	140	250	15	14	14	14.3333
128	HNBR 338	Mineral Oil	140	333	17	16	17	16.6667
129	HNBR 338	Mineral Oil	140	417	19	20	21	20
130	HNBR 338	Mineral Oil	140	500	23	21	23	22.3333
131	HNBR 338	Mineral Oil	130	168	9	9	10	9.33333
132	HNBR 338	Mineral Oil	130	250	10	9	10	9.66667
133	HNBR 338	Mineral Oil	130	333	12	11	12	11.6667
134	HNBR 338	Mineral Oil	130	417	15	16	15	15.3333
135	HNBR 338	Mineral Oil	130	500	19	20	19	19.3333
136	HNBR 338	Mineral Oil	120	168	5	4	5	4.66667
137	HNBR 338	Mineral Oil	120	250	7	6	8	7
138	HNBR 338	Mineral Oil	120	333	12	11	12	11.6667
139	HNBR 338	Mineral Oil	120	417	16	15	14	15
140	HNBR 338	Mineral Oil	120	500	17	16	17	16.6667

Table B 8: AEM/Vamac 336 change in volume results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
141	AEM/Vamac 336	Mineral Oil	150	168	11	10	11	10.6667
142	AEM/Vamac 336	Mineral Oil	150	250	12	11	12	11.6667
143	AEM/Vamac 336	Mineral Oil	150	333	13	14	14	13.6667
144	AEM/Vamac 336	Mineral Oil	150	417	14	14	13	13.6667
145	AEM/Vamac 336	Mineral Oil	150	500	15	14	14	14.3333
146	AEM/Vamac 336	Mineral Oil	140	168	6	5	5	5.33333
147	AEM/Vamac 336	Mineral Oil	140	250	7	8	8	7.66667
148	AEM/Vamac 336	Mineral Oil	140	333	10	9	8	9
149	AEM/Vamac 336	Mineral Oil	140	417	11	10	11	10.6667
150	AEM/Vamac 336	Mineral Oil	140	500	12	11	12	11.6667
151	AEM/Vamac 336	Mineral Oil	130	168	3	2	3	2.66667
152	AEM/Vamac 336	Mineral Oil	130	250	5	4	5	4.66667
153	AEM/Vamac 336	Mineral Oil	130	333	7	6	6	6.33333
154	AEM/Vamac 336	Mineral Oil	130	417	9	8	9	8.66667
155	AEM/Vamac 336	Mineral Oil	130	500	10	9	10	9.66667
156	AEM/Vamac 336	Mineral Oil	120	168	0	1	1	0.66667
157	AEM/Vamac 336	Mineral Oil	120	250	2	1	2	1.66667
158	AEM/Vamac 336	Mineral Oil	120	333	4	3	4	3.66667
159	AEM/Vamac 336	Mineral Oil	120	417	6	5	5	5.33333
160	AEM/Vamac 336	Mineral Oil	120	500	8	7	8	7.66667

Table B 9: Nitrile 321 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
161	Nitrile 321	Synthetic Oil	150	168	-5.03	-5.04	-5.03	-5.03
162	Nitrile 321	Synthetic Oil	150	250	-5.12	-5.14	-5.12	-5.13
163	Nitrile 321	Synthetic Oil	150	333	-5.17	-5.18	-5.17	-5.17
164	Nitrile 321	Synthetic Oil	150	417	-5.21	-5.24	-5.24	-5.23
165	Nitrile 321	Synthetic Oil	150	500	-5.27	-5.28	-5.28	-5.28
166	Nitrile 321	Synthetic Oil	140	168	-4.92	-4.93	-4.94	-4.93
167	Nitrile 321	Synthetic Oil	140	250	-4.94	-4.95	-4.96	-4.95
168	Nitrile 321	Synthetic Oil	140	333	-5.05	-5.07	-5.07	-5.06
169	Nitrile 321	Synthetic Oil	140	417	-5.13	-5.13	-5.13	-5.13
170	Nitrile 321	Synthetic Oil	140	500	-5.15	-5.15	-5.15	-5.15
171	Nitrile 321	Synthetic Oil	130	168	-4.85	-4.84	-4.83	-4.84
172	Nitrile 321	Synthetic Oil	130	250	-4.89	-4.89	-4.91	-4.90
173	Nitrile 321	Synthetic Oil	130	333	-4.96	-4.97	-4.97	-4.97
174	Nitrile 321	Synthetic Oil	130	417	-5.04	-5.04	-5.06	-5.05
175	Nitrile 321	Synthetic Oil	130	500	-5.17	-5.15	-5.18	-5.17
176	Nitrile 321	Synthetic Oil	120	168	-4.51	-4.52	-4.53	-4.52
177	Nitrile 321	Synthetic Oil	120	250	-4.61	-4.61	-4.65	-4.62
178	Nitrile 321	Synthetic Oil	120	333	-4.7	-4.71	-4.71	-4.71
179	Nitrile 321	Synthetic Oil	120	417	-4.81	-4.84	-4.84	-4.83
180	Nitrile 321	Synthetic Oil	120	500	-4.92	-4.92	-4.93	-4.92

Table B 10: Silicone 332 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
181	Silicon 332	Synthetic Oil	150	168	20.81	20.82	20.84	20.82
182	Silicon 332	Synthetic Oil	150	250	23.25	23.26	23.26	23.26
183	Silicon 332	Synthetic Oil	150	333	24.32	24.32	24.36	24.33
184	Silicon 332	Synthetic Oil	150	417	25.12	25.12	25.15	25.13
185	Silicon 332	Synthetic Oil	150	500	25.92	25.94	25.94	25.93
186	Silicon 332	Synthetic Oil	140	168	19.25	19.26	19.28	19.26
187	Silicon 332	Synthetic Oil	140	250	20.45	20.46	20.46	20.46
188	Silicon 332	Synthetic Oil	140	333	22.21	22.22	22.22	22.22
189	Silicon 332	Synthetic Oil	140	417	24.45	24.46	24.46	24.46
190	Silicon 332	Synthetic Oil	140	500	24.92	24.93	24.93	24.93
191	Silicon 332	Synthetic Oil	130	168	15.32	15.32	15.35	15.33
192	Silicon 332	Synthetic Oil	130	250	16.14	16.15	16.17	16.15
193	Silicon 332	Synthetic Oil	130	333	17.02	17.04	17.05	17.04
194	Silicon 332	Synthetic Oil	130	417	18.36	18.35	18.35	18.35
195	Silicon 332	Synthetic Oil	130	500	19.21	19.22	19.23	19.22
196	Silicon 332	Synthetic Oil	120	168	7.92	7.91	7.93	7.92
197	Silicon 332	Synthetic Oil	120	250	8.02	8.04	8.05	8.04
198	Silicon 332	Synthetic Oil	120	333	9.25	9.23	9.23	9.24
199	Silicon 332	Synthetic Oil	120	417	10.21	10.25	10.24	10.23
200	Silicon 332	Synthetic Oil	120	500	11.01	11.02	11.03	11.02

Table B 11: Nitrile 322 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
201	Nitrile 322	Synthetic Oil	150	168	-3.41	-3.42	-3.43	-3.42
202	Nitrile 322	Synthetic Oil	150	250	-3.92	-3.93	-3.94	-3.93
203	Nitrile 322	Synthetic Oil	150	333	-4.21	-4.23	-4.23	-4.2233
204	Nitrile 322	Synthetic Oil	150	417	-4.51	-4.52	-4.52	-4.5167
205	Nitrile 322	Synthetic Oil	150	500	-4.64	-4.64	-4.65	-4.6433
206	Nitrile 322	Synthetic Oil	140	168	-3.01	-3.02	-3.03	-3.02
207	Nitrile 322	Synthetic Oil	140	250	-3.14	-3.15	-3.15	-3.1467
208	Nitrile 322	Synthetic Oil	140	333	-3.21	-3.22	-3.22	-3.2167
209	Nitrile 322	Synthetic Oil	140	417	-3.37	-3.32	-3.35	-3.3467
210	Nitrile 322	Synthetic Oil	140	500	-3.41	-3.42	-3.45	-3.4267
211	Nitrile 322	Synthetic Oil	130	168	-2.51	-2.52	-2.52	-2.5167
212	Nitrile 322	Synthetic Oil	130	250	-2.64	-2.66	-2.64	-2.6467
213	Nitrile 322	Synthetic Oil	130	333	-2.71	-2.71	-2.72	-2.7133
214	Nitrile 322	Synthetic Oil	130	417	-2.82	-2.83	-2.83	-2.8267
216	Nitrile 322	Synthetic Oil	120	168	-2.01	-2.02	-2.02	-2.0167
217	Nitrile 322	Synthetic Oil	120	250	-2.14	-2.13	-2.13	-2.1333
218	Nitrile 322	Synthetic Oil	120	333	-2.21	-2.22	-2.22	-2.2167
219	Nitrile 322	Synthetic Oil	120	417	-2.37	-2.38	-2.38	-2.3767
220	Nitrile 322	Synthetic Oil	120	500	-2.45	-2.46	-2.46	-2.4567
212	Nitrile 322	Synthetic Oil	130	250	-2.64	-2.66	-2.64	-2.6467

Table B 12: Nitrile 333 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
221	Nitrile 333	Synthetic Oil	150	168	17.51	17.52	17.53	17.52
222	Nitrile 333	Synthetic Oil	150	250	18.01	18.02	18.03	18.02
223	Nitrile 333	Synthetic Oil	150	333	18.75	18.76	18.74	18.75
224	Nitrile 333	Synthetic Oil	150	417	19.21	19.22	19.24	19.2233
225	Nitrile 333	Synthetic Oil	150	500	20.05	20.06	20.05	20.0533
226	Nitrile 333	Synthetic Oil	140	168	15.21	15.22	15.21	15.2133
227	Nitrile 333	Synthetic Oil	140	250	16.01	16.02	16.05	16.0267
228	Nitrile 333	Synthetic Oil	140	333	17.14	17.16	17.1	17.1333
229	Nitrile 333	Synthetic Oil	140	417	17.85	17.92	17.92	17.8967
230	Nitrile 333	Synthetic Oil	140	500	19.25	19.26	19.22	19.2433
231	Nitrile 333	Synthetic Oil	130	168	13.72	13.71	13.73	13.72
232	Nitrile 333	Synthetic Oil	130	250	14.95	14.92	14.91	14.9267
233	Nitrile 333	Synthetic Oil	130	333	15.45	15.41	15.45	15.4367
234	Nitrile 333	Synthetic Oil	130	417	16.95	16.92	16.92	16.93
235	Nitrile 333	Synthetic Oil	130	500	17.05	17.09	17.09	17.0767
236	Nitrile 333	Synthetic Oil	120	168	11.25	11.26	11.26	11.25
237	Nitrile 333	Synthetic Oil	120	250	12.35	12.39	12.39	12.3767
238	Nitrile 333	Synthetic Oil	120	333	12.45	12.46	12.45	12.4533
239	Nitrile 333	Synthetic Oil	120	417	14.5	14.5	14.5	14.5
240	Nitrile 333	Synthetic Oil	120	500	15.01	15.02	15.01	15.0133

Table B 13: ACM 334 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
241	ACM 334	Synthetic Oil	150	168	5.82	5.83	5.85	5.83333
242	ACM 334	Synthetic Oil	150	250	6.75	6.76	6.77	6.76
243	ACM 334	Synthetic Oil	150	333	7.91	7.92	7.94	7.92333
244	ACM 334	Synthetic Oil	150	417	8.81	8.82	8.85	8.82667
245	ACM 334	Synthetic Oil	150	500	8.92	8.93	8.91	8.92
246	ACM 334	Synthetic Oil	140	168	4.24	4.23	4.24	4.23667
247	ACM 334	Synthetic Oil	140	250	5.21	5.24	5.23	5.22667
248	ACM 334	Synthetic Oil	140	333	6.05	6.06	6.05	6.05333
249	ACM 334	Synthetic Oil	140	417	6.91	6.95	6.92	6.92667
250	ACM 334	Synthetic Oil	140	500	7.05	7.06	7.05	7.05333
251	ACM 334	Synthetic Oil	130	168	3.45	3.42	3.46	3.44333
252	ACM 334	Synthetic Oil	130	250	3.82	3.84	3.85	3.83667
253	ACM 334	Synthetic Oil	130	333	3.97	3.98	3.95	3.96667
254	ACM 334	Synthetic Oil	130	417	4.05	4.06	4.05	4.05333
255	ACM 334	Synthetic Oil	130	500	4.23	4.24	4.23	4.23333
256	ACM 334	Synthetic Oil	120	168	2.92	2.93	2.95	2.93333
257	ACM 334	Synthetic Oil	120	250	2.99	2.99	2.98	2.98667
258	ACM 334	Synthetic Oil	120	333	3.05	3.02	3.05	3.04
259	ACM 334	Synthetic Oil	120	417	3.07	3.08	3.07	3.07333
260	ACM 334	Synthetic Oil	120	500	3.25	3.25	3.24	3.24667

Table B 14: Viton 337 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
261	Viton 337	Synthetic Oil	150	168	7.21	7.23	7.24	7.22667
262	Viton 337	Synthetic Oil	150	250	9.05	9.06	9.05	9.05333
263	Viton 337	Synthetic Oil	150	333	10.85	10.86	10.87	10.86
264	Viton 337	Synthetic Oil	150	417	12.82	12.85	12.84	12.8367
265	Viton 337	Synthetic Oil	150	500	13.45	13.46	13.45	13.4533
266	Viton 337	Synthetic Oil	140	168	6.05	6.06	6.05	6.05333
267	Viton 337	Synthetic Oil	140	250	7.21	7.22	7.21	7.21333
268	Viton 337	Synthetic Oil	140	333	8.35	8.36	8.35	8.35333
269	Viton 337	Synthetic Oil	140	417	9.41	9.42	9.42	9.41667
270	Viton 337	Synthetic Oil	140	500	11.01	11.02	11.05	11.0267
271	Viton 337	Synthetic Oil	130	168	4.03	4.04	4.05	4.04
272	Viton 337	Synthetic Oil	130	250	5.92	5.93	5.93	5.92667
273	Viton 337	Synthetic Oil	130	333	6.72	6.75	6.74	6.73667
274	Viton 337	Synthetic Oil	130	417	7.05	7.06	7.05	7.05333
275	Viton 337	Synthetic Oil	130	500	8.25	8.25	8.23	8.24333
276	Viton 337	Synthetic Oil	120	168	3.41	3.45	3.45	3.43667
277	Viton 337	Synthetic Oil	120	250	5.45	5.41	5.41	5.42333
278	Viton 337	Synthetic Oil	120	333	6.45	6.46	6.45	6.45333
279	Viton 337	Synthetic Oil	120	417	6.92	6.93	6.93	6.92667
280	Viton 337	Synthetic Oil	120	500	7.05	7.06	7.05	7.05333

Table B 15: HNBR 338 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
281	HNBR 338	Synthetic Oil	150	168	19	18	19	18.6667
282	HNBR 338	Synthetic Oil	150	250	20	21	20	20.3333
283	HNBR 338	Synthetic Oil	150	333	21	23	22	22
284	HNBR 338	Synthetic Oil	150	417	23	22	24	23
285	HNBR 338	Synthetic Oil	150	500	27	27	26	26.6667
286	HNBR 338	Synthetic Oil	140	168	13	14	13	13.3333
287	HNBR 338	Synthetic Oil	140	250	17	16	16	16.3333
288	HNBR 338	Synthetic Oil	140	333	19	18	19	18.6667
289	HNBR 338	Synthetic Oil	140	417	21	22	23	22
290	HNBR 338	Synthetic Oil	140	500	25	25	23	24.3333
291	HNBR 338	Synthetic Oil	130	168	11	11	12	11.3333
292	HNBR 338	Synthetic Oil	130	250	12	12	11	11.6667
293	HNBR 338	Synthetic Oil	130	333	14	13	14	13.6667
294	HNBR 338	Synthetic Oil	130	417	17	18	17	17.3333
295	HNBR 338	Synthetic Oil	130	500	22	21	21	21.3333
296	HNBR 338	Synthetic Oil	120	168	7	6	7	6.66667
297	HNBR 338	Synthetic Oil	120	250	9	8	10	9
298	HNBR 338	Synthetic Oil	120	333	14	12	14	13.3333
299	HNBR 338	Synthetic Oil	120	417	18	17	17	17.3333
300	HNBR 338	Synthetic Oil	120	500	19	18	19	18.6667

Table B 16: AEM 336 change in volume results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
301	AEM/Vamac 336	Synthetic Oil	150	168	13	13	12	12.6667
302	AEM/Vamac 336	Synthetic Oil	150	250	14	13	14	13.6667
303	AEM/Vamac 336	Synthetic Oil	150	333	15	16	16	15.6667
304	AEM/Vamac 336	Synthetic Oil	150	417	16	15	16	15.6667
305	AEM/Vamac 336	Synthetic Oil	150	500	16	17	16	16.3333
306	AEM/Vamac 336	Synthetic Oil	140	168	8	7	7	7.33333
307	AEM/Vamac 336	Synthetic Oil	140	250	10	9	10	9.66667
308	AEM/Vamac 336	Synthetic Oil	140	333	11	10	12	11
309	AEM/Vamac 336	Synthetic Oil	140	417	13	12	13	12.6667
310	AEM/Vamac 336	Synthetic Oil	140	500	14	13	14	13.6667
311	AEM/Vamac 336	Synthetic Oil	130	168	5	5	4	4.66667
312	AEM/Vamac 336	Synthetic Oil	130	250	7	7	6	6.66667
313	AEM/Vamac 336	Synthetic Oil	130	333	9	8	8	8.33333
314	AEM/Vamac 336	Synthetic Oil	130	417	11	10	11	10.6667
315	AEM/Vamac 336	Synthetic Oil	130	500	12	12	11	11.6667
316	AEM/Vamac 336	Synthetic Oil	120	168	2	3	3	2.66667
317	AEM/Vamac 336	Synthetic Oil	120	250	4	3	4	3.66667
318	AEM/Vamac 336	Synthetic Oil	120	333	5	5	6	5.33333
319	AEM/Vamac 336	Synthetic Oil	120	417	8	7	7	7.33333
320	AEM/Vamac 336	Synthetic Oil	120	500	10	10	9	9.66667

