{OPEN}

LIFETIME AND DEGRADATION BEHAVIOUR OF PTFE COOLANT HOSES

MASTER THESIS

Chris-Jan Bolks

Faculty of Engineering Technology, Mechanical Engineering

20-02-2025

Project type:	Master thesis
Version:	FINAL
Student:	Chris-Jan Bolks S2886650
Company:	Thales Nederland B.V.
Supervisors:	Anne Lotte Vissink & Robert Sauer
University:	University of Twente
Faculty:	Faculty of Engineering Technology
Specialization:	Maintenance engineering and organization
Research chair:	Dynamics Based Maintenance
Supervisor:	Prof.dr.ir. Tiedo Tinga

Summary

This master thesis investigates the degradation mechanisms, lifetime, and potential failure modes of polytetrafluoroethylene (PTFE) coolant hoses used in Thales' radar systems. The research aimed to determine if these hoses exhibit a practically infinite lifespan under typical conditions or if there are specific scenarios where degradation could lead to failure. The study utilized experimental and theoretical approaches to analyze the degradation behavior of PTFE hoses. A total of 150 PTFE samples were subjected to accelerated thermal aging under varying temperatures and durations, with a maximum of 250 °C and 24 days. The experimental results were analyzed using scanning electron microscopy (SEM) to observe surface morphology changes, differential scanning calorimetry (DSC) to evaluate thermal stability and crystallinity, and mechanical tests to measure hardness and tensile strength properties. These methodologies provided a thorough understanding of the material's degradation behavior over time.

The results indicated that thermal aging led to some measurable degradation in the material's mechanical properties, particularly at higher temperatures and extended exposure times. A general decline in maximum stress, maximum strain and a general increase in hardness was observed, along with microcracks and surface degradation detected through SEM imaging. DSC analysis revealed a negligible reduction in the melting temperature and crystallinity. Despite these changes, the hoses showed sufficient performance under nominal operating conditions, suggesting they are highly durable in typical naval applications. Arrhenius-based lifetime modeling indicated that the hoses could exceed a 50 years of service under operating conditions, supporting the hypothesis of a virtually infinite lifetime.

The findings highlight the durability of PTFE hoses but also suggest that extreme conditions, such as high temperatures or prolonged exposure to aggressive coolants, could accelerate degradation and potentially result in localized failures. They underscore the importance of periodic inspections and maintenance in critical systems to mitigate risks. The study contributes valuable insights to Thales, ensuring the reliability of their radar cooling systems.

However, some limitations should be noted. The controlled laboratory conditions used in the study cannot fully replicate the complex mechanical and chemical interactions present in real-world naval operations, such as coolant contamination or chemical degradation. Additionally, the small sample size limits the statistical robustness of the results, and long-term degradation was approximated through accelerated testing, which may not perfectly mirror actual aging behavior.

This thesis not only supports Thales in improving their understanding of PTFE hose performance but also offers an academically valuable methodology for assessing materials with potentially infinite lifespans. Future research could explore chemical aging, wrong handling of the hoses (kinking), or the impact of combined stressors to build upon these findings.

Contents

1. Introduction

This research concerns the understanding of the degradation behavior of PTFE coolant hoses and quantifies the lifetime used in different radar systems from Thales Netherlands B.V. In this introduction the framework of this master thesis will be explained. First, some company information will be described in order to understand the application environment. Secondly, a background section will dive deeper in the research topic followed by the problem definition and objectives. Finally the scope and an outline of the complete thesis will end this chapter.

1.1 Thales Group

Thales Nederland B.V. is a subsidiary of the French multinational company Thales Group based in the Netherlands [1]. Thales Group marks herself with a total of around 77.000 employees (2022), located in 65 countries and an achieved turnover of around 18 billion euro in 2023. Thales is a multinational company that designs, develops and manufactures electrical systems as well as devices and equipment for the aerospace, defence and security sectors. The Dutch branch in Hengelo was previously known as Hollandse Signaal Apparaten BV (HSA) and was founded in 1922 as NV Hazemeyer's signalling equipment factory. In 1956, Philips bought most of the shares from the Dutch government. In 1990, HSA was acquired from Philips by the French Thomson-CSF. In December 2000 the name was changed worldwide to Thales.

In the Netherlands, the corporate head office is located in Hengelo. Since 1922, when the roots were founded in Hengelo, the Dutch sites have been a worldwide leader in the latest and most innovative radar technologies and radar systems for naval ships. Thales in the Netherlands has sites in Hengelo, Huizen, Delft, Eindhoven, Breda, Rotterdam and Amersfoort. Roughly 1800 employees are working in Hengelo. This site specializes in Naval applications, as well as things such as environmental competence research, printed circuit boards and research into human behavior analytics. The existing products lines from Thales Naval can be seen in Figure 1.

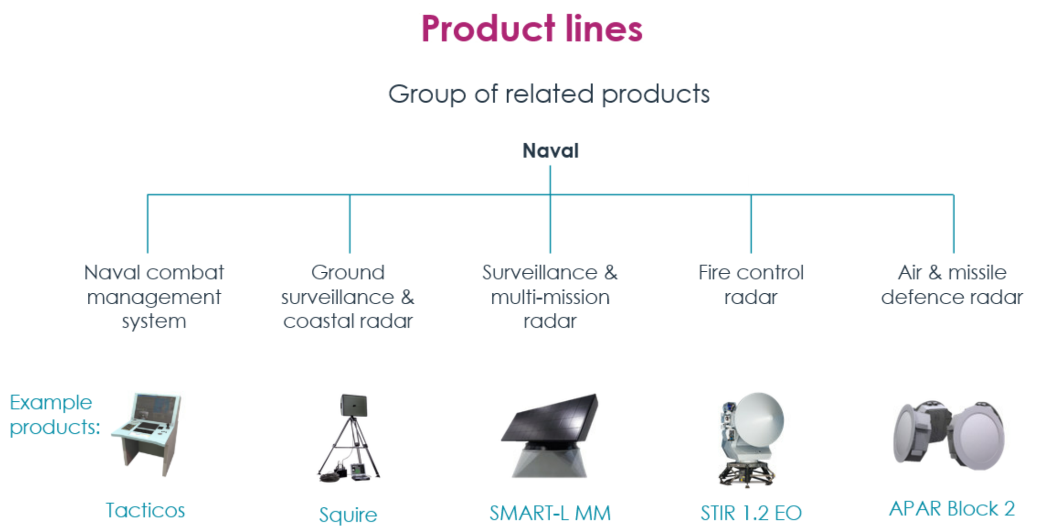


Figure 1: Thales Naval Product lines

It can be seen that the product lines mostly consist of radar products. Thales is the Original Equipment Manufacturer (OEM) of several radars. A small part of their portfolio is depicted in Figure 2. The radars are divided in three categories: Short range for self-defence of small ships, medium range for local area defence on medium ships/small frigates and long range for wide area defence on frigates.