Appendix C: Tensile strength results

Table C 1: Nitrile 321 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
1	Nitrile 321	Mineral Oil	150	168	4.53	4.52	4.52	4.52
2	Nitrile 321	Mineral Oil	150	250	4.43	4.43	4.43	4.43
3	Nitrile 321	Mineral Oil	150	333	4.2	4.21	4.2	4.20
4	Nitrile 321	Mineral Oil	150	417	4.13	4.14	4.15	4.14
5	Nitrile 321	Mineral Oil	150	500	4.03	4.02	4.02	4.02
6	Nitrile 321	Mineral Oil	140	168	5.92	5.91	5.91	5.91
7	Nitrile 321	Mineral Oil	140	250	5.83	5.84	5.84	5.84
8	Nitrile 321	Mineral Oil	140	333	5.62	5.63	5.63	5.63
9	Nitrile 321	Mineral Oil	140	417	5.12	5.13	5.13	5.13
10	Nitrile 321	Mineral Oil	140	500	4.92	4.93	4.93	4.93
11	Nitrile 321	Mineral Oil	130	168	6.82	6.83	6.83	6.83
12	Nitrile 321	Mineral Oil	130	250	6.74	6.74	6.74	6.74
13	Nitrile 321	Mineral Oil	130	333	6.52	6.53	6.51	6.52
14	Nitrile 321	Mineral Oil	130	417	6.23	6.23	6.23	6.23
15	Nitrile 321	Mineral Oil	130	500	6.01	6.02	6.02	6.02
16	Nitrile 321	Mineral Oil	120	168	9.23	9.24	9.24	9.24
17	Nitrile 321	Mineral Oil	120	250	8.88	8.89	8.89	8.89
18	Nitrile 321	Mineral Oil	120	333	8.52	8.53	8.53	8.53
19	Nitrile 321	Mineral Oil	120	417	8.21	8.22	8.22	8.22
20	Nitrile 321	Mineral Oil	120	500	8.11	8.12	8.13	8.12

Table C 2: Silicone 332 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
21	Silicon 332	Mineral Oil	150	168	4.27	4.25	4.22	4.25
22	Silicon 332	Mineral Oil	150	250	4.2	4.21	4.18	4.20
23	Silicon 332	Mineral Oil	150	333	4.17	4.15	4.15	4.16
24	Silicon 332	Mineral Oil	150	417	3.73	3.71	3.73	3.72
25	Silicon 332	Mineral Oil	150	500	3.5	3.52	3.61	3.54
26	Silicon 332	Mineral Oil	140	168	5.37	5.32	5.34	5.34
27	Silicon 332	Mineral Oil	140	250	5.03	5.01	5.01	5.02
28	Silicon 332	Mineral Oil	140	333	5.03	5.01	5	5.01
29	Silicon 332	Mineral Oil	140	417	4.93	4.91	4.9	4.91
30	Silicon 332	Mineral Oil	140	500	4.77	4.76	4.75	4.76
31	Silicon 332	Mineral Oil	130	168	5.53	5.51	5.51	5.52
32	Silicon 332	Mineral Oil	130	250	5.07	5.05	5.05	5.06
33	Silicon 332	Mineral Oil	130	333	5.05	5.04	5.03	5.04
34	Silicon 332	Mineral Oil	130	417	4.96	4.95	4.96	4.96
35	Silicon 332	Mineral Oil	130	500	4.82	4.8	4.81	4.81
36	Silicon 332	Mineral Oil	120	168	6.21	6.19	6.19	6.20
37	Silicon 332	Mineral Oil	120	250	6.02	6	6.04	6.02
38	Silicon 332	Mineral Oil	120	333	5.85	5.82	5.82	5.83
39	Silicon 332	Mineral Oil	120	417	5.81	5.79	5.76	5.79
40	Silicon 332	Mineral Oil	120	500	5.75	5.72	5.73	5.73

Table C 3: Nitrile 322 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
41	Nitrile 322	Mineral Oil	150	168	2.21	2.22	2.23	2.22
42	Nitrile 322	Mineral Oil	150	250	2.02	2.01	2.01	2.01333
43	Nitrile 322	Mineral Oil	150	333	1.98	1.97	1.96	1.97
44	Nitrile 322	Mineral Oil	150	417	1.84	1.82	1.83	1.83
45	Nitrile 322	Mineral Oil	150	500	1.76	1.77	1.77	1.76667
46	Nitrile 322	Mineral Oil	140	168	3.2	3.21	3.2	3.20333
47	Nitrile 322	Mineral Oil	140	250	3.01	3	3.02	3.01
48	Nitrile 322	Mineral Oil	140	333	2.87	2.85	2.85	2.85667
49	Nitrile 322	Mineral Oil	140	417	2.82	2.81	2.81	2.81333
50	Nitrile 322	Mineral Oil	140	500	2.74	2.72	2.7	2.72
51	Nitrile 322	Mineral Oil	130	168	5.2	5.21	5.23	5.21333
52	Nitrile 322	Mineral Oil	130	250	5.1	5.12	5.1	5.10667
53	Nitrile 322	Mineral Oil	130	333	4.95	4.96	4.95	4.95333
54	Nitrile 322	Mineral Oil	130	417	4.92	4.93	4.93	4.92667
55	Nitrile 322	Mineral Oil	130	500	4.72	4.71	4.7	4.71
56	Nitrile 322	Mineral Oil	120	168	7.6	7.62	7.61	7.61
57	Nitrile 322	Mineral Oil	120	250	7.21	7.22	7.23	7.22
58	Nitrile 322	Mineral Oil	120	333	7.03	7.01	7.01	7.01667
59	Nitrile 322	Mineral Oil	120	417	7	6.99	7.01	7
60	Nitrile 322	Mineral Oil	120	500	7	6.98	6.99	6.99

Table C 4: Nitrile 322 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
61	Nitrile 333	Mineral Oil	150	168	2.7	2.72	2.74	2.72
62	Nitrile 333	Mineral Oil	150	250	2.37	2.32	2.31	2.33333
63	Nitrile 333	Mineral Oil	150	333	1.93	1.96	1.94	1.94333
64	Nitrile 333	Mineral Oil	150	417	1.82	1.84	1.86	1.84
65	Nitrile 333	Mineral Oil	150	500	1.76	1.77	1.78	1.77
66	Nitrile 333	Mineral Oil	140	168	3.52	3.46	3.49	3.49
67	Nitrile 333	Mineral Oil	140	250	3.46	3.42	3.4	3.42667
68	Nitrile 333	Mineral Oil	140	333	3.29	3.32	3.31	3.30667
69	Nitrile 333	Mineral Oil	140	417	3.26	3.2	3.29	3.25
70	Nitrile 333	Mineral Oil	140	500	2.85	2.87	2.89	2.87
71	Nitrile 333	Mineral Oil	130	168	9.23	9.19	9.26	9.22667
72	Nitrile 333	Mineral Oil	130	250	8.8	8.82	8.84	8.82
73	Nitrile 333	Mineral Oil	130	333	7.54	7.5	7.54	7.52667
74	Nitrile 333	Mineral Oil	130	417	7.12	7.16	7.1	7.12667
75	Nitrile 333	Mineral Oil	130	500	6.86	6.68	6.89	6.81
76	Nitrile 333	Mineral Oil	120	168	12.12	12.05	12.07	12.08
77	Nitrile 333	Mineral Oil	120	250	11.54	11.52	11.56	11.54
78	Nitrile 333	Mineral Oil	120	333	10.62	10.66	10.69	10.6567
79	Nitrile 333	Mineral Oil	120	417	9.52	9.54	9.5	9.52
80	Nitrile 333	Mineral Oil	120	500	8.16	8.19	8.17	8.17333

Table C 5: ACM 334 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
81	ACM 334	Mineral Oil	150	168	14.21	14.22	14.23	14.22
82	ACM 334	Mineral Oil	150	250	13.23	13.25	13.24	13.24
83	ACM 334	Mineral Oil	150	333	11.12	11.13	11.12	11.1233
84	ACM 334	Mineral Oil	150	417	9.45	9.46	9.45	9.45333
85	ACM 334	Mineral Oil	150	500	7.52	7.53	7.54	7.53
86	ACM 334	Mineral Oil	140	168	17.23	17.26	17.25	17.2467
87	ACM 334	Mineral Oil	140	250	16.25	16.26	16.27	16.26
88	ACM 334	Mineral Oil	140	333	14.23	14.25	14.26	14.2467
89	ACM 334	Mineral Oil	140	417	12.12	12.14	12.16	12.14
90	ACM 334	Mineral Oil	140	500	10.52	10.54	10.52	10.5267
91	ACM 334	Mineral Oil	130	168	20.21	20.23	20.22	20.22
92	ACM 334	Mineral Oil	130	250	18.52	18.53	18.51	18.52
93	ACM 334	Mineral Oil	130	333	17.21	17.23	17.24	17.2267
94	ACM 334	Mineral Oil	130	417	16.23	16.25	16.24	16.24
95	ACM 334	Mineral Oil	130	500	15.23	15.24	15.26	15.2433
96	ACM 334	Mineral Oil	120	168	24.23	24.24	24.26	24.2433
97	ACM 334	Mineral Oil	120	250	22.12	22.14	22.14	22.1333
98	ACM 334	Mineral Oil	120	333	21.23	21.24	21.25	21.24
99	ACM 334	Mineral Oil	120	417	20.45	20.47	20.46	20.46
100	ACM 334	Mineral Oil	120	500	19.23	19.24	19.25	19.24

Table C 6: Viton 337 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
101	Viton 337	Mineral Oil	150	168	18.12	18.14	18.15	18.1367
102	Viton 337	Mineral Oil	150	250	16.46	16.47	16.48	16.47
103	Viton 337	Mineral Oil	150	333	14.23	14.24	14.25	14.24
104	Viton 337	Mineral Oil	150	417	13.23	13.24	13.24	13.2367
105	Viton 337	Mineral Oil	150	500	12.42	12.43	12.44	12.43
106	Viton 337	Mineral Oil	140	168	20.46	20.47	20.47	20.4667
107	Viton 337	Mineral Oil	140	250	19.21	19.22	19.21	19.2133
108	Viton 337	Mineral Oil	140	333	17.23	17.24	17.24	17.2367
109	Viton 337	Mineral Oil	140	417	16.12	16.13	16.14	16.13
110	Viton 337	Mineral Oil	140	500	15.24	15.26	15.26	15.2533
111	Viton 337	Mineral Oil	130	168	23.47	23.46	23.47	23.4667
112	Viton 337	Mineral Oil	130	250	21.23	21.24	21.25	21.24
113	Viton 337	Mineral Oil	130	333	19.26	19.27	19.27	19.2667
114	Viton 337	Mineral Oil	130	417	17.91	17.92	17.92	17.9167
115	Viton 337	Mineral Oil	130	500	15.21	15.23	15.24	15.2267
116	Viton 337	Mineral Oil	120	168	25.21	25.24	25.26	25.2367
117	Viton 337	Mineral Oil	120	250	24.21	24.23	24.25	24.23
118	Viton 337	Mineral Oil	120	333	21.26	21.29	21.27	21.2733
119	Viton 337	Mineral Oil	120	417	19.48	19.47	19.45	19.4667
120	Viton 337	Mineral Oil	120	500	17.12	17.14	17.12	17.1267

Table C 7:Viton 337 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
121	HNBR 338	Mineral Oil	150	168	14.26	14.25	14.27	14.26
122	HNBR 338	Mineral Oil	150	250	13.92	13.94	13.91	13.9233
123	HNBR 338	Mineral Oil	150	333	13.02	13.01	13.05	13.0267
124	HNBR 338	Mineral Oil	150	417	12.46	12.47	12.47	12.4667
125	HNBR 338	Mineral Oil	150	500	12.05	12.09	12.09	12.0767
126	HNBR 338	Mineral Oil	140	168	17.24	17.26	17.25	17.25
127	HNBR 338	Mineral Oil	140	250	16.91	16.94	16.97	16.94
128	HNBR 338	Mineral Oil	140	333	16.24	16.25	16.21	16.2333
129	HNBR 338	Mineral Oil	140	417	15.82	15.84	15.82	15.8267
130	HNBR 338	Mineral Oil	140	500	15.05	15.07	15.05	15.0567
131	HNBR 338	Mineral Oil	130	168	19.45	19.47	19.48	19.4667
132	HNBR 338	Mineral Oil	130	250	18.24	18.26	18.24	18.2467
133	HNBR 338	Mineral Oil	130	333	18.01	18.03	18.02	18.02
134	HNBR 338	Mineral Oil	130	417	17.74	17.75	17.75	17.7467
135	HNBR 338	Mineral Oil	130	500	16.92	19.94	16.94	17.9333
136	HNBR 338	Mineral Oil	120	168	20.14	20.16	20.17	20.1567
137	HNBR 338	Mineral Oil	120	250	19.74	19.76	19.76	19.7533
138	HNBR 338	Mineral Oil	120	333	19.21	19.24	19.25	19.2333
139	HNBR 338	Mineral Oil	120	417	18.92	18.93	18.91	18.92
140	HNBR 338	Mineral Oil	120	500	17.35	17.34	17.36	17.35

Table C 8: AEM/Vamac 336 tensile results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
141	AEM/Vamac 336	Mineral Oil	150	168	17.45	17.46	17.46	17.4567
142	AEM/Vamac 336	Mineral Oil	150	250	16.92	16.94	16.95	16.9367
143	AEM/Vamac 336	Mineral Oil	150	333	15.42	15.43	15.44	15.43
144	AEM/Vamac 336	Mineral Oil	150	417	14.72	14.72	14.75	14.73
145	AEM/Vamac 336	Mineral Oil	150	500	13.25	13.26	13.26	13.2567
146	AEM/Vamac 336	Mineral Oil	140	168	20.14	20.17	20.17	20.16
147	AEM/Vamac 336	Mineral Oil	140	250	18.24	18.26	18.26	18.2533
148	AEM/Vamac 336	Mineral Oil	140	333	17.92	17.94	17.96	17.94
149	AEM/Vamac 336	Mineral Oil	140	417	16.82	16.84	16.86	16.84
150	AEM/Vamac 336	Mineral Oil	140	500	15.84	15.86	15.84	15.8467
151	AEM/Vamac 336	Mineral Oil	130	168	22.01	22.04	22.04	22.03
152	AEM/Vamac 336	Mineral Oil	130	250	19.42	19.42	19.42	19.42
153	AEM/Vamac 336	Mineral Oil	130	333	18.72	18.74	18.74	18.7333
154	AEM/Vamac 336	Mineral Oil	130	417	17.32	17.34	17.32	17.3267
155	AEM/Vamac 336	Mineral Oil	130	500	16.95	16.98	16.98	16.97
156	AEM/Vamac 336	Mineral Oil	120	168	24.42	24.46	24.45	24.4433
157	AEM/Vamac 336	Mineral Oil	120	250	23.12	23.14	23.12	23.1267
158	AEM/Vamac 336	Mineral Oil	120	333	21.02	21.05	21.05	21.04
159	AEM/Vamac 336	Mineral Oil	120	417	20.92	20.94	20.96	20.94
160	AEM/Vamac 336	Mineral Oil	120	500	18.42	18.44	18.45	18.4367

Table C 9: Nitrile 321 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
161	Nitrile 321	Synthetic Oil	150	168	2.45	2.45	2.46	2.45
162	Nitrile 321	Synthetic Oil	150	250	2.4	2.41	2.41	2.41
163	Nitrile 321	Synthetic Oil	150	333	2.18	2.19	2.18	2.18
164	Nitrile 321	Synthetic Oil	150	417	2.08	2.07	2.07	2.07
165	Nitrile 321	Synthetic Oil	150	500	2.01	2.01	2.01	2.01
166	Nitrile 321	Synthetic Oil	140	168	2.86	2.87	2.87	2.87
167	Nitrile 321	Synthetic Oil	140	250	2.81	2.81	2.82	2.81
168	Nitrile 321	Synthetic Oil	140	333	2.75	2.74	2.74	2.74
169	Nitrile 321	Synthetic Oil	140	417	2.44	2.45	2.44	2.44
170	Nitrile 321	Synthetic Oil	140	500	2.35	2.35	2.35	2.35
171	Nitrile 321	Synthetic Oil	130	168	4.75	4.76	4.77	4.76
172	Nitrile 321	Synthetic Oil	130	250	4.65	4.65	4.65	4.65
173	Nitrile 321	Synthetic Oil	130	333	4.45	4.46	4.46	4.46
174	Nitrile 321	Synthetic Oil	130	417	4.34	4.34	4.35	4.34
175	Nitrile 321	Synthetic Oil	130	500	4.21	4.22	4.22	4.22
176	Nitrile 321	Synthetic Oil	120	168	7.32	7.34	7.32	7.33
177	Nitrile 321	Synthetic Oil	120	250	7.01	7.01	7.02	7.01
178	Nitrile 321	Synthetic Oil	120	333	6.92	6.93	6.93	6.93
179	Nitrile 321	Synthetic Oil	120	417	6.45	6.45	6.46	6.45
180	Nitrile 321	Synthetic Oil	120	500	6.41	6.41	6.45	6.42