Figure 2: Thales naval partly product portfolio

The Services department at Thales Hengelo plays an important role in ensuring the safety, reliability, and operational efficiency of the systems delivered to their clients. Their primary focus is to provide comprehensive support throughout the entire lifecycle of Thales products, from initial setup and commissioning to daily operations and long-term maintenance. This department collaborates closely with customers to offer solutions that optimize asset performance. By leveraging advanced analytics and digital tools, the services department helps clients proactively address potential issues, minimize downtime, and extend the lifespan of their systems. In addition to routine maintenance and spare parts supply, the department provides life cycle support services. This could include systematic monitoring of installed systems and offering recommendations for upgrades or component replacements to maintain optimal performance. For example, Thales often advises clients to replace parts that are subjected to wear in order to ensure continued reliability and compliance with standards. Furthermore, they also advise to replace Commercially Of The Shelf (COTS) Processing Hardware to reduce obsolescence.

The motivation for this research originated within the services department, as they are focused on understanding and improving the degradation behavior and lifespan of key components.

1.2 Background

"How long will it last?" is one of the most regular questions asked by suppliers and users when evaluating a product, second only to questions regarding price and delivery time [2]. This is particularly difficult to answer for materials like rubber and polymers, as their expected lifetimes is often realized in decades, their service conditions are highly variable, and clear durability data is hard to find. Over the years, efforts have been made to measuring and predicting material durability, and this work remains ongoing in the pursuit of reliability and efficiency.

Returning to the radar products of Thales and highlighting the SMART-S Mk2. This radar is part of the Surveillance & multi-mission radar product line. SMART-S Mk2 is the naval 3D air and surface surveillance radar operating in S-band frequency. The multi-beam concept creates a long time-on-target resulting in excellent performance over the whole coverage. The system has two operating modes: medium range up to 150 km (81 nmi) at 27 RPM and long range up to 250 km (130 nmi) at 13.5 RPM [3]. Figure 3 and Figure 4 show an example of the SMART-S Mk2 radar positioned on a navy frigate and a detailed photo of the radar respectively.


Figure 3: SMART-S Mk2 on a navy frigate

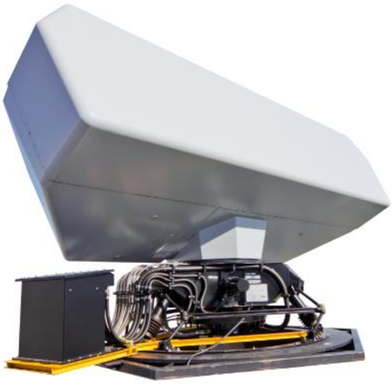


Figure 4: Detailed photo of the SMART-S Mk2

In high-performance systems such as the SMART-S Mk2 radar system, the question of durability becomes critical. Radar systems, especially those used in naval applications, rely on uninterrupted operation to ensure optimal performance. All components inside the antenna assembly have to operate in a temperature and humidity controlled environment to last as long as possible during its lifetime of at least 30 years. When a radar system is receiving and transmitting, one of the main concerns is that the electrical components of the antenna, especially of the transmit and receive (TR) system, produce heat. As a result of this, the components require a continuous flow of coolant fluid to ensure a high reliability and availability of the system. The antenna assembly receives continuous flow of coolant fluid in order to guarantee proper functioning of these internal components. The radar's internal and external coolant system includes several coolant hoses, which are critical components for transporting coolant fluid and dissipating the large amounts of heat generated.

After studying the cooling liquid circuit it was noticed that different hoses are used between the equipment. The main differences are in terms of diameter, length and material used. The most commonly used coolant hose that was found, consists of a Polytetrafluorethylene (PTFE) inner core with aramid or stainless steel (SS) braided outer core. Figure 5 shows a schematic example of how these hoses are generally constructed.

Figure 5: 3D model of a general PTFE hose construction

Moreover, Figure [redacted] shows an applied example of the PTFE-Aramid coolant hoses inside the antenna assembly which is providing coolant to the TR system. The current main supplier of the PTFE hoses is Teesing B.V. which subsequently purchases the hoses from the Original Equipment Manufacturer (OEM); Goodridge.

A hose distinct itself from a conventional pipeline systems by providing flexibility which gives the hose easier freedom of movement and provides dampening effects. Compared to a pipeline system, which is a static system and has little to none flexibility. Industrial hoses play a critical role in a wide range of applications, including military, chemical, and hydraulic systems [5]. These hoses are specifically designed to transport liquids, gases, and solids efficiently and safely, often in environments that demand high durability and adaptability. Industrial hoses are usually made of various materials such as rubber, metal, PVC, polyurethane or other types of plastic. In essence a hose always functions as a hose assembly, in which certain coupling or fitting elements are needed to connect the hose to its adjacent systems and serve its function. The subcomponents of a general industrial hose assembly are depicted in Figure 6. In industrial applications, braided hoses are generally preferred due to their high flexibility and ability to provide hose movements [6]. Compared to non-braided corrugated hoses, braided hoses effectively prevent the longitudinal expansion typically seen in corrugated designs. Additionally, braided stainless steel hoses are used to compensate for misalignment or thermal expansion of gas pressure during operation. They also absorb vibrations and noise from major equipment like pumps, compressors, and engines during operation.

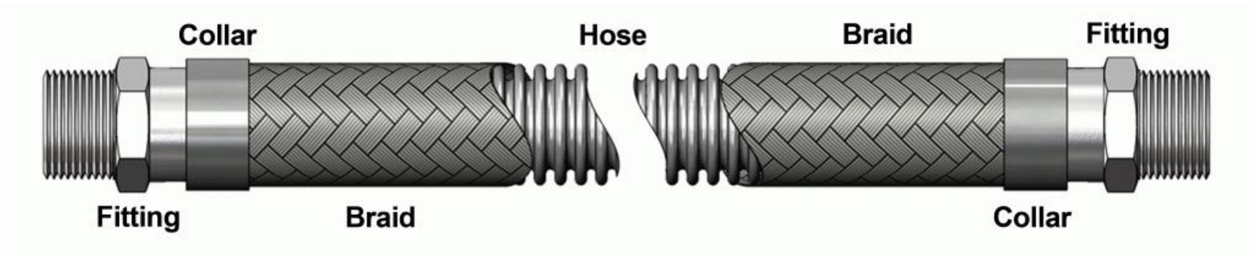


Figure 6: Subcomponents of a general industrial braided hose [7]

Hoses can be categorized based on their material composition, design, and intended application, [6]. Generally, these hoses are classified by types which are non-metallic and metallic.