Table C 10: Silicone 332 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
181	Silicon 332	Synthetic Oil	150	168	3.35	3.34	3.35	3.35
182	Silicon 332	Synthetic Oil	150	250	3.26	3.24	3.21	3.24
183	Silicon 332	Synthetic Oil	150	333	3.19	3.15	3.14	3.16
184	Silicon 332	Synthetic Oil	150	417	2.81	2.82	2.84	2.82
185	Silicon 332	Synthetic Oil	150	500	2.51	2.52	2.51	2.51
186	Silicon 332	Synthetic Oil	140	168	4.2	4.23	4.23	4.22
187	Silicon 332	Synthetic Oil	140	250	4.05	4.03	4.01	4.03
188	Silicon 332	Synthetic Oil	140	333	4.03	4	4.01	4.01
189	Silicon 332	Synthetic Oil	140	417	3.85	3.84	3.83	3.84
190	Silicon 332	Synthetic Oil	140	500	3.72	3.74	3.76	3.74
191	Silicon 332	Synthetic Oil	130	168	4.51	4.52	4.51	4.51
192	Silicon 332	Synthetic Oil	130	250	4.12	4.14	4.14	4.13
193	Silicon 332	Synthetic Oil	130	333	4.03	4.04	4.03	4.03
194	Silicon 332	Synthetic Oil	130	417	3.92	3.95	3.96	3.94
195	Silicon 332	Synthetic Oil	130	500	3.85	3.84	3.84	3.84
196	Silicon 332	Synthetic Oil	120	168	5.32	5.32	5.34	5.33
197	Silicon 332	Synthetic Oil	120	250	5.12	5.13	5.13	5.13
198	Silicon 332	Synthetic Oil	120	333	4.82	4.82	4.82	4.82
199	Silicon 332	Synthetic Oil	120	417	4.75	4.79	4.74	4.76
200	Silicon 332	Synthetic Oil	120	500	4.75	4.72	4.73	4.73

Table C 11: Nitrile 322 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
201	Nitrile 322	Synthetic Oil	150	168	1.24	1.26	1.26	1.25333
202	Nitrile 322	Synthetic Oil	150	250	1.04	1.05	1.06	1.05
203	Nitrile 322	Synthetic Oil	150	333	0.94	0.95	0.96	0.95
204	Nitrile 322	Synthetic Oil	150	417	0.82	0.81	0.81	0.81333
205	Nitrile 322	Synthetic Oil	150	500	0.72	0.74	0.74	0.73333
206	Nitrile 322	Synthetic Oil	140	168	2.32	2.34	2.34	2.33333
207	Nitrile 322	Synthetic Oil	140	250	2.12	2.14	2.14	2.13333
208	Nitrile 322	Synthetic Oil	140	333	2.01	2.03	2.03	2.02333
209	Nitrile 322	Synthetic Oil	140	417	1.85	1.85	1.85	1.85
210	Nitrile 322	Synthetic Oil	140	500	1.74	1.7	1.72	1.72
211	Nitrile 322	Synthetic Oil	130	168	4.32	4.31	4.31	4.31333
212	Nitrile 322	Synthetic Oil	130	250	4.21	4.22	4.23	4.22
213	Nitrile 322	Synthetic Oil	130	333	3.97	3.99	3.99	3.98333
214	Nitrile 322	Synthetic Oil	130	417	3.91	3.92	3.92	3.91667
215	Nitrile 322	Synthetic Oil	130	500	3.75	3.74	3.74	3.74333
216	Nitrile 322	Synthetic Oil	120	168	6.51	6.52	6.52	6.51667
217	Nitrile 322	Synthetic Oil	120	250	6.35	6.34	6.34	6.34333
218	Nitrile 322	Synthetic Oil	120	333	6.12	6.14	6.16	6.14
219	Nitrile 322	Synthetic Oil	120	417	5.95	5.96	5.96	5.95667
220	Nitrile 322	Synthetic Oil	120	500	5.85	5.89	5.89	5.87667

Table C 12: Nitrile 333 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
221	Nitrile 333	Synthetic Oil	150	168	1.2	1.3	1.32	1.27333
222	Nitrile 333	Synthetic Oil	150	250	1.01	1.02	1.05	1.02667
223	Nitrile 333	Synthetic Oil	150	333	0.92	0.93	0.94	0.93
224	Nitrile 333	Synthetic Oil	150	417	0.85	0.82	0.82	0.83
225	Nitrile 333	Synthetic Oil	150	500	0.71	0.72	0.73	0.72
226	Nitrile 333	Synthetic Oil	140	168	2.35	2.36	2.39	2.36667
227	Nitrile 333	Synthetic Oil	140	250	2.15	2.15	2.15	2.15
228	Nitrile 333	Synthetic Oil	140	333	2.01	2.05	2.05	2.03667
229	Nitrile 333	Synthetic Oil	140	417	1.85	1.82	1.81	1.82667
230	Nitrile 333	Synthetic Oil	140	500	1.45	1.42	1.43	1.43333
231	Nitrile 333	Synthetic Oil	130	168	7.02	7.02	7.05	7.03
232	Nitrile 333	Synthetic Oil	130	250	6.61	6.65	6.65	6.63667
233	Nitrile 333	Synthetic Oil	130	333	6.01	6.03	6.02	6.02
234	Nitrile 333	Synthetic Oil	130	417	5.35	5.36	5.39	5.36667
235	Nitrile 333	Synthetic Oil	130	500	5.01	5.02	5.05	5.02667
236	Nitrile 333	Synthetic Oil	120	168	10.02	10.02	10.05	10.03
237	Nitrile 333	Synthetic Oil	120	250	9.25	9.24	9.24	9.24333
238	Nitrile 333	Synthetic Oil	120	333	8.45	8.45	8.45	8.45
239	Nitrile 333	Synthetic Oil	120	417	7.35	7.36	7.37	7.36
240	Nitrile 333	Synthetic Oil	120	500	6.14	6.14	6.14	6.14

Table C 13: ACM 334 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
241	ACM 334	Synthetic Oil	150	168	11.05	11.02	11.05	11.04
242	ACM 334	Synthetic Oil	150	250	10.25	10.26	10.26	10.2567
243	ACM 334	Synthetic Oil	150	333	8.35	8.36	8.35	8.35333
244	ACM 334	Synthetic Oil	150	417	6.05	6.02	6.01	6.02667
245	ACM 334	Synthetic Oil	150	500	4.52	4.53	4.54	4.53
246	ACM 334	Synthetic Oil	140	168	14.01	14.02	14.06	14.03
247	ACM 334	Synthetic Oil	140	250	13.25	13.2	13.2	13.2167
248	ACM 334	Synthetic Oil	140	333	11.45	11.42	11.49	11.4533
249	ACM 334	Synthetic Oil	140	417	9.91	9.89	9.9	9.9
250	ACM 334	Synthetic Oil	140	500	7.25	7.21	7.26	7.24
251	ACM 334	Synthetic Oil	130	168	17.01	17.05	17.04	17.0333
252	ACM 334	Synthetic Oil	130	250	15.21	15.26	15.24	15.2367
253	ACM 334	Synthetic Oil	130	333	14.2	14.25	14.26	14.2367
254	ACM 334	Synthetic Oil	130	417	13.05	13.06	13.05	13.0533
255	ACM 334	Synthetic Oil	130	500	12.75	12.76	12.75	12.7533
256	ACM 334	Synthetic Oil	120	168	21.24	21.26	21.26	21.2533
257	ACM 334	Synthetic Oil	120	250	19.09	19.07	19.07	19.0767
258	ACM 334	Synthetic Oil	120	333	18.26	18.26	18.25	18.2567
259	ACM 334	Synthetic Oil	120	417	17.46	17.49	17.49	17.48
260	ACM 334	Synthetic Oil	120	500	16.61	16.62	16.65	16.6267

Table C 14: Viton 337 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
261	Viton 337	Synthetic Oil	150	168	15.05	15.02	15.01	15.0267
262	Viton 337	Synthetic Oil	150	250	13.21	13.22	13.26	13.23
263	Viton 337	Synthetic Oil	150	333	11.45	11.46	11.45	11.4533
264	Viton 337	Synthetic Oil	150	417	11.03	11.03	11.05	11.0367
265	Viton 337	Synthetic Oil	150	500	9.45	9.46	9.46	9.45667
266	Viton 337	Synthetic Oil	140	168	17.25	17.26	17.25	17.2533
267	Viton 337	Synthetic Oil	140	250	16.61	16.62	16.65	16.6267
268	Viton 337	Synthetic Oil	140	333	14.05	14.06	14.05	14.0533
269	Viton 337	Synthetic Oil	140	417	13.12	13.14	13.14	13.1333
270	Viton 337	Synthetic Oil	140	500	12.21	12.22	12.24	12.2233
271	Viton 337	Synthetic Oil	130	168	20.12	20.14	20.14	20.1333
272	Viton 337	Synthetic Oil	130	250	18.05	18.06	18.04	18.05
273	Viton 337	Synthetic Oil	130	333	16.21	16.22	16.22	16.2167
274	Viton 337	Synthetic Oil	130	417	14.45	14.46	14.45	14.4533
275	Viton 337	Synthetic Oil	130	500	13.21	13.22	13.24	13.2233
276	Viton 337	Synthetic Oil	120	168	22.35	22.36	22.36	22.3567
277	Viton 337	Synthetic Oil	120	250	21.04	21.06	21.06	21.0533
278	Viton 337	Synthetic Oil	120	333	18.35	18.32	18.32	18.33
279	Viton 337	Synthetic Oil	120	417	16.21	16.21	16.26	16.2267
280	Viton 337	Synthetic Oil	120	500	14.02	14.02	14.05	14.03

Table C 15: HNBR 338 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
281	HNBR 338	Synthetic Oil	150	168	12.01	12.02	12.03	12.02
282	HNBR 338	Synthetic Oil	150	250	11.25	11.26	11.27	11.26
283	HNBR 338	Synthetic Oil	150	333	11.01	11.02	11.02	11.0167
284	HNBR 338	Synthetic Oil	150	417	10.36	10.35	10.36	10.3567
285	HNBR 338	Synthetic Oil	150	500	10.01	10.01	10.03	10.0167
286	HNBR 338	Synthetic Oil	140	168	15.25	15.25	15.22	15.24
287	HNBR 338	Synthetic Oil	140	250	14.84	14.84	14.85	14.8433
288	HNBR 338	Synthetic Oil	140	333	14.01	14.05	14.05	14.0367
289	HNBR 338	Synthetic Oil	140	417	13.82	13.82	13.84	13.8267
290	HNBR 338	Synthetic Oil	140	500	13.12	13.15	13.12	13.13
291	HNBR 338	Synthetic Oil	130	168	17.21	17.25	17.21	17.2233
292	HNBR 338	Synthetic Oil	130	250	16.36	16.36	16.35	16.3567
293	HNBR 338	Synthetic Oil	130	333	16.04	16.04	16.06	16.0467
294	HNBR 338	Synthetic Oil	130	417	15.45	15.45	15.43	15.4433
295	HNBR 338	Synthetic Oil	130	500	14.91	14.92	14.92	14.9167
296	HNBR 338	Synthetic Oil	120	168	18.01	18.01	18.02	18.0133
297	HNBR 338	Synthetic Oil	120	250	17.82	17.85	17.85	17.84
298	HNBR 338	Synthetic Oil	120	333	17.24	17.24	17.25	17.2433
299	HNBR 338	Synthetic Oil	120	417	16.05	16.06	16.06	16.0567
300	HNBR 338	Synthetic Oil	120	500	15.31	15.31	15.35	15.3233

Table C 16: AEM 336 tensile results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
301	AEM/Vamac 336	Synthetic Oil	150	168	14.32	14.33	14.35	14.3333
302	AEM/Vamac 336	Synthetic Oil	150	250	13.85	13.82	13.82	13.83
303	AEM/Vamac 336	Synthetic Oil	150	333	12.21	12.22	12.23	12.22
304	AEM/Vamac 336	Synthetic Oil	150	417	11.92	11.93	11.94	11.93
305	AEM/Vamac 336	Synthetic Oil	150	500	10.25	10.25	10.22	10.24
306	AEM/Vamac 336	Synthetic Oil	140	168	17.02	17.05	17.02	17.03
307	AEM/Vamac 336	Synthetic Oil	140	250	15.21	15.21	15.25	15.2233
308	AEM/Vamac 336	Synthetic Oil	140	333	14.35	14.36	14.36	14.3567
309	AEM/Vamac 336	Synthetic Oil	140	417	13.75	13.72	13.71	13.7267
310	AEM/Vamac 336	Synthetic Oil	140	500	12.06	12.05	12.06	12.0567
311	AEM/Vamac 336	Synthetic Oil	130	168	19.02	19.02	19.05	19.03
312	AEM/Vamac 336	Synthetic Oil	130	250	16.46	16.45	16.46	16.4567
313	AEM/Vamac 336	Synthetic Oil	130	333	15.85	15.82	15.82	15.83
314	AEM/Vamac 336	Synthetic Oil	130	417	14.32	14.32	14.33	14.3233
315	AEM/Vamac 336	Synthetic Oil	130	500	13.75	13.75	13.76	13.7533
316	AEM/Vamac 336	Synthetic Oil	120	168	21.26	21.26	21.25	21.2567
317	AEM/Vamac 336	Synthetic Oil	120	250	20.05	20.06	20.06	20.0567
318	AEM/Vamac 336	Synthetic Oil	120	333	18.01	18.02	18.02	18.0167
319	AEM/Vamac 336	Synthetic Oil	120	417	17.75	17.76	17.76	17.7567
320	AEM/Vamac 336	Synthetic Oil	120	500	15	15.01	15.02	15.01

Appendix D: Elongation results

Table D 1: Nitrile 321 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
1	Nitrile 321	Mineral Oil	150	168	60	62	61.5	61.17
2	Nitrile 321	Mineral Oil	150	250	55	56.2	57.3	56.17
3	Nitrile 321	Mineral Oil	150	333	49.25	49.75	52.25	50.42
4	Nitrile 321	Mineral Oil	150	417	45.6	46.5	46.2	46.10
5	Nitrile 321	Mineral Oil	150	500	41.13	42.12	43.52	42.26
6	Nitrile 321	Mineral Oil	140	168	85	85.65	86.36	85.67
7	Nitrile 321	Mineral Oil	140	250	82.12	82.36	81	81.83
8	Nitrile 321	Mineral Oil	140	333	78	78.63	78.21	78.28
9	Nitrile 321	Mineral Oil	140	417	75	74	74.23	74.41
10	Nitrile 321	Mineral Oil	140	500	72.45	72.36	72.48	72.43
11	Nitrile 321	Mineral Oil	130	168	105	104.2	103.9	104.37
12	Nitrile 321	Mineral Oil	130	250	100	101	101.1	100.70
13	Nitrile 321	Mineral Oil	130	333	95	93	93.54	93.85
14	Nitrile 321	Mineral Oil	130	417	92.12	92.56	92	92.23
15	Nitrile 321	Mineral Oil	130	500	90.23	90.14	90.78	90.38
16	Nitrile 321	Mineral Oil	120	168	190	188	188.3	188.77
17	Nitrile 321	Mineral Oil	120	250	185	186.2	186.3	185.83
18	Nitrile 321	Mineral Oil	120	333	175	174	174.5	174.50
19	Nitrile 321	Mineral Oil	120	417	170	172	171	171.00
20	Nitrile 321	Mineral Oil	120	500	165.5	165.2	164	164.90

Table D 2: Silicone 332 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	∆ Hardness (Shore A)			Avg
21	Silicon 332	Mineral Oil	150	168	583.33	583.01	583	583.11
22	Silicon 332	Mineral Oil	150	250	524.26	526.21	523.17	524.55
23	Silicon 332	Mineral Oil	150	333	416.21	416.25	418.41	416.96
24	Silicon 332	Mineral Oil	150	417	417.21	419.21	417.1	417.84
25	Silicon 332	Mineral Oil	150	500	400.25	400.27	403.92	401.48
26	Silicon 332	Mineral Oil	140	168	652.21	651.23	652.97	652.14
27	Silicon 332	Mineral Oil	140	250	642.12	642.65	641.89	642.22
28	Silicon 332	Mineral Oil	140	333	621.23	621.02	620.89	621.05
29	Silicon 332	Mineral Oil	140	417	614.85	613.95	614.96	614.59
30	Silicon 332	Mineral Oil	140	500	599.00	599.67	600.01	599.56
31	Silicon 332	Mineral Oil	130	168	701.25	701.20	701.96	701.47
32	Silicon 332	Mineral Oil	130	250	691.25	691.63	692.15	691.68
33	Silicon 332	Mineral Oil	130	333	674.87	672.85	674.96	674.23
34	Silicon 332	Mineral Oil	130	417	652.25	653.35	654.27	653.29
35	Silicon 332	Mineral Oil	130	500	624.12	625.78	625.13	625.01
36	Silicon 332	Mineral Oil	120	168	751.23	751.45	750.27	750.98
37	Silicon 332	Mineral Oil	120	250	745.67	745.52	745.66	745.62
38	Silicon 332	Mineral Oil	120	333	740.78	740.69	740.96	740.81
39	Silicon 332	Mineral Oil	120	417	733.46	733.47	734.56	733.83
40	Silicon 332	Mineral Oil	120	500	700.05	700.00	700.15	700.07