Metallic hoses, often constructed from stainless steel, used in applications requiring high-pressure resistance, temperature tolerance, and strength. They are divided into two primary categories; Stripwound hoses and corrugated hoses. The stripwound hoses are made from interlocked spirals of metal, offering exceptional flexibility. However, this design sacrifices gas-tightness. The first metal hose technically was a stripwound hose. It was invented in 1885 by the jewellery manufacturer Heinrich Witzenmann (1829–1906) of Pforzheim, Germany, together with the French engineer Eugène Levavassèur [8]. Figure 7 and Figure 8 shows the first design of the stripwound hose and a schematic detail of the profile respectively.

Figure 7: First print design of a stripwound hose [8]

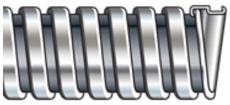


Figure 8 : Section view of a stripwound hose [9]

Corrugated hoses, on the other hand, are made by rolling stainless steel strips into thin-walled, gas-tight tubes. These are further reinforced with braided outer sheaths, making them both pressure- and vacuum-tight. Due to their robustness, corrugated hoses are often employed in chemical and hydraulic systems, where maintaining system integrity under extreme conditions is paramount. Figure 9 and Figure 10 shows an example of a corrugated hose and a schematic detail of the profile respectively.

Figure 9 : Section view corrugated hose [10]

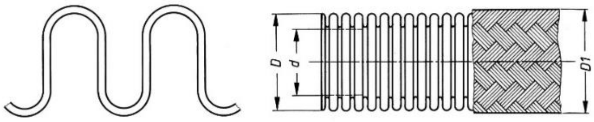


Figure 10 : Profile detail corrugated hose [8]

On the other side, non-metallic hoses, commonly made from materials such as PTFE, rubber or Polyvinyl Chloride (PVC), are valued for their lightweight, cost-effectiveness, and versatility [11]. Their ease of installation and low maintenance appeals them for general industrial applications. The remainder of this thesis will only focus on the non-metallic hoses. In particular the PTFE hoses which are employed in the radar products of Thales.

1.3 Problem definition and current maintenance approach

The SMART-S Mk2 radar is positioned on naval ships and since these vessels sail through different weather conditions across the globe, certain impacts are induced on most of the components that are in direct contact with the outside environment. This also applies to the coolant hoses that are exposed to the outside environment. If a hose leaks, it could result in significant radar downtime, underscoring the criticality of these components. The radar's coolant hoses play a key role in maintaining thermal management under these conditions. Despite their importance, Thales has limited understanding of the coolant hoses' degradation behaviour and lifetime, especially under the combined effects of physical, chemical, and environmental stressors. As a result of this, the coolant hoses of the radar systems are expected to fail at some point in time. However, it was unknown what the failure modes are for these hoses and their useful life.

To summarize, Thales has no clear view or knowledge of their PTFE coolant hose failures and its subsequent lifetime. The company is interested to gain new knowledge regarding degradation behaviour and lifetime of the coolant hoses applied in Thales' products. This research seeks to close critical knowledge gaps by identifying degradation mechanisms, failure modes, and predictive lifetime models for PTFE coolant hoses. Additionally, the study could demonstrate whether these hoses possess a lifetime exceeding the radar system's lifecycle, potentially rejecting the need for preventive replacement altogether.

1.4 Aim and objective

The aim of this research is to investigate the degradation behaviour and predict the lifetime of PTFE coolant hoses under extreme environmental and operational conditions. This study seeks to identify key degradation mechanisms and failure modes, focusing on both chemical and physical impacts due to coolant fluids and external environmental factors such as temperature fluctuations, UV radiation, and salt-laden air.

The objective is to develop a clear understanding of the hoses' performance and durability, enabling Thales to use predictive lifetime models. The thesis results will provide recommendations for maintenance strategies, such as whether and when to replace coolant hoses preventively, possibly aligning with the 10-year overhaul schedule.

In terms of relevance, when this research goal is achieved, new knowledge could be gained on degradation behaviour and the lifetime of PTFE coolant hoses. Knowing this, it will be easier to substantiate overhaul activities to customers of Thales with more confidence, since a better understanding is gained of the degradation behaviour and lifetime of PTFE coolant hoses. Thales can now provide customers with evidence-based recommendations for maintenance, enhancing trust and transparency. This substantiation will support the promotion of overhauls by offering clear, data-driven justifications for hose replacement or continued use. Customers will be more inclined to follow Thales' maintenance guidelines if backed by research.

1.5 Research questions

This chapter concludes the problem definition for this research and consequently summarizes these in the form of a main research question and sub-questions.

The main research question is constructed based upon the problem definition:

What is the lifetime and degradation behavior of PTFE coolant hoses?

The main research question could be answered with the help of the following sub-questions:

1. Which failure- modes and mechanisms are most critical for PTFE coolant hoses?
2. What are the governing loads exerted on the PTFE coolant hoses?
3. How to determine the useful life of PTFE coolant hoses?
4. How to design an experimental setup for measuring useful life?
5. How to analyse the test data and interpret them?

1.6 Scope

This section describes the scope of the thesis project. The following points were included in order to specify and narrow down the scope of this research study.

- **Applications**: The radar systems developed by Thales are utilized in both naval (e.g., on frigates) and land-based applications (e.g., on vehicles or stationary setups). These environments expose the radar systems to extreme operating conditions. This project focuses primarily on coolant hoses used in naval applications, with the SMART-S Mk2 radar system serving as the reference system. Analysis revealed that several radar systems of Thales operate under similar coolant fluid pressures and temperatures, making the findings of this research applicable to various naval radar systems. Although land-based applications show comparable conditions, additional factors such as sand and dust, which are not covered in this study, introduce unique challenges. Nevertheless, the results of this research could still provide valuable insights for improving the performance and reliability of land-based radar systems.

- **Hoses**: In the introduction section it was mentioned that focus will be on the PTFE coolant hoses. Notice that this is different compared to hydraulic hose applications (higher pressures). There are different PTFE hoses used in the Thales radar systems. For example, in the Antenna assembly alone are already three different PTFE hoses used from the supplier Goodridge. The research is limited in a sense that not every hose type could be evaluated on lifetime. In literature it was found that lots of hose failure analyses were focused on the coupling components. Electrochemical Degradation (ECD) is one of the most critical failures in this case. For this thesis project it has been chosen to not include analysis of the hose couplings in the scope. Lastly, this research only focusses on hoses from the companies Goodridge and Eriks which are direct suppliers from Thales.

- **Degradation agents:** This study focuses on evaluating the degradation of PTFE coolant hoses under thermal aging conditions, with temperature selected as the primary degradation agent for experimental analysis. While other potential degradation agents, such as mechanical stress, chemical exposure, and environmental factors (e.g., UV radiation, humidity, fluid contaminations), are relevant to the overall failure mechanisms, they are not explicitly tested in detail through experiments. However, these additional degradation agents are considered in the failure analysis and the broader interpretation of the results. This ensures that the findings remain relevant to real-world applications, despite the experimental focus on temperature.

1.7 Approach

This section describes the research approach that was followed for this thesis project. It explains for example why the failure analysis is included or why the accelerated test method were chosen.

A strategic research approach has been developed and is depicted in Figure 11. This approach is made up of three major sequential stages: Theory & Foundation, Analysis and Design, and Experiments and Results. The description below also indicates the sections where the earlier stated sub-research questions (SRQ) are answered.

Part I: Theory & Foundation

The initial phase begins with identifying the problem of PTFE hose degradation in operational systems. A pre-evaluation is conducted to assess the relevance and feasibility of addressing the research problem. Literature research forms an important component of this phase, offering insights into other studies, degradation mechanisms, and analytical methods applicable to PTFE materials. This foundation sets the basis for the upcoming phases of the research. SRQ 3,4 and 5 are partially answered in this section.

Part II: Analysis and Design

In the second phase, a failure analysis is performed to evaluate the operational and environmental conditions contributing to potential hose degradation. Expert interviews play a crucial role in this phase, providing different perspectives from across the company. These insights are integrated with findings from literature and Failure Analysis techniques such as FTA (Fault Tree Analysis) and FMEA (Failure Mode and Effects Analysis). Based on the outcomes of the failure analysis, experimental designs are developed to test and characterize the PTFE hoses under controlled conditions. The design phase includes a feedback loop of communication and assessment, ensuring alignment with the research objectives and limitations. SRQ 1 and 2 are answered in this section.

Part III: Experiments and Results

The final phase focuses on executing the designed experiments to simulate thermal aging, mechanical stress, and other relevant degradation scenarios. Morphological, mechanical, and thermal analyses are employed to characterize the PTFE material's behaviour and assess the extent of degradation. The experimental results are then analysed to come up with conclusions regarding the degradation mechanisms, potential failure modes, and estimated lifetime of the hoses.

The thesis concludes with a discussion part, a summary of findings and recommendations for future research and practical applications. This approach ensures a comprehensive investigation into PTFE hose degradation. SRQ 3,4 and 5 are further answered in this section.

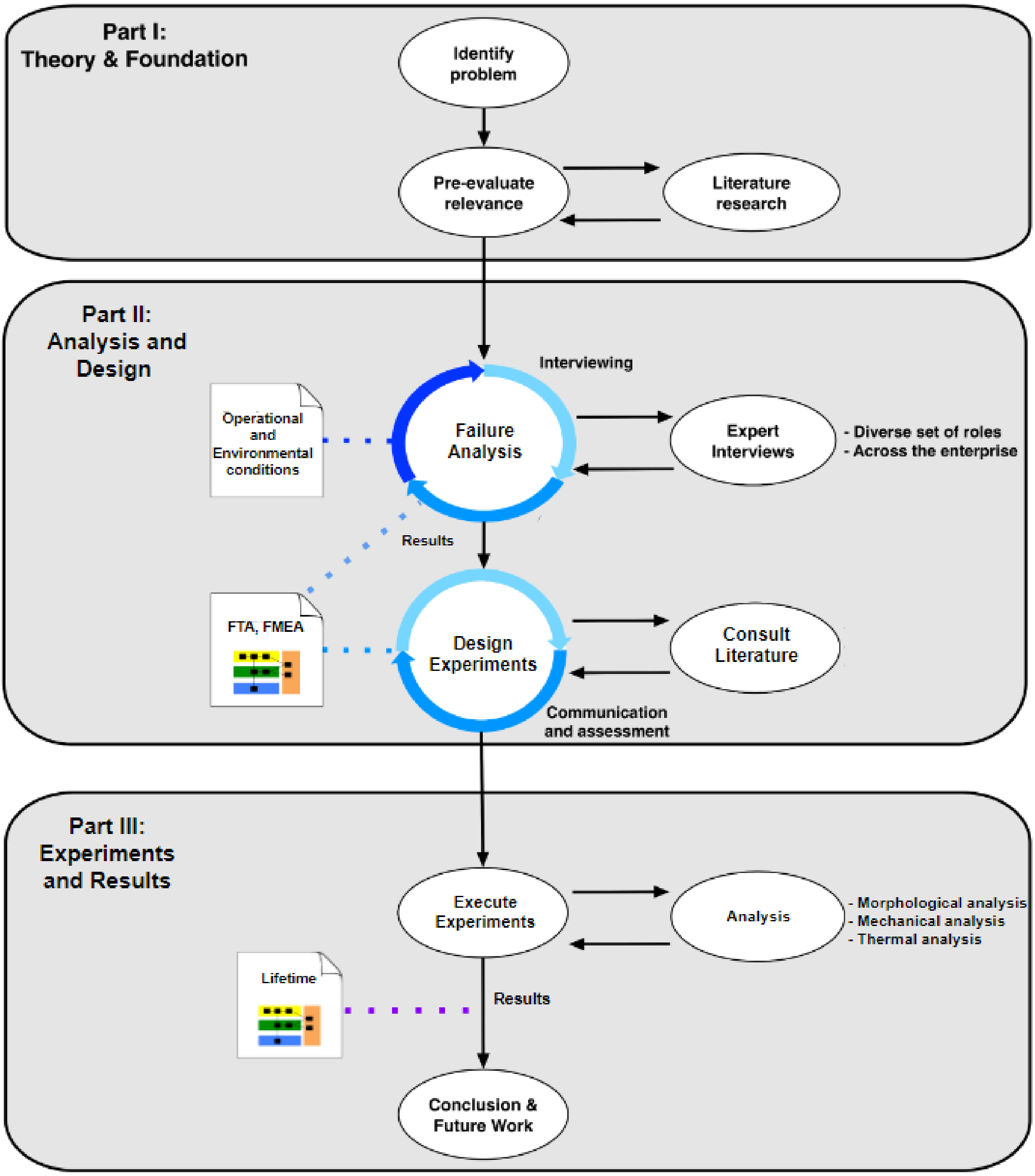


Figure 11: Thesis approach schematic

1.8 Thesis outline

This section outlines the structure of this thesis. It describes the general content of each chapter individually.

Chapter 1: Introduces the research and touches upon the problem definition, research questions, the scope and the followed approach.

Chapter 2: Describes the literature review that was conducted. It touches upon PTFE as a material, hose reliability and the different ways to approach accelerated testing.