Table D 3: Nitrile 322 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
41	Nitrile 322	Mineral Oil	150	168	178.12	178.26	178.12	178.167
42	Nitrile 322	Mineral Oil	150	250	172.23	172.96	172.01	172.4
43	Nitrile 322	Mineral Oil	150	333	165.39	165.47	165.92	165.593
44	Nitrile 322	Mineral Oil	150	417	160.12	160.23	160.98	160.443
45	Nitrile 322	Mineral Oil	150	500	152.23	151.98	151.75	151.987
46	Nitrile 322	Mineral Oil	140	168	201.2	200	200.5	200.567
47	Nitrile 322	Mineral Oil	140	250	185.23	184.25	184.96	184.813
48	Nitrile 322	Mineral Oil	140	333	174.69	174.72	174.63	174.68
49	Nitrile 322	Mineral Oil	140	417	168.25	168.02	168.05	168.107
50	Nitrile 322	Mineral Oil	140	500	162.12	162.14	162.18	162.147
51	Nitrile 322	Mineral Oil	130	168	325.21	325.74	326.21	325.72
52	Nitrile 322	Mineral Oil	130	250	300.21	300.96	300.45	300.54
53	Nitrile 322	Mineral Oil	130	333	291.23	291.45	290.89	291.19
54	Nitrile 322	Mineral Oil	130	417	285.23	284.26	284.21	284.567
55	Nitrile 322	Mineral Oil	130	500	274.23	274.23	274.12	274.193
56	Nitrile 322	Mineral Oil	120	168	525.12	524.96	524.75	524.943
57	Nitrile 322	Mineral Oil	120	250	500.25	500	500.12	500.123
58	Nitrile 322	Mineral Oil	120	333	485.23	485.96	485.78	485.657
59	Nitrile 322	Mineral Oil	120	417	475.24	475.02	475.23	475.163
60	Nitrile 322	Mineral Oil	120	500	450.5	450.23	450.7	450.477

Table D 4: Nitrile 322 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	∆ Hardness (Shore A)			Avg
61	Nitrile 333	Mineral Oil	150	168	95.23	95.26	95.24	95.2433
62	Nitrile 333	Mineral Oil	150	250	85.92	85.96	85.97	85.95
63	Nitrile 333	Mineral Oil	150	333	79.42	79.46	79.49	79.4567
64	Nitrile 333	Mineral Oil	150	417	62.75	62.65	62.62	62.6733
65	Nitrile 333	Mineral Oil	150	500	56.67	56.62	56.63	56.64
66	Nitrile 333	Mineral Oil	140	168	120.42	120.41	120.42	120.417
67	Nitrile 333	Mineral Oil	140	250	110.94	110.92	110.91	110.923
68	Nitrile 333	Mineral Oil	140	333	100.54	100.52	100.51	100.523
69	Nitrile 333	Mineral Oil	140	417	90.23	90.24	90.26	90.2433
70	Nitrile 333	Mineral Oil	140	500	85.23	85.25	85.26	85.2467
71	Nitrile 333	Mineral Oil	130	168	160.2	160.21	160.24	160.217
72	Nitrile 333	Mineral Oil	130	250	150.65	150.67	150.68	150.667
73	Nitrile 333	Mineral Oil	130	333	140.9	140.92	140.94	140.92
74	Nitrile 333	Mineral Oil	130	417	130.6	130.64	130.66	130.633
75	Nitrile 333	Mineral Oil	130	500	120.72	120.76	120.77	120.75
76	Nitrile 333	Mineral Oil	120	168	180.45	180.46	180.45	180.453
77	Nitrile 333	Mineral Oil	120	250	170.23	170.24	170.26	170.243
78	Nitrile 333	Mineral Oil	120	333	160.25	160.29	160.27	160.27
79	Nitrile 333	Mineral Oil	120	417	150.21	150.24	150.26	150.237
80	Nitrile 333	Mineral Oil	120	500	140.5	140.52	140.56	140.527

Table D 5: ACM 334 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
81	ACM 334	Mineral Oil	150	168	171.21	171.22	171.23	171.22
82	ACM 334	Mineral Oil	150	250	162.21	169.23	169.22	166.887
83	ACM 334	Mineral Oil	150	333	150.21	150.22	150.24	150.223
84	ACM 334	Mineral Oil	150	417	145.23	145.26	145.25	145.247
85	ACM 334	Mineral Oil	150	500	136.21	136.24	136.23	136.227
86	ACM 334	Mineral Oil	140	168	190.27	190.29	190.26	190.273
87	ACM 334	Mineral Oil	140	250	180.21	180.23	180.24	180.227
88	ACM 334	Mineral Oil	140	333	172.41	172.43	172.45	172.43
89	ACM 334	Mineral Oil	140	417	163.21	163.24	163.22	163.223
90	ACM 334	Mineral Oil	140	500	152.35	152.37	152.36	152.36
91	ACM 334	Mineral Oil	130	168	220.26	220.27	220.29	220.273
92	ACM 334	Mineral Oil	130	250	204.21	204.23	204.25	204.23
93	ACM 334	Mineral Oil	130	333	190.46	190.47	190.48	190.47
94	ACM 334	Mineral Oil	130	417	176.25	176.27	176.26	176.26
95	ACM 334	Mineral Oil	130	500	165.49	165.5	165.52	165.503
96	ACM 334	Mineral Oil	120	168	240.32	240.34	240.36	240.34
97	ACM 334	Mineral Oil	120	250	230.79	230.82	230.84	230.817
98	ACM 334	Mineral Oil	120	333	214.27	214.29	214.28	214.28
99	ACM 334	Mineral Oil	120	417	201.38	201.39	201.37	201.38
100	ACM 334	Mineral Oil	120	500	192.97	192.98	192.96	192.97

Table D 6: Viton 337 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
101	Viton 337	Mineral Oil	150	168	300.14	300.15	300.17	300.153
102	Viton 337	Mineral Oil	150	250	272.24	272.26	272.29	272.263
103	Viton 337	Mineral Oil	150	333	245.12	245.1	245.1	245.107
104	Viton 337	Mineral Oil	150	417	223.92	223.95	223.96	223.943
105	Viton 337	Mineral Oil	150	500	201.45	201.47	201.48	201.467
106	Viton 337	Mineral Oil	140	168	310.16	310.17	310.17	310.167
107	Viton 337	Mineral Oil	140	250	292.26	292.27	292.29	292.273
108	Viton 337	Mineral Oil	140	333	274.72	274.76	274.71	274.73
109	Viton 337	Mineral Oil	140	417	264.62	264.69	264.69	264.667
110	Viton 337	Mineral Oil	140	500	250.14	250.16	250.18	250.16
111	Viton 337	Mineral Oil	130	168	320.41	320.46	320.46	320.443
112	Viton 337	Mineral Oil	130	250	315.21	315.14	315.19	315.18
113	Viton 337	Mineral Oil	130	333	302.98	302.94	302.96	302.96
114	Viton 337	Mineral Oil	130	417	290.41	290.43	290.43	290.423
115	Viton 337	Mineral Oil	130	500	276.23	276.24	276.26	276.243
116	Viton 337	Mineral Oil	120	168	336.45	336.41	336.45	336.437
117	Viton 337	Mineral Oil	120	250	324.49	324.48	324.41	324.46
118	Viton 337	Mineral Oil	120	333	314.25	314.27	314.26	314.26
119	Viton 337	Mineral Oil	120	417	291.74	291.72	291.76	291.74
120	Viton 337	Mineral Oil	120	500	280.4	280.4	280.45	280.417

Table D 7: Viton 337 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
121	HNBR 338	Mineral Oil	150	168	140.21	140.24	140.24	140.23
122	HNBR 338	Mineral Oil	150	250	125.21	125.23	125.2	125.213
123	HNBR 338	Mineral Oil	150	333	114.27	114.29	114.29	114.283
124	HNBR 338	Mineral Oil	150	417	102.34	102.35	102.4	102.363
125	HNBR 338	Mineral Oil	150	500	100.01	100.05	100.05	100.037
126	HNBR 338	Mineral Oil	140	168	190.72	190.79	190.79	190.767
127	HNBR 338	Mineral Oil	140	250	184.02	184.01	184.01	184.013
128	HNBR 338	Mineral Oil	140	333	174.21	174.26	174.25	174.24
129	HNBR 338	Mineral Oil	140	417	152.01	152.04	152.07	152.04
130	HNBR 338	Mineral Oil	140	500	145.21	145.2	145.2	145.203
131	HNBR 338	Mineral Oil	130	168	195.46	195.47	195.47	195.467
132	HNBR 338	Mineral Oil	130	250	187.23	187.24	187.25	187.24
133	HNBR 338	Mineral Oil	130	333	178.45	178.46	178.46	178.457
134	HNBR 338	Mineral Oil	130	417	162.67	162.67	162.69	162.677
135	HNBR 338	Mineral Oil	130	500	159.23	159.24	159.25	159.24
136	HNBR 338	Mineral Oil	120	168	200.24	200.27	200.27	200.26
137	HNBR 338	Mineral Oil	120	250	192.35	192.37	192.37	192.363
138	HNBR 338	Mineral Oil	120	333	185.46	185.47	185.48	185.47
139	HNBR 338	Mineral Oil	120	417	176.62	176.63	176.62	176.623
140	HNBR 338	Mineral Oil	120	500	165.64	165.65	165.64	165.643

Table D 8: AEM/Vamac 336 elongation results of rubber exposed to increased temperatures and service intervals

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
141	AEM/Vamac 336	Mineral Oil	150	168	180.05	180.06	180.07	180.06
142	AEM/Vamac 336	Mineral Oil	150	250	174.26	174.29	174.29	174.28
143	AEM/Vamac 336	Mineral Oil	150	333	163.21	163.24	163.24	163.23
144	AEM/Vamac 336	Mineral Oil	150	417	151.82	151.84	151.85	151.837
145	AEM/Vamac 336	Mineral Oil	150	500	150.01	150	150.03	150.013
146	AEM/Vamac 336	Mineral Oil	140	168	185.12	185.14	185.14	185.133
147	AEM/Vamac 336	Mineral Oil	140	250	176.21	176.22	176.22	176.217
148	AEM/Vamac 336	Mineral Oil	140	333	169.62	169.62	169.65	169.63
149	AEM/Vamac 336	Mineral Oil	140	417	155.39	155.36	155.35	155.367
150	AEM/Vamac 336	Mineral Oil	140	500	152.05	152.07	152.09	152.07
151	AEM/Vamac 336	Mineral Oil	130	168	197.26	197.24	197.26	197.253
152	AEM/Vamac 336	Mineral Oil	130	250	189.21	189.23	189.26	189.233
153	AEM/Vamac 336	Mineral Oil	130	333	174.21	174.23	174.27	174.237
154	AEM/Vamac 336	Mineral Oil	130	417	162.35	162.34	162.34	162.343
155	AEM/Vamac 336	Mineral Oil	130	500	159.12	159.14	159.14	159.133
156	AEM/Vamac 336	Mineral Oil	120	168	210.45	210.41	210.41	210.423
157	AEM/Vamac 336	Mineral Oil	120	250	202.01	202.05	202.05	202.037
158	AEM/Vamac 336	Mineral Oil	120	333	195.23	195.26	195.24	195.243
159	AEM/Vamac 336	Mineral Oil	120	417	182.23	182.24	182.24	182.237
160	AEM/Vamac 336	Mineral Oil	120	500	175.72	175.72	175.65	175.697

Table D 9: Nitrile 321 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
161	Nitrile 321	Synthetic Oil	150	168	50.21	51.23	51.24	50.89
162	Nitrile 321	Synthetic Oil	150	250	45.36	45.12	46.24	45.57
163	Nitrile 321	Synthetic Oil	150	333	39.45	39.92	40.12	39.83
164	Nitrile 321	Synthetic Oil	150	417	36.21	36.92	37.01	36.71
165	Nitrile 321	Synthetic Oil	150	500	31.25	31.45	31.47	31.39
166	Nitrile 321	Synthetic Oil	140	168	75.63	75.42	75.42	75.49
167	Nitrile 321	Synthetic Oil	140	250	72.36	72.25	72.36	72.32
168	Nitrile 321	Synthetic Oil	140	333	68.21	68.23	68.92	68.45
169	Nitrile 321	Synthetic Oil	140	417	65.21	65.75	65.74	65.57
170	Nitrile 321	Synthetic Oil	140	500	62.01	62.07	62.21	62.10
171	Nitrile 321	Synthetic Oil	130	168	95.26	95.01	95.27	95.18
172	Nitrile 321	Synthetic Oil	130	250	90.45	90.47	90.47	90.46
173	Nitrile 321	Synthetic Oil	130	333	85.23	85.24	85.29	85.25
174	Nitrile 321	Synthetic Oil	130	417	82.05	82.07	82.35	82.16
175	Nitrile 321	Synthetic Oil	130	500	80.92	80.94	80.24	80.70
176	Nitrile 321	Synthetic Oil	120	168	180.94	180.92	180.92	180.93
177	Nitrile 321	Synthetic Oil	120	250	175.75	175.76	175.24	175.58
178	Nitrile 321	Synthetic Oil	120	333	165.01	165.89	165	165.30
179	Nitrile 321	Synthetic Oil	120	417	160.45	160	160.45	160.30
180	Nitrile 321	Synthetic Oil	120	500	145.05	145.35	145.4	145.27

Table D 10: Silicone 332 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
181	Silicon 332	Synthetic Oil	150	168	383.21	383.24	383.92	383.46
182	Silicon 332	Synthetic Oil	150	250	324.51	324.62	325.12	324.75
183	Silicon 332	Synthetic Oil	150	333	217.21	217.25	218.02	217.49
184	Silicon 332	Synthetic Oil	150	417	216.50	216.50	216.61	216.54
185	Silicon 332	Synthetic Oil	150	500	200.23	200.24	200.92	200.46
186	Silicon 332	Synthetic Oil	140	168	453.12	452.20	452.25	452.52
187	Silicon 332	Synthetic Oil	140	250	445.21	445.35	445.45	445.34
188	Silicon 332	Synthetic Oil	140	333	421.02	421.04	421.04	421.03
189	Silicon 332	Synthetic Oil	140	417	412.02	412.04	412.05	412.04
190	Silicon 332	Synthetic Oil	140	500	395.12	395.92	395.05	395.36
191	Silicon 332	Synthetic Oil	130	168	501.24	502.23	502.12	501.86
192	Silicon 332	Synthetic Oil	130	250	495.23	495.24	495.29	495.25
193	Silicon 332	Synthetic Oil	130	333	479.21	479.23	479.25	479.23
194	Silicon 332	Synthetic Oil	130	417	462.62	462.64	462.64	462.63
195	Silicon 332	Synthetic Oil	130	500	412.12	412.36	412.92	412.47
196	Silicon 332	Synthetic Oil	120	168	545.21	546.21	546.32	545.91
197	Silicon 332	Synthetic Oil	120	250	532.21	532.24	532.24	532.23
198	Silicon 332	Synthetic Oil	120	333	521.01	521.05	521.06	521.04
199	Silicon 332	Synthetic Oil	120	417	515.23	515.29	515.29	515.27
200	Silicon 332	Synthetic Oil	120	500	500.01	500.02	500.02	500.02

Table D 11: Nitrile 322 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	∆ Hardness (Shore A)			Avg
201	Nitrile 322	Synthetic Oil	150	168	165.12	164.23	164.24	164.53
202	Nitrile 322	Synthetic Oil	150	250	160.16	160.14	160.14	160.147
203	Nitrile 322	Synthetic Oil	150	333	151.21	151.23	151.23	151.223
204	Nitrile 322	Synthetic Oil	150	417	145.01	145.02	145.04	145.023
205	Nitrile 322	Synthetic Oil	150	500	135.21	135.25	135.29	135.25
206	Nitrile 322	Synthetic Oil	140	168	175.32	175.34	175.35	175.337
207	Nitrile 322	Synthetic Oil	140	250	170.21	170.22	170.23	170.22
208	Nitrile 322	Synthetic Oil	140	333	165.66	165.66	165.65	165.657
209	Nitrile 322	Synthetic Oil	140	417	151.25	151.24	151.24	151.243
210	Nitrile 322	Synthetic Oil	140	500	150.12	150.14	150.14	150.133
211	Nitrile 322	Synthetic Oil	130	168	195.21	195.22	195.23	195.22
212	Nitrile 322	Synthetic Oil	130	250	185.45	185.46	185.46	185.457
213	Nitrile 322	Synthetic Oil	130	333	177.21	177.23	177.29	177.243
214	Nitrile 322	Synthetic Oil	130	417	151.25	151.27	151.27	151.263
215	Nitrile 322	Synthetic Oil	130	500	145.21	145.22	145.26	145.23
216	Nitrile 322	Synthetic Oil	120	168	220.25	220.25	220.28	220.26
217	Nitrile 322	Synthetic Oil	120	250	212.21	221.23	212.25	215.23
218	Nitrile 322	Synthetic Oil	120	333	202.12	203.12	204.16	203.133
219	Nitrile 322	Synthetic Oil	120	417	195.21	195.22	195.22	195.217
220	Nitrile 322	Synthetic Oil	120	500	185.25	185.25	185.25	185.25