Chapter 3: Comprehends the failure analysis part which was done in one of the earlier stages of this research in order to find the critical degradation agents. It includes analyses like FTA and FMEA.

Chapter 4: Describes the experimental methods used for this research and consequently the designs of the experimental part.

Chapter 5: Discusses the results of the analyses methods used and makes the translation from experimental data to lifetime predictions.

Chapter 6: Discusses the results from this thesis research.

Chapter 7: Finalizes the research by making conclusion and further recommendations.

2. Literature review

This chapter provides the literature review that was constructed during the thesis research. It touches upon PTFE as a material, hose reliability and introduces ways to determine useful life of polymer components.

During the literature research, a search strategy template was used to search for literature in a strategic way. Furthermore, a certain matrix was constructed in Excel. This so called literature review matrix created an overview for the student regarding every reviewed author or scholar from several papers and indicates which materials, degradation agents and analysis methods were investigated in these articles. The full matrix can be found in Appendix A.

2.1 Polytetrafluorethylene (PTFE)

Polytetrafluoroethylene (PTFE) is an engineered fluoropolymer of tetrafluoroethylene, a type of polymer that contains carbon and fluorine atoms. Its chemical structure can be seen in Figure 12.

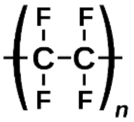


Figure 12: Chemical structure of PTFE [12]

PTFE is known for its unique properties, making it particularly valuable in different industries [13]. The commonly known brand name of PTFE-based composition is Teflon by Chemours [14]; a spin-off from DuPont, which originally discovered the compound in 1938 [14] [12]. PTFE is composed of a long chain of carbon atoms, each bonded to fluorine atoms. This molecular configuration gives PTFE high chemical resistance, a very low friction coefficient, and the ability to withstand high temperatures, making it one of the most inert materials available [15]. Figure 13 illustrates the 3D chemical structure and polymerization process of PTFE. On the left side, the monomer Tetrafluoroethylene (C2F4) is shown, consisting of the carbon and fluorine atoms. The process of polymerization, indicated by the arrow, links multiple monomer units to form the PTFE polymer molecule, depicted on the right side [16]. The resulting polymer chain is highly stable due to the strong carbon-fluorine (C-F) bonds, which give PTFE its remarkable properties.

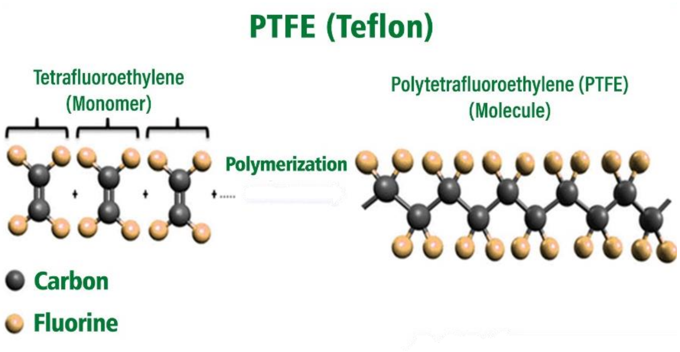


Figure 13: Polymerization process of PTFE [16]

PTFE is widely known for its application as a non-stick coating in cookware, including frying pans and baking sheets. Beyond its culinary uses, PTFE is extensively employed in various industrial applications. Its low friction coefficient makes it ideal for use in bearings, seals [17] and gaskets.

Additionally, PTFE serves as an effective electrical insulator due to its high dielectric strength [12] [15]. PTFE naturally has a white colour, while black PTFE is an improvement due to various additives, like graphite, carbon, molybdenum disulphide. This increases the temperature range, reduces wear, makes it more flexible and has greater resistance to electricity conduction. Black PTFE shows greater resistance to creep, where material moves or deforms due to pressure. White Teflon is sensitive to ESD (electrostatic discharge) and is usually not recommended [12].

A more notable application of PTFE is in the form of PTFE lined hoses. These hoses are used for transferring fluids, especially in industries where chemical resistance and high temperature resistance are crucial. PTFE hoses are flexible, durable, and can withstand harsh environments. These hoses ensure reliable and efficient coolant flow in a variety of industrial [16] and automotive applications [18] [19]. A broad temperature range of -54°C to 260°C [15] makes this hose material suitable for the majority of fluids and ambient temperature conditions found in most industries. PTFE hoses feature an extremely low coefficient of friction (0.05 to 0.20), providing a non-stick surface. PTFE's water absorption is minimal, less than 0.01% per ASTM tests, and it is FDA-approved for food and pharmaceutical use [15]. Additionally, PTFE can endure flexing and vibration without early failure from bending fatigue. Standard braiding reinforcement includes Type 304 or 316 stainless steel wire braid. This enhances durability and wear protection.

The use of these non-metallic hoses or plastic pipes to transfer liquids and gases has significantly expanded in recent decades thanks to their moderate cost, ease of handling and installation, long service life, reduced long-term maintenance and replacement costs, and resistance to degradation compared with materials such as corrugated steel [20]. Due to these advantages, the worldwide plastic pipe industry was predicted to grow at double-digit rates over the next 10 years and reach $500 billion by 2024. In the US alone, sales were expected to reach $57.3 billion, with a total of 3,6 million kilometers of plastic pipe [21]

Operational performance of naval radar systems has increased in recent years due to advances in radar technology, data processing capabilities and much more. Thus, so too have the demands placed upon the systems. In particular, coolant systems must be capable of transporting fluid in extreme marine environments. As a result conventional plastic hoses (e.g. PE, PVC) and rubber hose assemblies have been developed to the limit of their operational capabilities. Recognition of the limitations of these conventional hose sparked the interested to seek an alternative hose lining and construction [22]. In this case, PTFE hoses offer an excellent alternative. An example of a PTFE hose with stainless steel braiding can be seen in Figure 14.

Figure 14: PTFE hose with Stainless Steel outer braiding

Moreover, the demand for PTFE pipes and hoses is growing, with the market projected to increase from $2.8 billion in 2024 to $3.5 billion by 2029 at a compound annual growth rate (CAGR) of 4.3% [23]. This growth is driven by their ability to provide excellent durability and performance compared to other materials. On the other hand, despite its advantages, PTFE hoses and fittings face challenges like high initial costs and environmental concerns related to manufacturing processes [12], [23], [24], [25]. However, their reliability in critical industrial scenarios often outweighs these drawbacks.

2.2 Hose reliability

2.2.1 Environmental and Operational Conditions for Naval Applications

Before diving into the reliability of hoses, it is essential to first consider the environmental and operational conditions that define the naval application context. The performance and lifetime of hoses in naval systems are not solely determined by material properties but are also significantly influenced by external stresses such as temperature fluctuations, pressure cycles, and the harsh marine atmosphere. Mapping these conditions provides valuable insights into the potential degradation mechanisms and failure modes that can occur and serves directly as a foundation for the Failure Analysis in Chapter 3.