Table D 12: Nitrile 333 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

221	Nitrile 333	Synthetic Oil	150	168	75.21	75.22	75.25	75.2267
222	Nitrile 333	Synthetic Oil	150	250	70.01	70.05	70.05	70.0367
223	Nitrile 333	Synthetic Oil	150	333	62.24	62.25	62.24	62.2433
224	Nitrile 333	Synthetic Oil	150	417	50.12	50.12	50.15	50.13
225	Nitrile 333	Synthetic Oil	150	500	45.21	45.22	45.22	45.2167
226	Nitrile 333	Synthetic Oil	140	168	100.05	100.01	100.01	100.023
227	Nitrile 333	Synthetic Oil	140	250	92.15	92.15	92.17	92.1567
228	Nitrile 333	Synthetic Oil	140	333	80.25	80.22	80.22	80.23
229	Nitrile 333	Synthetic Oil	140	417	71.25	71.25	71.28	71.26
230	Nitrile 333	Synthetic Oil	140	500	62.25	62.25	62.25	62.25
231	Nitrile 333	Synthetic Oil	130	168	145.02	145.05	145.02	145.03
232	Nitrile 333	Synthetic Oil	130	250	135.21	135.25	135.27	135.243
233	Nitrile 333	Synthetic Oil	130	333	122.25	122.2	122.2	122.217
234	Nitrile 333	Synthetic Oil	130	417	105.12	105.15	105.12	105.13
235	Nitrile 333	Synthetic Oil	130	500	95.15	95.17	95.18	95.1667
236	Nitrile 333	Synthetic Oil	120	168	160.45	160.46	160.46	160.457
237	Nitrile 333	Synthetic Oil	120	250	150.25	150.26	150.29	150.267
238	Nitrile 333	Synthetic Oil	120	333	142.25	142.29	142.29	142.27
239	Nitrile 333	Synthetic Oil	120	417	132.28	132.28	132.25	132.27
240	Nitrile 333	Synthetic Oil	120	500	120.5	120.51	120.46	120.49

Table D 13: ACM 334 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
241	ACM 334	Synthetic Oil	150	168	142.21	142.24	142.25	142.233
242	ACM 334	Synthetic Oil	150	250	135.21	135.24	169.22	146.557
243	ACM 334	Synthetic Oil	150	333	120.92	120.95	120.96	120.943
244	ACM 334	Synthetic Oil	150	417	115.02	115.05	115.07	115.047
245	ACM 334	Synthetic Oil	150	500	102.45	102.47	102.49	102.47
246	ACM 334	Synthetic Oil	140	168	160.25	160.27	160.29	160.27
247	ACM 334	Synthetic Oil	140	250	150.01	150.04	150.06	150.037
248	ACM 334	Synthetic Oil	140	333	143.5	143.52	143.51	143.51
249	ACM 334	Synthetic Oil	140	417	134.25	134.26	134.21	134.24
250	ACM 334	Synthetic Oil	140	500	131.21	131.24	131.24	131.23
251	ACM 334	Synthetic Oil	130	168	190.21	190.22	190.23	190.22
252	ACM 334	Synthetic Oil	130	250	170.01	170.05	170.04	170.033
253	ACM 334	Synthetic Oil	130	333	162.21	162.24	162.25	162.233
254	ACM 334	Synthetic Oil	130	417	145.02	145.05	145.06	145.043
255	ACM 334	Synthetic Oil	130	500	132.01	132.05	132.05	132.037
256	ACM 334	Synthetic Oil	120	168	210.27	210.28	210.29	210.28
257	ACM 334	Synthetic Oil	120	250	200.02	200.03	200.04	200.03
258	ACM 334	Synthetic Oil	120	333	185.25	185.26	185.27	185.26
259	ACM 334	Synthetic Oil	120	417	172.21	172.25	172.25	172.237
260	ACM 334	Synthetic Oil	120	500	163.21	163.22	163.25	163.227

Table D 14: Viton 337 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
261	Viton 337	Synthetic Oil	150	168	270.25	270.26	270.24	270.25
262	Viton 337	Synthetic Oil	150	250	243.21	243.21	243.22	243.213
263	Viton 337	Synthetic Oil	150	333	212.06	212.05	212.06	212.057
264	Viton 337	Synthetic Oil	150	417	195.21	195.21	195.22	195.213
265	Viton 337	Synthetic Oil	150	500	170.36	170.36	170.37	170.363
266	Viton 337	Synthetic Oil	140	168	282.12	282.14	282.15	282.137
267	Viton 337	Synthetic Oil	140	250	265.15	265.16	265.16	265.157
268	Viton 337	Synthetic Oil	140	333	242.02	242.02	242.05	242.03
269	Viton 337	Synthetic Oil	140	417	235.1	235.12	235.14	235.12
270	Viton 337	Synthetic Oil	140	500	220.25	220.26	220.26	220.257
271	Viton 337	Synthetic Oil	130	168	290.14	290.19	290.16	290.163
272	Viton 337	Synthetic Oil	130	250	285.45	285.46	285.47	285.46
273	Viton 337	Synthetic Oil	130	333	270.21	270.22	270.23	270.22
274	Viton 337	Synthetic Oil	130	417	260.27	260.27	260.29	260.277
275	Viton 337	Synthetic Oil	130	500	245.21	245.26	245.26	245.243
276	Viton 337	Synthetic Oil	120	168	330.21	330.25	330.25	330.237
277	Viton 337	Synthetic Oil	120	250	296.21	296.21	296.25	296.223
278	Viton 337	Synthetic Oil	120	333	285.01	285.04	285.04	285.03
279	Viton 337	Synthetic Oil	120	417	261.23	261.24	261.24	261.237
280	Viton 337	Synthetic Oil	120	500	249.46	249.45	249.46	249.457

Table D 15: HNBR 338 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
281	HNBR 338	Synthetic Oil	150	168	120.21	120.22	120.22	120.217
282	HNBR 338	Synthetic Oil	150	250	100.01	100.02	100.02	100.017
283	HNBR 338	Synthetic Oil	150	333	90.21	90.22	90.23	90.22
284	HNBR 338	Synthetic Oil	150	417	81.23	81.25	81.23	81.2367
285	HNBR 338	Synthetic Oil	150	500	80.05	80.05	80.05	80.05
286	HNBR 338	Synthetic Oil	140	168	170.86	170.85	170.86	170.857
287	HNBR 338	Synthetic Oil	140	250	162.02	162.02	162.05	162.03
288	HNBR 338	Synthetic Oil	140	333	151.25	151.25	151.26	151.253
289	HNBR 338	Synthetic Oil	140	417	143.21	143.22	143.22	143.217
290	HNBR 338	Synthetic Oil	140	500	126.26	126.25	126.25	126.253
291	HNBR 338	Synthetic Oil	130	168	175.01	175.02	175.03	175.02
292	HNBR 338	Synthetic Oil	130	250	164.21	164.21	164.25	164.223
293	HNBR 338	Synthetic Oil	130	333	152.21	152.21	152.25	152.223
294	HNBR 338	Synthetic Oil	130	417	141.02	141.03	141.04	141.03
295	HNBR 338	Synthetic Oil	130	500	137.25	137.26	137.25	137.253
296	HNBR 338	Synthetic Oil	120	168	180.25	180.26	180.26	180.257
297	HNBR 338	Synthetic Oil	120	250	174.24	174.24	174.26	174.247
298	HNBR 338	Synthetic Oil	120	333	166.61	166.65	166.65	166.637
299	HNBR 338	Synthetic Oil	120	417	149.46	149.45	149.46	149.457
300	HNBR 338	Synthetic Oil	120	500	135.24	135.24	135.25	135.243

Table D 16: AEM 336 elongation results of rubber exposed to increased temperatures and service intervals using synthetic oil

Test number	Material	Medium	Temp.	Service interval (hrs)	Δ Hardness (Shore A)			Avg
301	AEM/Vamac 336	Synthetic Oil	150	168	150.02	150.02	150.05	150.03
302	AEM/Vamac 336	Synthetic Oil	150	250	141.25	141.25	141.26	141.253
303	AEM/Vamac 336	Synthetic Oil	150	333	130.02	130.02	130.03	130.023
304	AEM/Vamac 336	Synthetic Oil	150	417	120.12	120.12	120.15	120.13
305	AEM/Vamac 336	Synthetic Oil	150	500	115.15	115.15	115.17	115.157
306	AEM/Vamac 336	Synthetic Oil	140	168	152.35	152.36	152.36	152.357
307	AEM/Vamac 336	Synthetic Oil	140	250	143.21	143.22	143.24	143.223
308	AEM/Vamac 336	Synthetic Oil	140	333	135.46	135.45	135.46	135.457
309	AEM/Vamac 336	Synthetic Oil	140	417	122.24	122.24	122.26	122.247
310	AEM/Vamac 336	Synthetic Oil	140	500	117.02	117.02	117.05	117.03
311	AEM/Vamac 336	Synthetic Oil	130	168	162.23	162.23	162.24	162.233
312	AEM/Vamac 336	Synthetic Oil	130	250	153.21	153.23	153.24	153.227
313	AEM/Vamac 336	Synthetic Oil	130	333	145.22	145.23	145.23	145.227
314	AEM/Vamac 336	Synthetic Oil	130	417	134.45	134.46	134.46	134.457
315	AEM/Vamac 336	Synthetic Oil	130	500	127.05	127.07	127.07	127.063
316	AEM/Vamac 336	Synthetic Oil	120	168	180.32	180.35	180.36	180.343
317	AEM/Vamac 336	Synthetic Oil	120	250	172.05	172.06	172.06	172.057
318	AEM/Vamac 336	Synthetic Oil	120	333	163.21	163.25	163.21	163.223
319	AEM/Vamac 336	Synthetic Oil	120	417	154.05	154.05	154.05	154.05
320	AEM/Vamac 336	Synthetic Oil	120	500	151.35	151.35	151.35	151.35

Appendix E: DOE

The Box Behnken method was chosen to determine the responses materials Nitrile 321 represented as -1 on the DOE software, ACM 334 represented as 0 on the DOE software and Viton 337 represented as -1 on the DOE software.

Table E.1 shows the layout in standard order for a Box-Behnken for all variables used in this investigation. The DOE software allows for data to be sorted for multiple variables to find effects on the overall responses. For occurrence, data can be sorted by any of the variables and thereafter understand the effect it has on the overall response. The impact of each variable on the response variable is found in the correlation graph (under Graph Columns) in DOE Software.

1. Raw data inputted into DOE software resulting in scatter plots

Table E 1: Raw data

Std	Run	Factor 1 A: Materials	Factor 2 B: Temperature (°C)	Factor 3 C: Time (h)	Response 1 Hardness (Shore A)	Response 2 Volume (%)	Response 3 Strength (N/mm^2)	Response 4 Elongation (%)
3	1	-1	150	334	10.33	-3.2	4.2	50.4
17	2	0	135	334	11.5	2.995	15.74	181.45
2	3	1	120	334	0.666667	4.23	21.27	314.26
5	4	-1	135	168	6.83	-2.58	6.37	95.02
10	5	0	150	168	15.3333	3.96	14.22	171.22
14	6	0	135	334	11.5	2.995	15.74	181.45
6	7	1	135	168	1.83	3.02	21.96	315.31

Table E.1 (continued)

Std	Run	Factor 1 A: Materials	Factor 2 B: Temperature (°C)	Factor 3 C: Time (h)	Response 1 Hardness (Shore A)	Response 2 Volume (%)	Response 3 Strength (N/mm^2)	Response 4 Elongation (%)
7	8	-1	135	500	11.67	-2.77	5.47	81.41
12	9	0	150	500	19.3333	6.95	7.53	136.23
13	10	0	135	334	11.5	2.995	15.74	181.45
4	11	1	150	334	7.33333	8.87	14.24	245.11
16	12	0	135	334	11.5	2.995	15.74	181.45
1	13	-1	120	334	4.33	-2.48	8.53	174.5
15	14	0	135	334	11.5	2.995	15.74	181.45
9	15	0	120	168	0.333333	0.96	24.24	240.34
8	16	1	135	500	7.5	7.9	15.2	263.2
11	17	0	120	500	7.33333	1.21	19.24	192.97

Figure E.1, E.2, E.3 and E.4 show the impact of temperature on hardness, change in volume, tensile strength and elongation respectively. The impact of service intervals on hardness, change in volume, tensile strength and elongation is illustrated by figure E.5, E.6, E.7 and E.8 respectively.

The correlation graph shows the response versus variable graph for all the data points that were entered in DOE Software. With three points for each variable (-1, 0, 1), a linear plot is generated for each variable. Since this was a linear plot, the correlation was given by the slope of the graph.

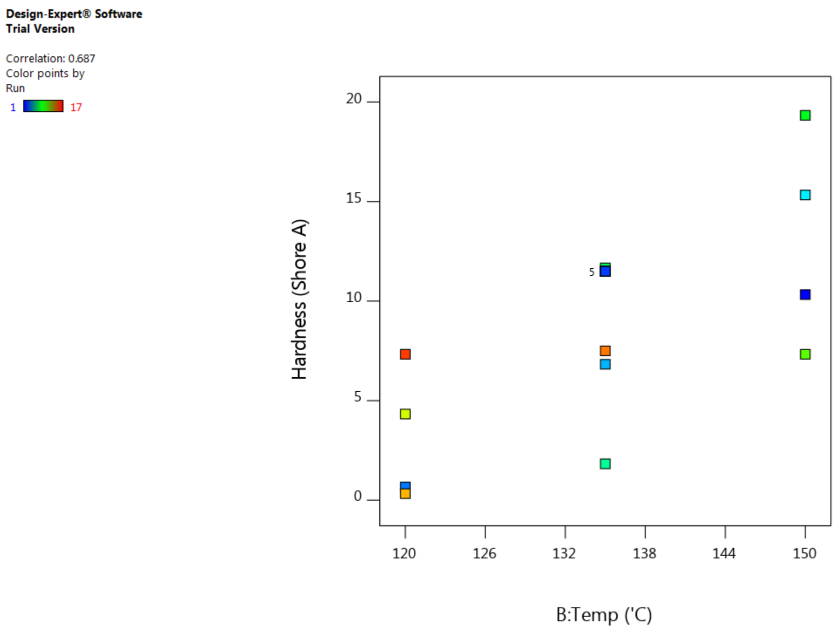

Figure E 1: Temperature effect on hardness mineral oil

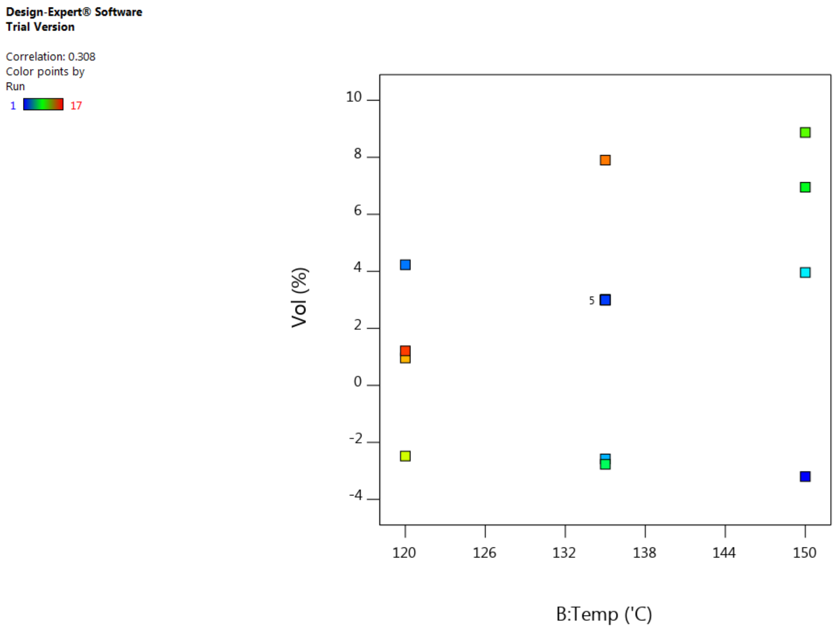

Figure E 2: Temperature effect on change in volume mineral oil

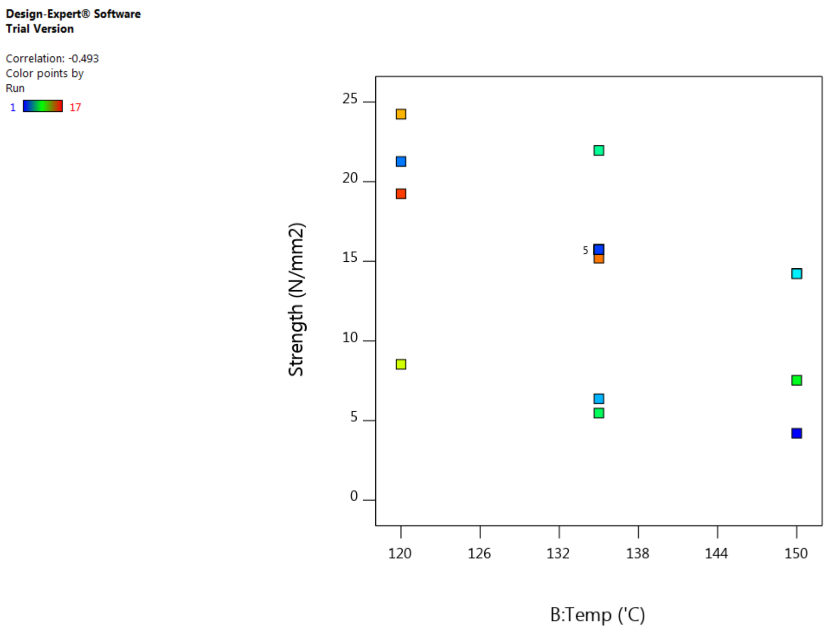

Figure E 3: Temperature effect on change in volume mineral oil

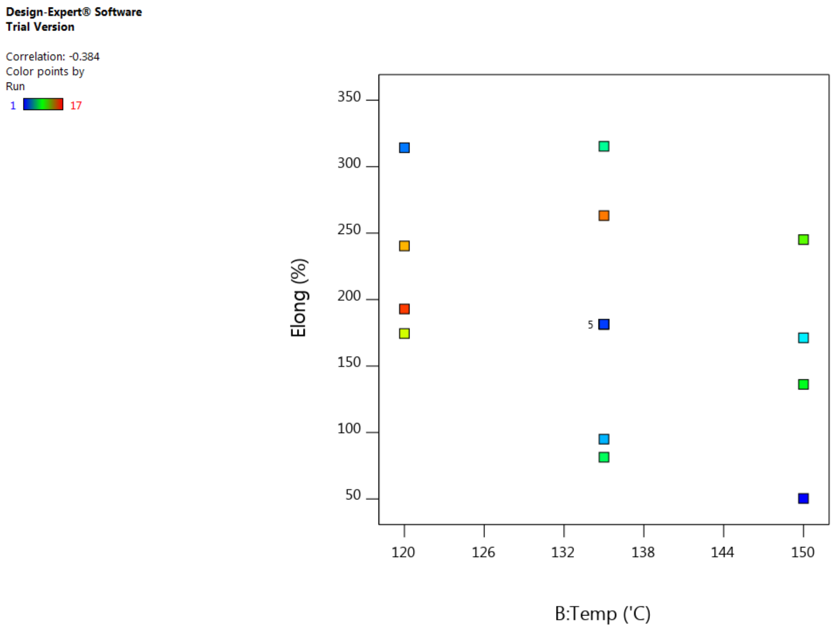

Figure E 4: Temperature effect on change in elongation mineral oil

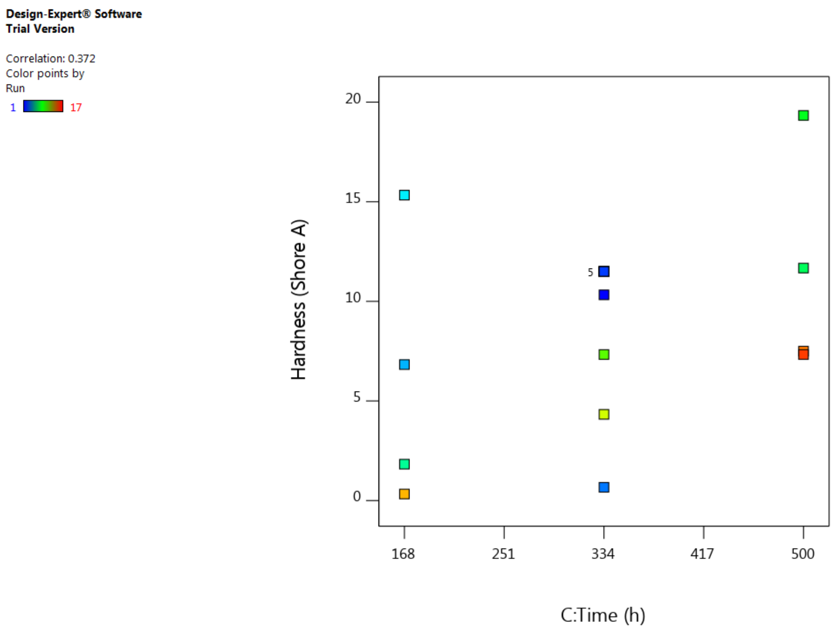

Figure E 5: Service interval effect on change in hardness mineral oil

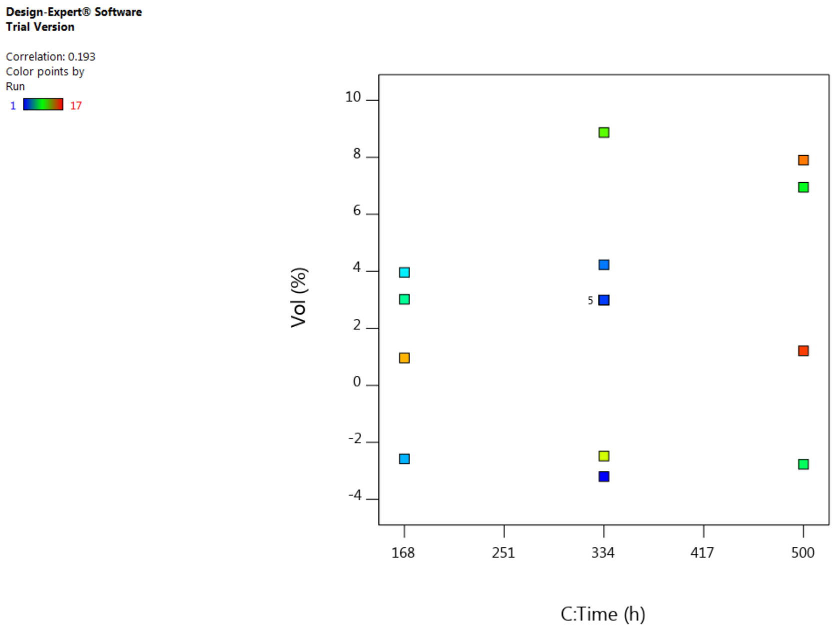

Figure E 6: Service interval effect on change in volume mineral oil

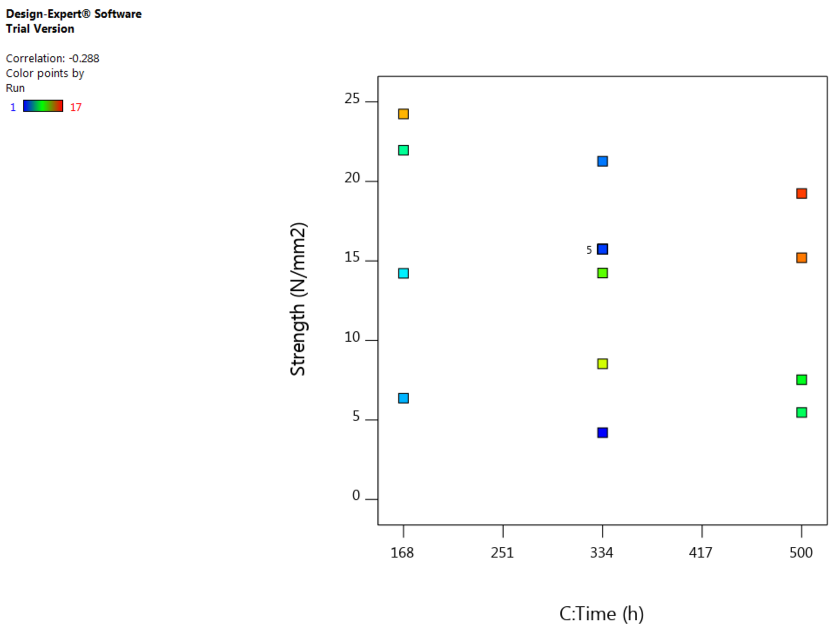

Figure E 7: Service interval effect on tensile strength mineral oil

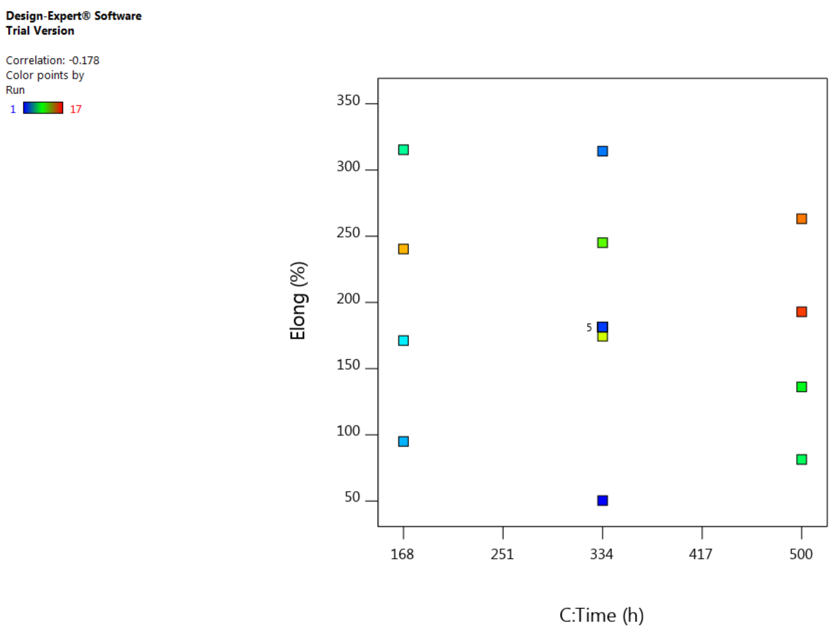

Figure E 8: Service interval effect on elongation mineral oil

An additional useful indicator of the effect of a variable on the response is the correlation grid box, which in DOE Software is situated at the intersection of the variables in the graph columns.

Figure E.9, E.10, E.11 and E.12 show the effect of temperature on hardness, change in volume, tensile strength and elongation whereas Figure E.13, E.14, E.15 and E.16 show the effect of service interval on hardness, change in volume, tensile strength and elongation.

The correlation value (shown on the legend – left hand-side of the figures) indicates how much each variable affects the response, ranging from negative 1 to positive 1. A correlation with a positive value implies that the response increases with an increase in variable, while a negative value implies that the response decreases with an increase in variable.

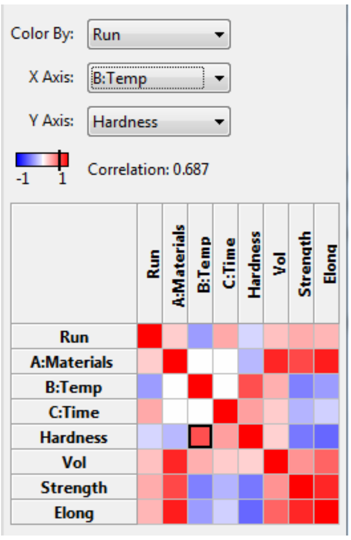

Figure E 9: Correlation grid of temperature effect on hardness mineral oil

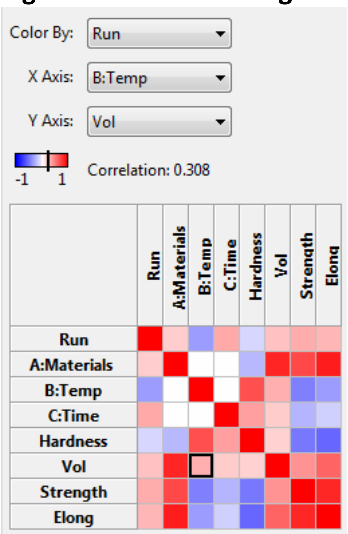

Figure E 10: Correlation grid of temperature effect on change in volume mineral oil

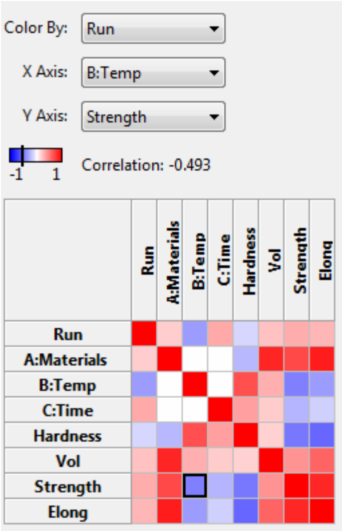

Figure E 11: Correlation grid of temperature effect on tensile strength mineral oil

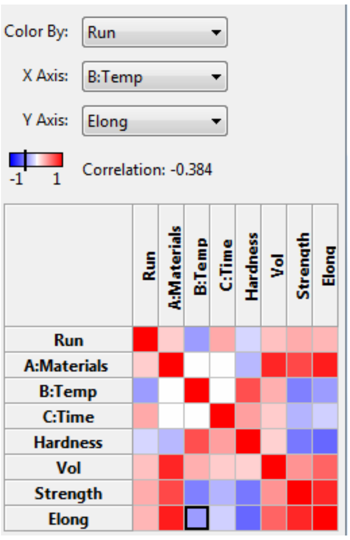

Figure E 12: Correlation grid of temperature effect on elongation mineral oil

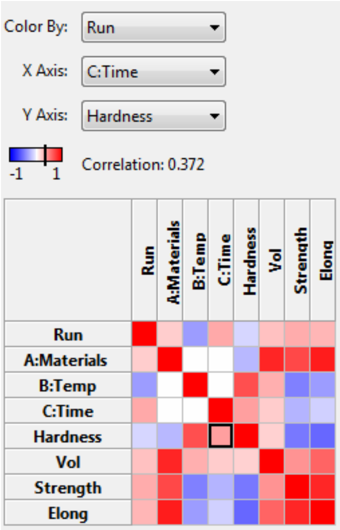

Figure E 13: Correlation grid of service interval effect on hardness mineral oil

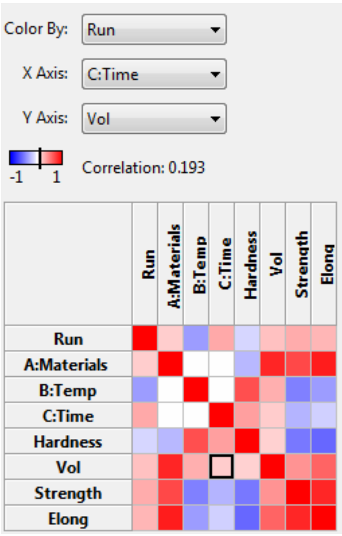

Figure E 14: Correlation grid of service interval effect on change in volume mineral oil

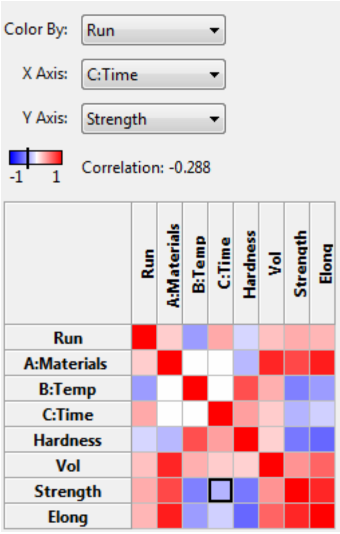

Figure E 15: Correlation grid of service interval effect on tensile strength mineral oil

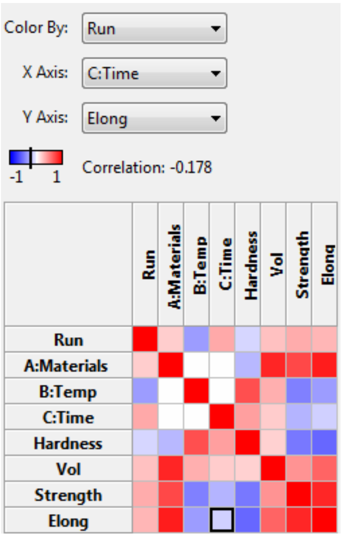

Figure E 16: Correlation grid of service interval effect on elongation mineral oil

Figure E9 shows a positive correlation which indicates that as hardness increases temperature increases. Figure E10 shows a positive correlation which indicates that as temperature increases change in volume increases. Figure E11 shows a negative correlation which indicates that as temperature increases tensile strength decreases. Figure E12 shows a negative correlation which indicates that as temperature increases elongation decreases. Figure E13 shows a positive correlation which indicates that as service intervals increase hardness increases. Figure E14 has a positive correlation which shows that as service intervals increase change in volume increases.

Figure E15 has a negative correlation which indicates that as service intervals increase tensile strength decreases. Figure E16 has a negative correlation which indicates that as service intervals increase elongation decreases.

2. Transformation

Figure E.17, E.18, E.19 and E.20 show the transformation graphs for hardness, change in volume, tensile strength and elongation results respectively.