Laan [68] describes the temperature extremes across the globe for marine environments. It shows that a maximum of 49 °C could occur combined with 1120 W/m^2 solar radiation (Figure 15) and a minimum of -40 °C in cold environments.

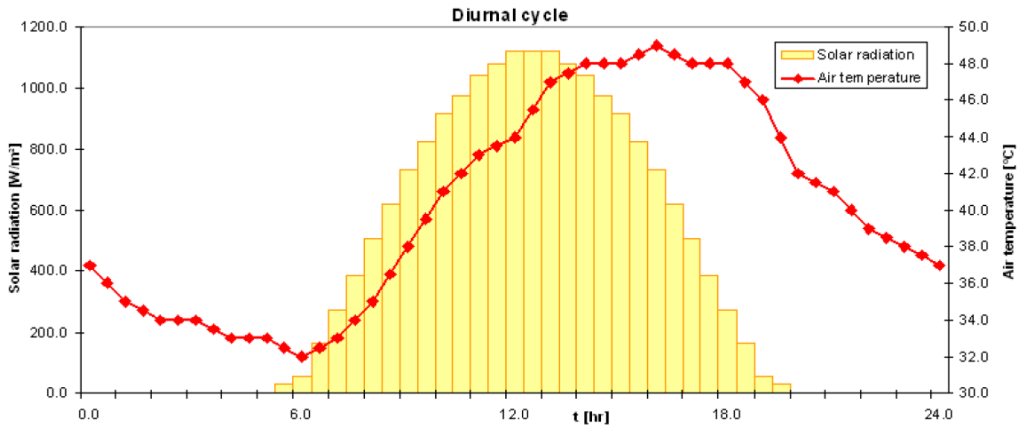


Figure 15: Diumal cycle in hot environment

Mayya et al. [26] explains the criticality of high moisture environments and the resulting degradation to fibre reinforced polymers, which are greatly used in marine systems. Furthermore, prolonged exposure to ultraviolet (UV) radiation can degrade non-metal components like rubber seals, plastic housings, and paint coatings. UV radiation in naval environments can weaken these materials, reducing their service life [27]. Besides these environmental conditions are the operational stress factors which also play a significant role. Barutzki et al. [28] describes the importance of vibration damping to marine pipeline systems. Naval vessels are subject to various sources of vibration, including engine operations and sea conditions. Operational vibrations, even with small displacements and stresses, can lead to pipe fatigue and increased vibration-induced corrosion over time. Cycling stresses could lead to submicroscopic cracks that may develop into significant structural issues.

2.2.2 Hose lifetime prediction and failure analyses

Different scholars utilized the knowledge of the mentioned environmental and operational conditions to predict the lifetime of PTFE hoses and other materials.

One of the most insightful papers found, is from Kai et al. [29] [30], whom investigated the fatigue behavior of PTFE hoses subjected to pulsating pressures with the combined effect of different high-low temperatures, vibrations, and improper installation. They emphasized the complexity of the steel wire braided structure, where numerical finite element analysis (FEA) and experimental validation were essential for understanding failure mechanisms. Fatigue failure was primarily caused by fracture in the steel braid, with stress concentrations at the braid intersections (Figure 16a and b).

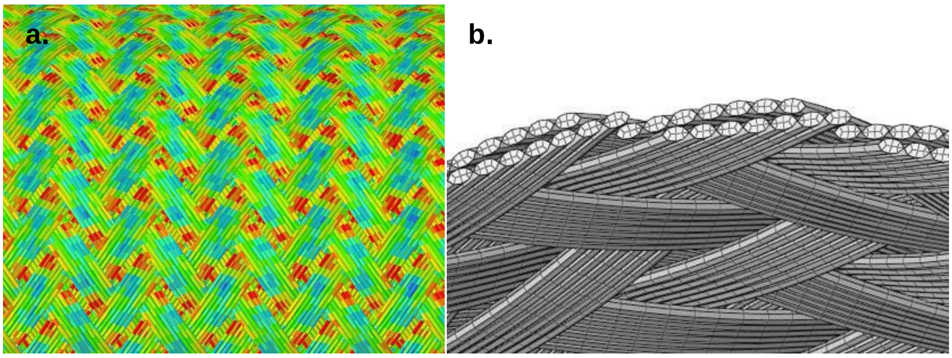


Figure 16: Fatigue stress concentrations of the SS outer braiding (a) and a section view of the modelled braiding (b)

It was found that the pulsating pressure and the level of bending radius of the hose is the main factor affecting the service life of the PTFE hose. Secondly, the vibration load spectrum of the actual operation of the engine has little influence on the service life of the hose. Thirdly, low temperature has little effect on the service life of the hose. On the other hand, high temperature has a greater effect; the service life decreases with 23,5% at 240 °C. Lastly, hose joint torsion also has a great impact on lifetime. At 15°, the lifetime will be reduced by 37.5%. While a straight hose shows a near-infinite lifespan.

Eleena Rahim [6] showed, with the help of numerical simulations, that an S-shaped hose contains the highest stresses and conducted FMEA and FTA for a failed PTFE hose in the chemical industry from PETRONAS.

Sytyi et al. [31] investigated the crack propagation of the PTFE material used in hoses under thermal cycling (-60°C to +230°C), high pressures and exposure to hydraulic fluid. The study revealed that cracks appear along the inner hose surface in the axial direction due to anisotropy in the PTFE's mechanical properties caused by the extrusion process.

Yao et al. [32] developed an analytical model for calculating the capacitance of stainless steel braided PTFE aviation hoses. Its analytical approach provides a more detailed overview of the forces and stress balances inside the Teflon hoses compared to other scholars (Figure 17).

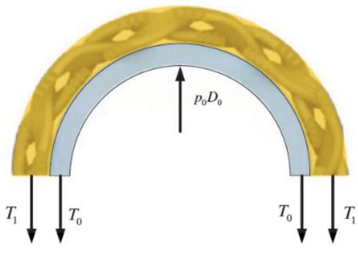


Figure 17: Force balance inside a PTFE hose

Finally, Longchao et al. [33], who presented a parametric modeling approach to construct a constitutive model for double-layer stainless steel braided PTFE hoses. The model evaluates the influence of braiding parameters, such as wire diameter, number of braided strands, braiding angle, hose inner diameter, and hose length, on pressure transfer characteristics. The study demonstrates the potential for precise prediction of pressure transfer effects in stainless steel braided hoses but identifies experimental limitations as an area for future improvement.

On the other part of the spectrum, human errors could also lead to failure of the PTFE hoses. Wang et al. [34] showed that the wrong installation and a nick on the inner surface of the PTFE hose are the primary factors which influence the reliability of the PTFE hose during in commission.

The study investigated failure modes of high-pressure PTFE hose assemblies used in aviation, focusing on the causes of cracks and proposing reliability improvements. It was found that cracks originate at areas of excessive bending due to incorrect installation. Stress tends to concentrate there, causing micro-cracks that propagate through the hose wall. Cracks originating from linear nicks or defects on the inner hose surface are likely caused during the machining process. Stress concentration at bends combined with pulsing pressure, vibration, and temperature changes accelerates crack growth. Cracks from nicks often develop internally and eventually form leaks. Exceeding minimum bend radius will greatly reduce hose assembly life. Figure 18 and Figure 19 show the location and size of the cracks developing on the outer- and inner surface respectively.

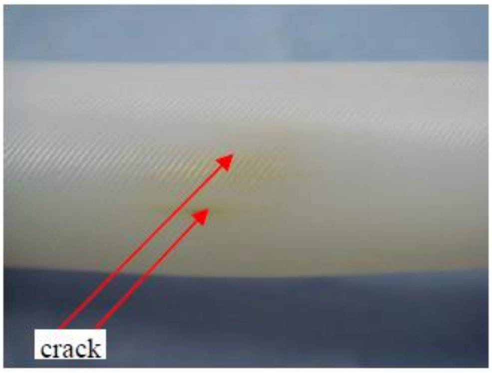


Figure 18: Crack at outer surface

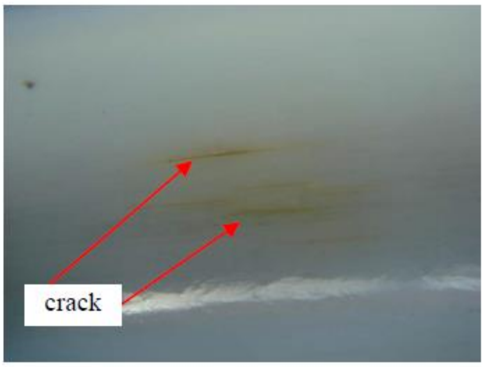


Figure 19: Crack at inner surface

Further papers [34], [35], [36], [37] focus more on post-mortem analysis with the help of failure analyses to study the root causes of PTFE hose failure within their company or industry. While typical hose failure modes and mechanisms are: Leaking

Conclusion of this part of the literature review is that there is lack in study of PTFE hoses, particularly on the thermal aging effects of PTFE hose degradation.

2.2.3 Maintenance strategies of PTFE Hose systems:

Despite the hoses' prevalence, there is a notable gap in literature and open internet sources regarding the lifetime, failure modes, and failure mechanics of PTFE hoses. This lack of information presents a challenge for engineers and maintenance professionals who rely on these components for critical operations. While some sources provide general insights into the properties and advantages of PTFE lined hoses, detailed studies or comprehensive data on their long-term performance and failure characteristics are scarce. For example, the Journal of Fluorine Chemistry and various technical datasheets from manufacturers such as Parker Hannifin and Swagelok provide valuable information on the material properties and basic application guidelines. However, these sources fall short in offering detailed analyses of failure mechanisms, such as fatigue, creep, chemical degradation, or mechanical damage over time. They also mention that the life expectancy of the PTFE hoses are strongly dependent on operating conditions. The absence of robust, empirical data on the lifespan and failure modes of PTFE lined hoses with reinforced braiding underscores the need for further research.

The problem is that PTFE hose assemblies can only be inspected by their outer surface, they cannot be inspected properly without being detached. PTFE hose assemblies can become dimensionally stable by ageing and high temperature. By disassembling them, the inner tube can be deformed or corrupted. The risk is increasing with the radius of the hoses. Hose assemblies with an inner tube bigger than 12,7 mm (0,5'') tend to kink very easily [38].

It is interesting to note that hose manufacturers like Hoseflex [15] and Parker Hannifin [39] claim that their PTFE hoses will not break down or deteriorate in service. They are convinced that it has an unlimited shelf life because properties do not change with age or exposure to weather.

2.2.4 Other applications

In the aviation and aerospace industry, PTFE hoses have become mainstream for external pipeline systems due to their ability to reduce assembly stress and vibration, ensuring the safe operation of aero engines. The hoses in this industry are generally used as fuel line systems. The vibrations from rotating parts, and combined temperature and pressure stresses significantly affect the fatigue life of hoses. According to Yijun [40] the failure of external pipelines leads to the launch of aviation Aircraft parking and crash accidents account for more than 50% of the number of accidents, so the fatigue life prediction of external pipelines is of great significance for arranging regular engine maintenance and ensuring the safe operation of the engine.

Several aviation documents and forums users discuss the lifetime of the PTFE hoses used in their aircrafts [39], [41], [42]. The conclusion is that no definitive lifetime could be given for the PTFE hoses. These hoses are only replaced ‘’on condition’’. In other words, only if visible damage can be seen. An article by WMT [38] describes that the decision regarding when to replace PTFE aircraft hose assemblies is made by the type certificate holder (i.e. the Federal Aviation Administration (FAA) or the European Union Aviation Safety Agency (EASA)), who is responsible for ensuring that the component continues to meet regulatory safety standards and specifying maintenance and replacement intervals based on operational performance and safety considerations. The common perception of an unlimited service life for these hose assemblies should be critically evaluated and approached with caution. On Condition is an unclear meaning that leaves a lot of space for interpretation. The responsibility should still go over to the owner and the inspector.

The Airworthiness Bulletin: Flexible Hose Assemblies – Maintenance Practices [43] emphasizes the importance of proper inspection, handling, and replacement of flexible hoses in aircraft systems, particularly those carrying flammable fluids. The bulletin addresses the recurring issue of premature hose failures due to chemical incompatibility, incorrect installation, and fatigue from pressure pulsations and vibrations. It highlights that flexible hoses have a finite service life, with engine compartment hoses typically requiring replacement every five years and airframe hoses every ten years. However, failures have been reported even earlier (4 years in service) [44], often linked to issues such as improper installation, including kinking, twisting, and inadequate routing, which lead to localized stress and eventual rupture. The bulletin stresses the need for routine in-situ inspections for signs of chafing, cracking, brittleness, and leaks. The bulletin also acknowledges the prevalence of PTFE. They appear to have overcome many of the problems associated with rubber compound hoses, such as shelf-life, deterioration due to chemical interaction with oil and fuel as well as hardening and cracking due to age and heat. Despite these advantages, PTFE hoses in the aviation industry appear to be more susceptible to damage resulting from careless handling and incorrect installation than rubber compound hoses. Eriks B.V. acknowledged this and mentioned that 80% of hose failures is due to human error.