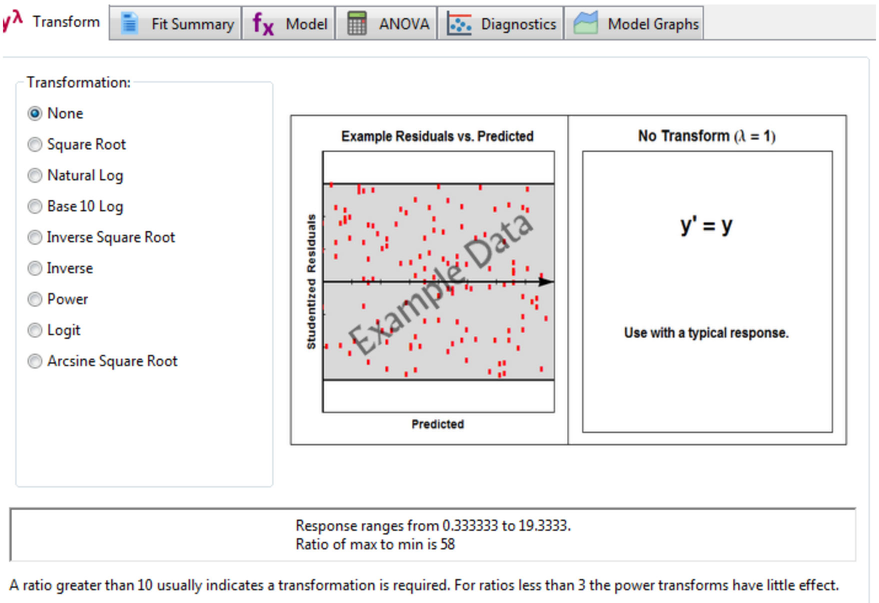

Figure E 17: Transformation for hardness mineral oil

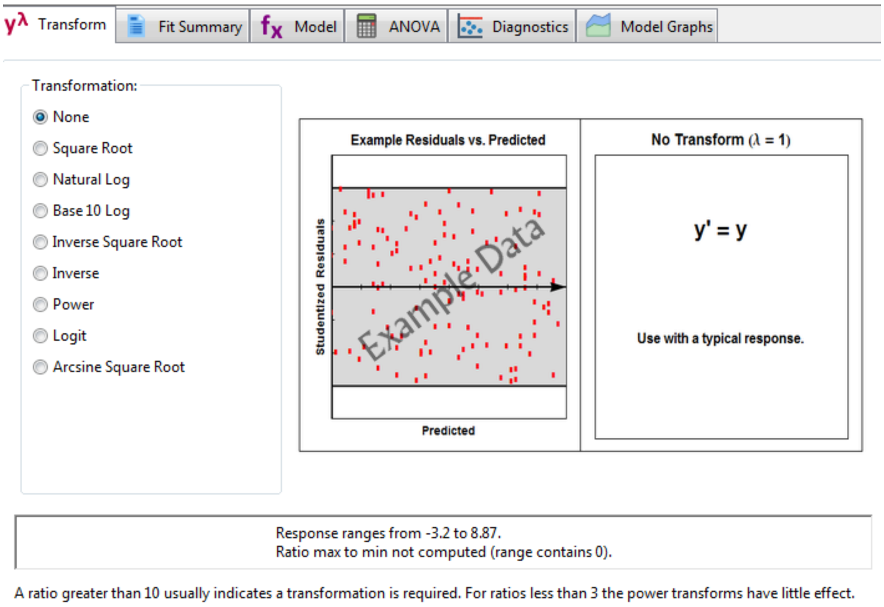

Figure E 18: Transformation for change in volume mineral oil

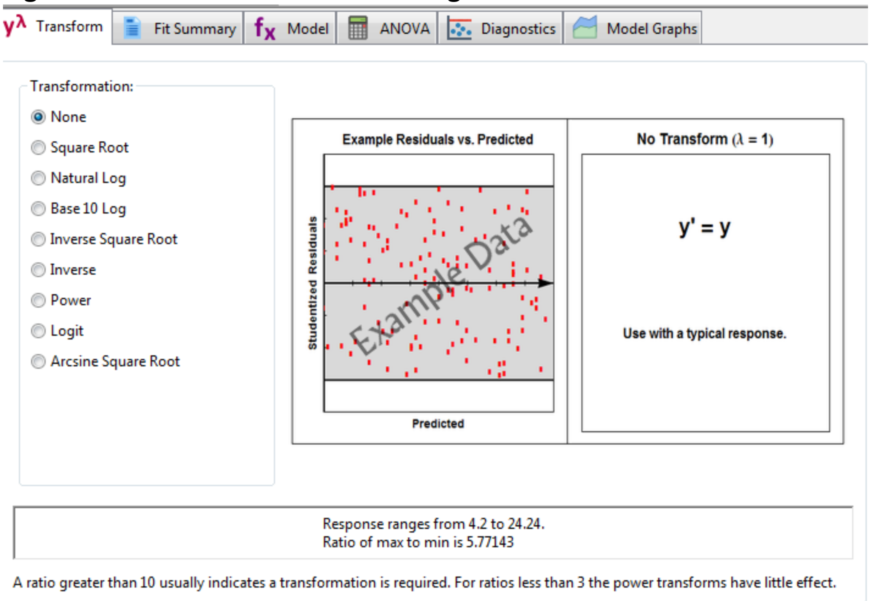

Figure E 19: Transformation for tensile strength mineral oil

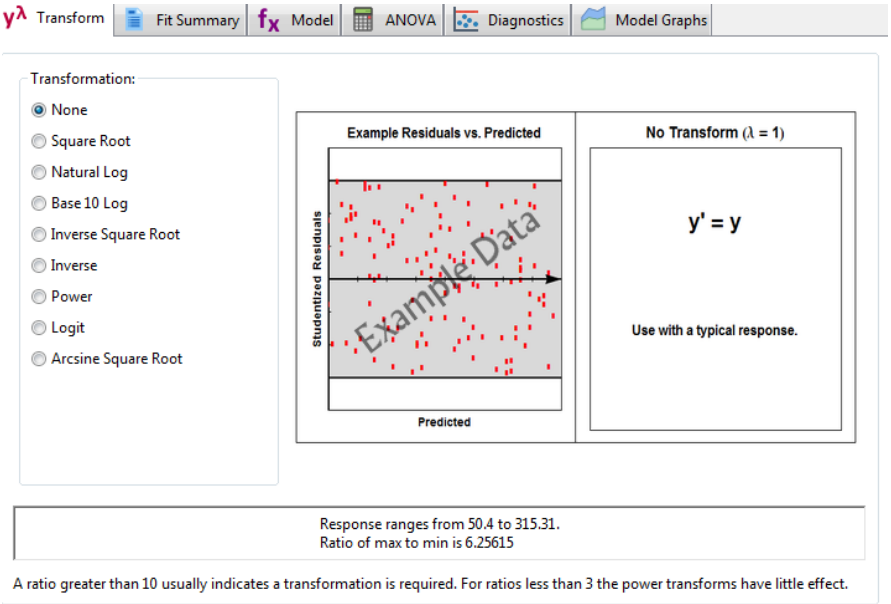

Figure E 20: Transformation for elongation mineral oil

The response values for hardness represented by figure E.17 ranged from 0.33 to 19.33 which resulted in a ratio of 58 indicating that a transformation is required as a ratio greater than 10 usually indicates that a transformation is required. Figure E.18 values ranged from -3.2 to 8.87 and therefore did not pick up a ratio. Figure E.19 values ranged from 4.2 to 24.24 and resulted in a ratio of 5.77 therefore not requiring a transformation. Figure E.20 values ranged from 50.4 to 315.31 which resulted in a ratio of 6.26 indicating that a transformation is not required.

3. Fit summary

Fit summary gives the fit of points for all types of model or transforms, and the model with the best fit may be chosen. The models that were tested were linear, quadratic and cubic models. Fit summary results are illustrated for hardness, change in volume, tensile strength and elongation in tables E.2, E.3, E.4 and E.5 respectively. Sequential model sum results are illustrated for hardness, change in volume, tensile strength and elongation in tables E.6, E.7, E.8 and E.9 respectively.

The highest order polynomial where the additional terms are significant and the model is not aliased were chosen.

Table E 2: Fit summary for hardness mineral oil

Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Linear	**0.0014**	**0.6131**	**0.4236**	**Suggested**
2FI	0.9769	0.5067	-0.2444	
Quadratic	**0.0085**	**0.8547**	**-0.0169**	**Suggested**
Cubic		1.0000		Aliased

Table E 3: Fit summary for change in volume mineral oil

Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Linear	**< 0.0001**	**0.8280**	**0.7151**	**Suggested**
2FI	0.0507	0.8938	0.6911	
Quadratic	**0.0246**	**0.9572**	**0.7001**	**Suggested**
Cubic		1.0000		Aliased

Table E 4: Fit summary for tensile strength mineral oil

Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Linear	**< 0.0001**	**0.8022**	**0.6842**	**Suggested**
2FI	0.7120	0.7744	0.3616	
Quadratic	**0.0083**	**0.9340**	**0.5377**	**Suggested**
Cubic		1.0000		Aliased

Table E 5: Fit summary for elongation mineral oil

Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Linear	**< 0.0001**	**0.9594**	**0.9330**	**Suggested**
2FI	0.1380	0.9688	0.9084	
Quadratic	0.4463	0.9689	0.7820	
Cubic		1.0000		Aliased

Table E 6: Sequential model sum for hardness mineral oil

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	1329.24	1	1329.24			
Linear vs Mean	**285.84**	**3**	**95.28**	**9.45**	**0.0014**	**Suggested**
2FI vs Linear	2.53	3	0.8444	0.0657	0.9769	
Quadratic vs 2FI	**102.03**	**3**	**34.01**	**8.98**	**0.0085**	**Suggested**
Cubic vs Quadratic	26.50	3	8.83			Aliased
Residual	0.0000	4	0.0000			
Total	1746.14	17	102.71			

Table E 7: Sequential model sum for change in volume mineral oil

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	99.10	1	99.10			
Linear vs Mean	**181.46**	**3**	**60.49**	**26.67**	**< 0.0001**	**Suggested**
2FI vs Linear	15.49	3	5.16	3.69	0.0507	
Quadratic vs 2FI	**10.04**	**3**	**3.35**	**5.93**	**0.0246**	**Suggested**
Cubic vs Quadratic	3.95	3	1.32			Aliased
Residual	0.0000	4	0.0000			
Total	310.04	17	18.24			

Table E 8: Sequential model sum for tensile strength mineral oil

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	3421.35	1	3421.35			
Linear vs Mean	**472.87**	**3**	**157.62**	**22.63**	**< 0.0001**	**Suggested**
2FI vs Linear	11.12	3	3.71	0.4667	0.7120	
Quadratic vs 2FI	**63.15**	**3**	**21.05**	**9.05**	**0.0083**	**Suggested**
Cubic vs Quadratic	16.28	3	5.43			Aliased
Residual	0.0000	4	0.0000			
Total	3984.77	17	234.40			

Table E 9: Sequential model sum for elongation mineral oil

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	5.976E+05	1	5.976E+05			
Linear vs Mean	**83283.10**	**3**	**27761.03**	**127.01**	**< 0.0001**	**Suggested**
2FI vs Linear	1163.75	3	387.92	2.31	0.1380	
Quadratic vs 2FI	504.06	3	168.02	1.00	0.4463	
Cubic vs Quadratic	1173.68	3	391.23			Aliased
Residual	0.0000	4	0.0000			
Total	6.837E+05	17	40216.23			

In table E.2, E.3, E.4, E.6, E.7 and E.8 the quadratic model has the highest adjusted R-Squared value and p-value whereas the linear model has the highest Predicted R-Squared value and F-value. The model can either be linear or quadratic. The cubic model cannot be chosen as it is aliased. The linear model was chosen for hardness, change in volume and tensile strength.

In table E.5 and E.9 the quadratic model has p-value whereas the linear model has adjusted R-Squared, the highest Predicted R-Squared value and F-value. The cubic model cannot be chosen as it is aliased. The model suggested was linear opposed to quadratic.

4. Diagnostics

The main diagnostic graph to look at is the predicted versus actual graph. The points should be linearly distributed along the 45 degree line, indicating that the model has almost predicted the actual points. Figure E.21, E.22, E.23 and E.24 represent the predicted versus actual graphs for hardness, change in volume, tensile strength and elongation.

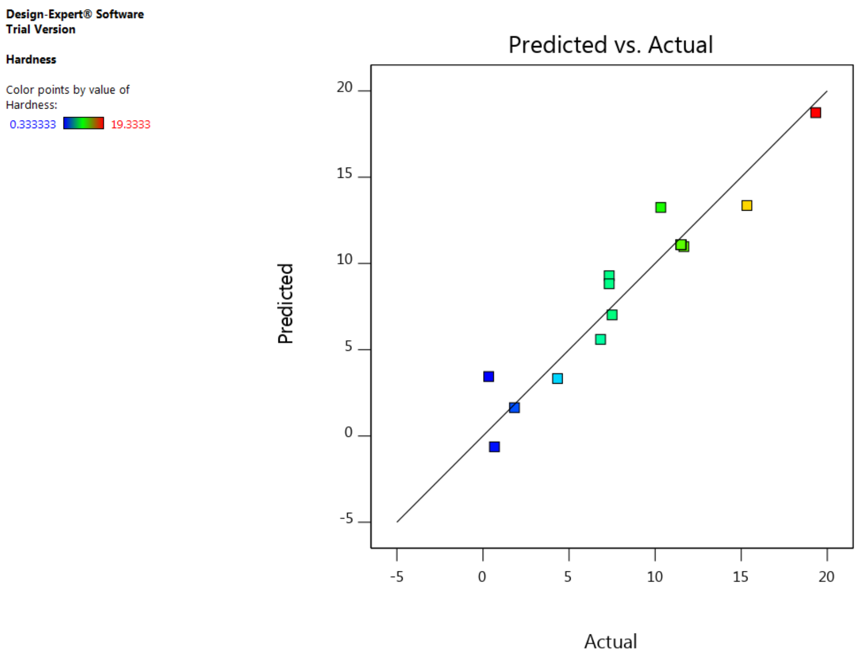

Figure E 21: Predicted versus actual plot for hardness mineral oil

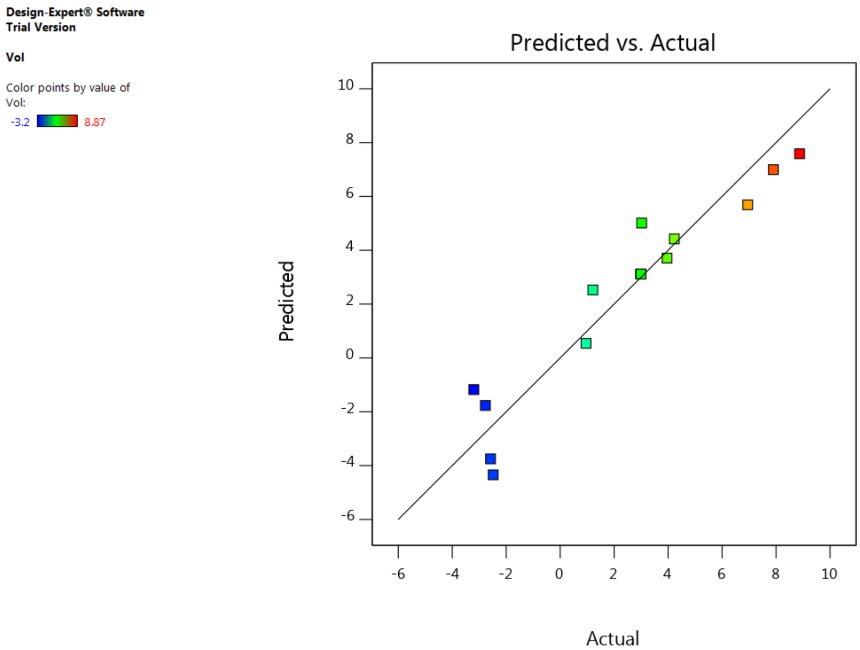

Figure E 22: Predicted versus actual plot for change in volume mineral oil

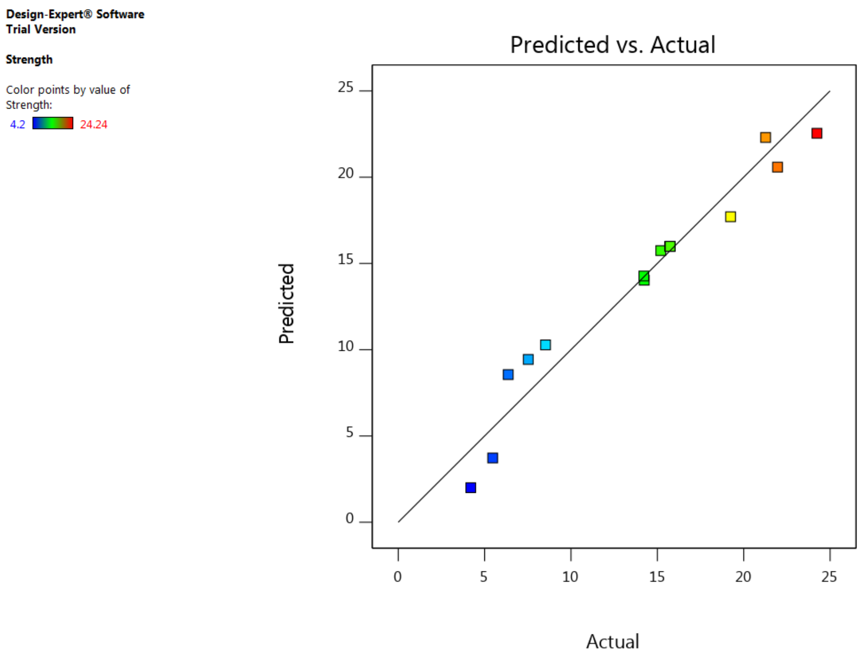

Figure E 23: Predicted versus actual plot for tensile strength mineral oil

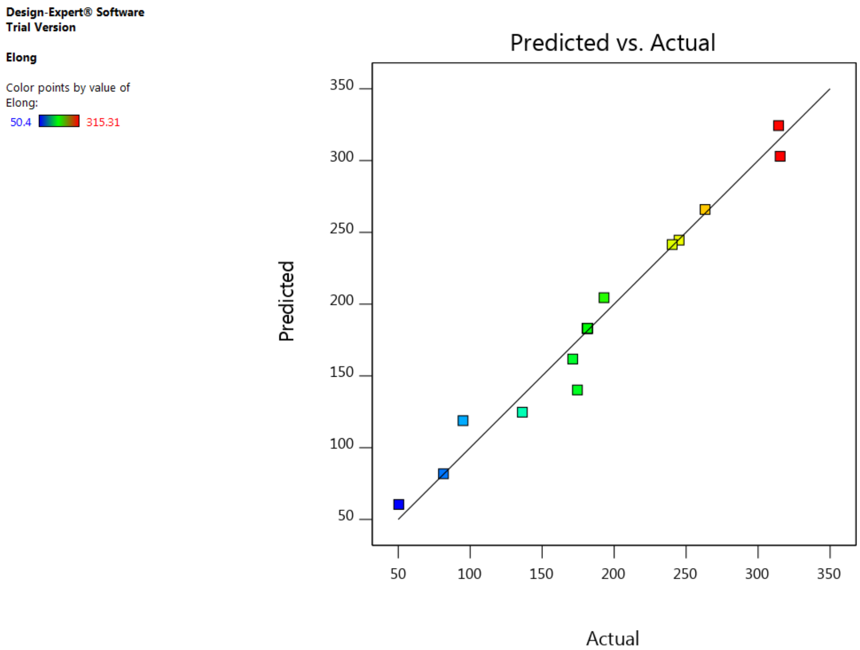

Figure E 24: Predicted versus actual plot for elongation mineral oil

Table E.10, E.11, E.12 and E.13 represent diagnostic reports on hardness, change in elongation, tensile strength and elongation respectively.

Table E 10: Diagnostics report on hardness mineral oil

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	10.33	13.25	-2.92	0.375	-2.185	-2.697	0.573	-2.089[1]	3
2	11.50	11.09	0.4074	0.111	0.256	0.246	0.002	0.087	17
3	0.6667	-0.6258	1.29	0.375	0.968	0.965	0.112	0.748	2
4	6.83	5.60	1.23	0.375	0.920	0.914	0.102	0.708	5
5	15.33	13.36	1.97	0.361	1.460	1.541	0.241	1.159	10
6	11.50	11.09	0.4074	0.111	0.256	0.246	0.002	0.087	14
7	1.83	1.64	0.1863	0.375	0.139	0.134	0.002	0.104	6
8	11.67	10.98	0.6912	0.375	0.518	0.501	0.032	0.388	7
9	19.33	18.74	0.5937	0.361	0.440	0.424	0.022	0.319	12
10	11.50	11.09	0.4074	0.111	0.256	0.246	0.002	0.087	13
11	7.33	9.29	-1.96	0.375	-1.466	-1.549	0.258	-1.200	4
12	11.50	11.09	0.4074	0.111	0.256	0.246	0.002	0.087	16
13	4.33	3.33	0.9983	0.375	0.748	0.733	0.067	0.568	1
14	11.50	11.09	0.4074	0.111	0.256	0.246	0.002	0.087	15
15	0.3333	3.45	-3.11	0.361	-2.305	-2.956	0.601	-2.223[1]	9
16	7.50	7.02	0.4787	0.375	0.359	0.345	0.015	0.267	8
17	7.33	8.82	-1.49	0.361	-1.103	-1.114	0.138	-0.838	11

[1] Exceeds limits.

Table E 11: Diagnostics report on change in volume mineral oil

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	-3.20	-1.17	-2.03	0.375	-1.982	-2.314	0.472	-1.793 [1]	3
2	3.00	3.12	-0.1222	0.111	-0.100	-0.096	0.000	-0.034	17
3	4.23	4.42	-0.1925	0.375	-0.188	-0.181	0.004	-0.140	2
4	-2.58	-3.75	1.17	0.375	1.144	1.161	0.157	0.899	5
5	3.96	3.71	0.2515	0.361	0.244	0.234	0.007	0.176	10
6	3.00	3.12	-0.1222	0.111	-0.100	-0.096	0.000	-0.034	14
7	3.02	5.01	-1.99	0.375	-1.952	-2.262	0.457	-1.752 [1]	6
8	-2.77	-1.77	-1.00	0.375	-0.983	-0.981	0.116	-0.760	7
9	6.95	5.69	1.26	0.361	1.219	1.247	0.168	0.937	12
10	3.00	3.12	-0.1222	0.111	-0.100	-0.096	0.000	-0.034	13
11	8.87	7.59	1.28	0.375	1.255	1.290	0.189	0.999	4
12	3.00	3.12	-0.1222	0.111	-0.100	-0.096	0.000	-0.034	16
13	-2.48	-4.34	1.86	0.375	1.821	2.049	0.398	1.587	1
14	3.00	3.12	-0.1222	0.111	-0.100	-0.096	0.000	-0.034	15
15	0.9600	0.5435	0.4165	0.361	0.403	0.389	0.018	0.292	9
16	7.90	7.00	0.9038	0.375	0.885	0.876	0.094	0.679	8
17	1.21	2.53	-1.32	0.361	-1.274	-1.312	0.184	-0.986	11

[1] Exceeds limits.

Table E 12: Diagnostics report on tensile strength mineral oil

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	4.20	2.01	2.19	0.375	1.811	2.033	0.393	1.575	3
2	15.74	15.99	-0.2522	0.111	-0.175	-0.167	0.001	-0.059	17
3	21.27	22.30	-1.03	0.375	-0.853	-0.843	0.087	-0.653	2
4	6.37	8.56	-2.19	0.375	-1.808	-2.030	0.392	-1.572	5
5	14.22	14.27	-0.0547	0.361	-0.045	-0.043	0.000	-0.032	10
6	15.74	15.99	-0.2522	0.111	-0.175	-0.167	0.001	-0.059	14
7	21.96	20.59	1.37	0.375	1.134	1.149	0.154	0.890	6
8	5.47	3.72	1.75	0.375	1.441	1.517	0.249	1.175	7
9	7.53	9.44	-1.91	0.361	-1.557	-1.669	0.274	-1.254	12
10	15.74	15.99	-0.2522	0.111	-0.175	-0.167	0.001	-0.059	13
11	14.24	14.03	0.2088	0.375	0.172	0.165	0.004	0.128	4
12	15.74	15.99	-0.2522	0.111	-0.175	-0.167	0.001	-0.059	16
13	8.53	10.28	-1.75	0.375	-1.443	-1.520	0.250	-1.177	1
14	15.74	15.99	-0.2522	0.111	-0.175	-0.167	0.001	-0.059	15
15	24.24	22.55	1.69	0.361	1.382	1.443	0.216	1.085	9
16	15.20	15.75	-0.5487	0.375	-0.453	-0.437	0.025	-0.339	8
17	19.24	17.71	1.53	0.361	1.249	1.282	0.176	0.964	11

Table E 13: Diagnostics report on elongation mineral oil

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	50.40	60.44	-10.04	0.375	-0.884	-0.876	0.094	-0.678	3
2	181.45	183.11	-1.66	0.111	-0.123	-0.118	0.000	-0.042	17
3	314.26	324.36	-10.10	0.375	-0.889	-0.881	0.095	-0.682	2
4	95.02	118.84	-23.82	0.375	-2.098	-2.524	0.528	-1.955(1)	5
5	171.22	161.73	9.49	0.361	0.826	0.815	0.077	0.612	10
6	181.45	183.11	-1.66	0.111	-0.123	-0.118	0.000	-0.042	14
7	315.31	302.98	12.33	0.375	1.086	1.095	0.141	0.848	6
8	81.41	81.82	-0.4125	0.375	-0.036	-0.035	0.000	-0.027	7
9	136.23	124.71	11.52	0.361	1.003	1.003	0.114	0.754	12
10	181.45	183.11	-1.66	0.111	-0.123	-0.118	0.000	-0.042	13
11	245.11	244.58	0.5288	0.375	0.047	0.045	0.000	0.035	4
12	181.45	183.11	-1.66	0.111	-0.123	-0.118	0.000	-0.042	16
13	174.50	140.22	34.28	0.375	3.019	5.891(2)	1.093(1)	4.563(1)	1
14	181.45	183.11	-1.66	0.111	-0.123	-0.118	0.000	-0.042	15
15	240.34	241.51	-1.17	0.361	-0.102	-0.098	0.001	-0.073	9
16	263.20	265.96	-2.76	0.375	-0.243	-0.233	0.007	-0.181	8
17	192.97	204.49	-11.52	0.361	-1.003	-1.004	0.114	-0.755	11

(1) Exceeds limits.

(2) Observation with |External Stud. Residuals| > 3.80

5. Optimisation

The limits specified for hardness, change in volume, tensile strength and elongation are represented in table E.14. From these limits, solutions are derived and the most desired solution is suggested.

Table E 14: Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Materials	is in range	-1	1	1	1	3
B:Temp	is in range	120	150	1	1	3
C:Time	is in range	168	500	1	1	3
Hardness	is in range	0.333333	19.3333	1	1	3
Vol	is in range	-3.2	8.87	1	1	3
Strength	is in range	4.2	24.24	1	1	3
Elong	is in range	50.4	315.31	1	1	3

There were 100 solutions found according to the DOE software with the desired solution being obtained and represented in table E15. 5 out of the 100 solutions are reflected in table E12.

Table E 15: Desired solution

Number	Materials	Temp	Time	Hardness	Vol	Strength	Elong	Desirability	Selected
1	**-0.290**	**124.484**	**172.026**	**5.164**	**-0.358**	**19.182**	**203.178**	**1.000**	**Selected**
2	0.000	135.000	334.000	11.093	3.117	15.992	183.112	1.000	
3	-0.778	146.667	311.867	13.237	-0.095	6.100	88.566	1.000	
4	0.000	120.000	500.000	8.823	2.526	17.710	204.491	1.000	
5	-0.867	122.000	356.133	5.277	-3.041	11.161	142.399	1.000	

The desired solution is closest to material ACM 334 at a temperature of 124 degree celsius and service interval of 172 h.

6. Contour and 3D plots

Three dimensional (3D) and counter diagrams were plotted to have an understanding of non-linearity. The three dimensional (3D) and counter diagrams were plotted for the selected solution.

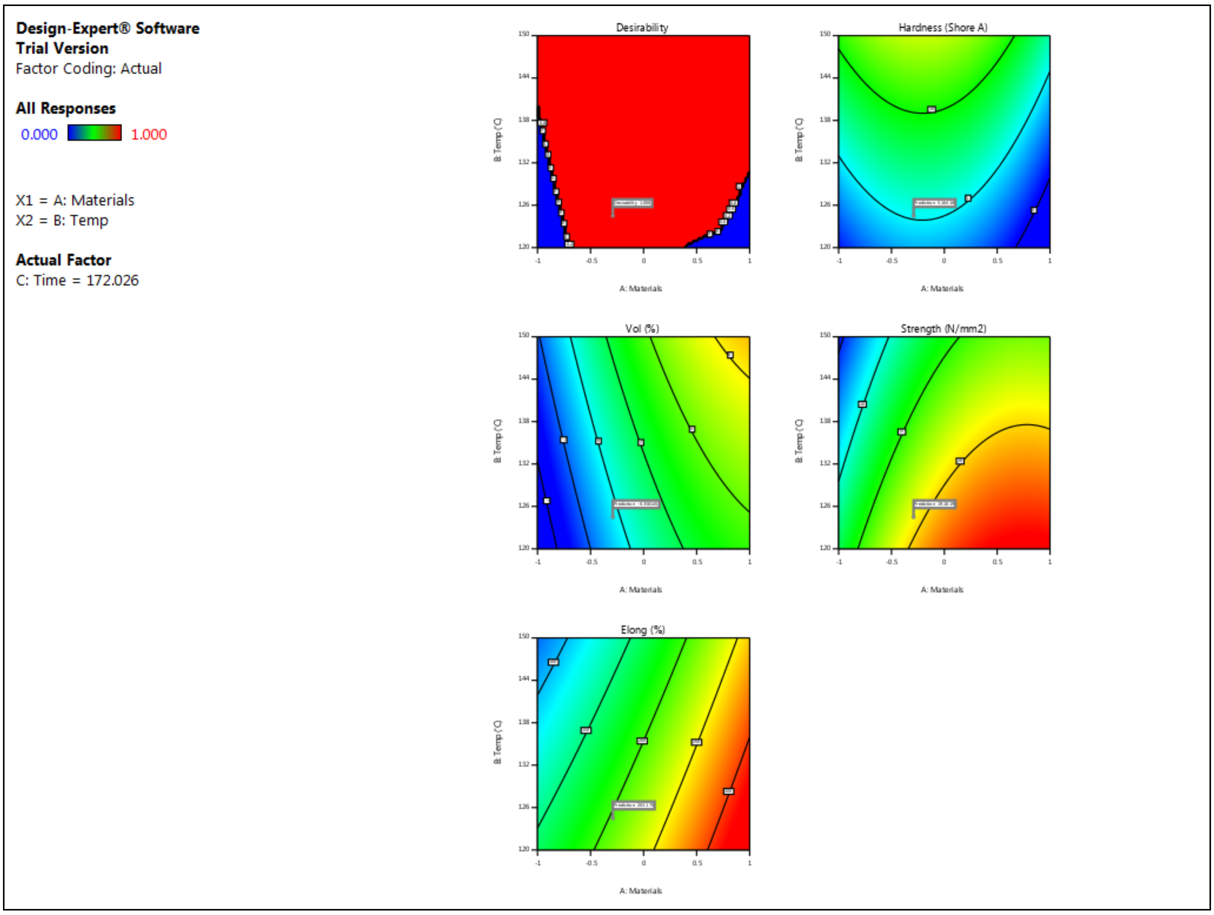

Figure E 25: Selected solution contour graphs

The red colour represents the material Viton 337, the blue colour Nitrile 321 and the green colour ACM 334.

The counter graphs shown above only illustrate two dimensional views of the results, which makes it difficult to comprehend the exact optimum response. A three dimensional (3D) surface makes it easy to understand how things derive from this investigation.

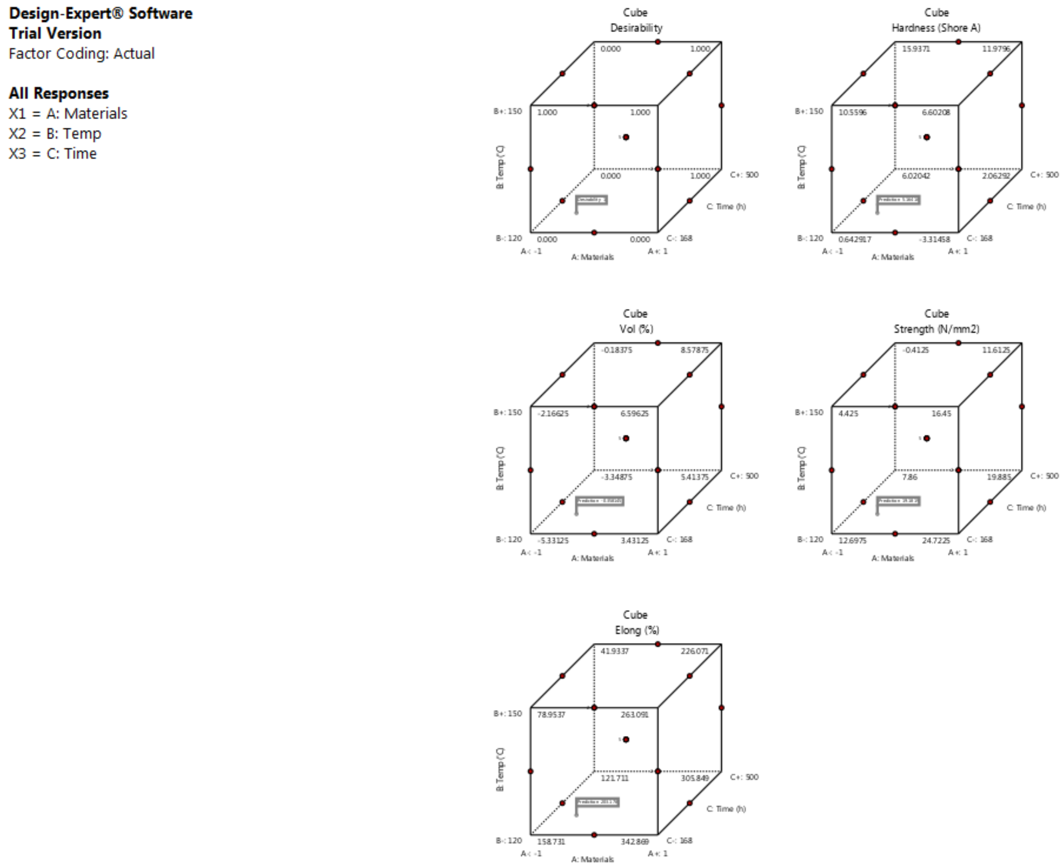

Figure E 26: Selected solution 3D

7. Point prediction

Table E.16 illustrates the confidence level of the model. The confidence level is 95% which shows that this model can be used.

Table E 16: Point Prediction for selected solution

Two-sided Confidence = 95% Population = 99%

Solution 1 of 100 Response	Predicted Mean	Predicted Median	Std Dev	SE Mean	95% CI low for Mean	95% CI high for Mean	95% TI low for 99% Pop	95% TI high for 99% Pop
Hardness	5.16418	5.16418	1.68918	0.901835	3.19925	7.12911	-3.03636	13.3647
Vol	-0.358145	-0.358145	1.29215	0.689866	-1.86123	1.14494	-6.63121	5.91492
Strength	19.1819	19.1819	1.53264	0.818264	17.399	20.9647	11.7413	26.6225
Elong	203.178	203.178	14.3644	7.66904	186.469	219.888	133.442	272.914

Appendix F: Editing certificate

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EDITING CERTIFICATE

Re: **Sherese Naidoo**
Master's dissertation: **OPTIMISATION OF RUBBER SELECTION IN THE AUTOMOTIVE FILTRATION INDUSTRY**

I confirm that I have edited this dissertation and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). During my 13 years as a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology I supervised numerous Master's degree dissertations.

Dr Richard Steele
09 April 2019
per email