In contrast to PTFE coolant hoses, the development and maintenance of hydraulic rubber hoses, particularly in high-stress applications such as automotive brake systems, appear to be more systematically defined. These hoses are designed to endure significantly higher working pressures and larger cyclic deformations, making them highly susceptible to fatigue-related failures being one of the most frequently observed failure mechanisms in this category. This phenomenon is also acknowledged and investigated by several papers; [45], [46], [47].

It must be noted that a lot more information could be found regarding rubber hydraulic hoses. It seems that they are more researched upon and that their service life is more defined.

A key difference in the control of hydraulic rubber hoses is the emphasis on regulated maintenance schedules and predefined service lifetimes. For example, DIN 20066:2002-10 – a guidelines for the assembly, installation, and maintenance of hydraulic hose assemblies- explicitly limits the total service life of rubber hydraulic hoses to 10 years, factoring in a maximum storage time of 4 years. Although this standard provides useful guidance based on systems, it also acknowledges the complexity of predicting hose longevity due to the various environmental, mechanical, and chemical factors. This contrasts with the PTFE coolant guidelines, being less defined and which often rely on empirical observations rather than structured maintenance protocols.

2.3 Accelerated tests and predictive lifetime modelling

The performance and reliability of PTFE coolant hoses are critical in ensuring the proper operation of radar systems in maritime environments. Due to the high reliability of PTFE, failures may occur only after prolonged service, making lifetime prediction challenging without large time-consuming tests. An example can be found in a paper from Taherzadehboroujeni et al. [20] in which the accelerated test method allowed the prediction of hose service lifetimes in excess of 50 years using experiments conducted over approximately 10 days. This shows the importance of accelerated testing methods that simulate long-term aging and degradation within shorter timeframes.

Accelerated testing is a fundamental methodology used to predict the lifespan of products by exposing them to intensified stressors that replicate real-world conditions [48]. As emphasized by Nelson in "Accelerated Testing" [49], the goal of accelerated life testing (ALT) is to subject samples to elevated levels of temperature, pressure, mechanical stress, or chemical exposure to induce failures more quickly. This allows for the collection of failure time data that can be extrapolated to estimate the product's reliability under normal service conditions [48]. Nelson categorized accelerated testing into 1. Accelerated Life Testing (ALT), which records failure times under increased stress levels, and 2. Accelerated Degradation Testing (ADT), which tracks the gradual decline in performance metrics before the point of failure. This distinction is particularly relevant for this study.

1. Accelerated Life Testing (ALT)

McLinn [50], emphasizes that ALT aims to replicate failure mechanisms without introducing unrealistic conditions that could produce non-representative failures. In the context of PTFE coolant hoses, ALT typically involves subjecting hoses to cycles of elevated temperatures and internal pressure fluctuations until the hose fails to its most prominent failure mode ‘’leakage or burst’’. This process accelerates thermal aging and fatigue, both of which contribute to material degradation. Furthermore, the Arrhenius model, discussed in detail by Lee et al. [51] is generally used to quantify the effect of temperature on aging. The Arrhenius equation relates the rate of chemical reactions (such as polymer degradation) to temperature, allowing the calculation of an acceleration factor. By converting aging conditions to an "equivalent aging time," this model enables predictions about hose service life under normal operating temperatures based on high-temperature test results.

2. Accelerated Degradation Testing (ADT)

For highly reliable materials like PTFE, ADT offers an alternative approach by monitoring degradation over time instead of waiting for complete failure. Collins [52] suggests that this method is effective for materials that exhibit a gradual decline in properties, such as hardness, tensile strength, or elasticity. For PTFE coolant hoses used in naval radar systems, ADT may be especially useful due to the high durability of the material. By tracking performance degradation metrics (e.g., flexibility, tensile strength, or microcrack formation), researchers can predict hose lifespan without waiting for catastrophic failure. An example can be seen in Figure 20 in which the progression of crack length in a material is shown as a function of loading cycles. The individual curves represent different tests, all showing a gradual increase in crack length until reaching the critical crack length, after which catastrophic failure occurs. For highly reliable materials like PTFE, such data from ADT can be used to model microcrack growth and predict the service life before reaching the critical crack size.

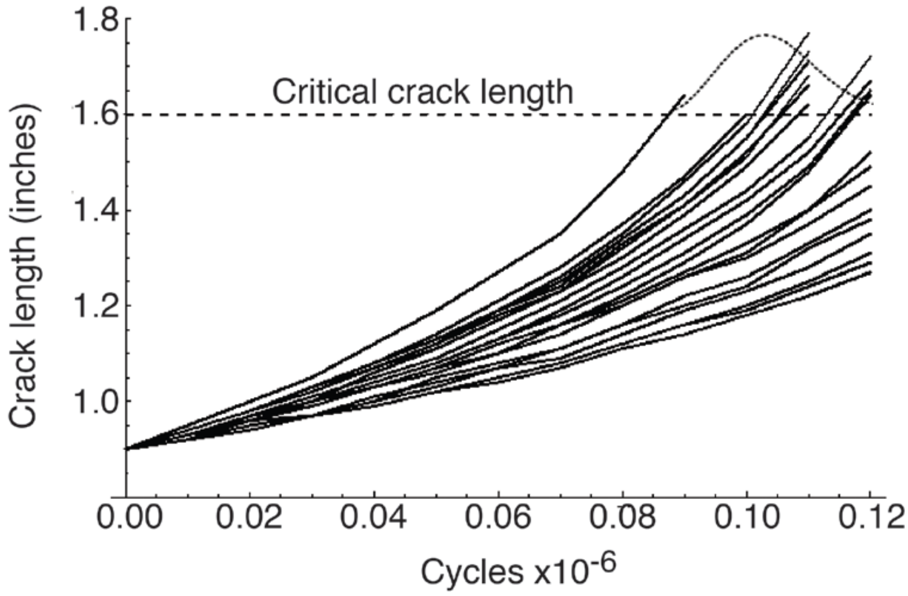


Figure 20: ADT approach; measuring crack length [52]

PTFE has a melting point of roughly 327 °C and a glass transition temperature of roughly 131,9 °C [65],[58]. It was found that significant research has been conducted with degradation of PTFE above the melting temperature. However, for this research it is not of interest to thermally age the hoses above the melting temperature since these temperature values will never occur in operation and does correlate with the correct failure mechanism.

A few papers analyzed the degradation behavior of PTFE with temperature values below the melting temperature. Qu et al. [60] used aging intervals of 0h, 48h, 96 h, 144h, 192h and 240 h (0-10 days) with a temperature value of 120 °C. The results of the microscopic analysis ,using SEM, are shown in Figure 21. It indicates that a change in morphology can be observed during thermal aging.

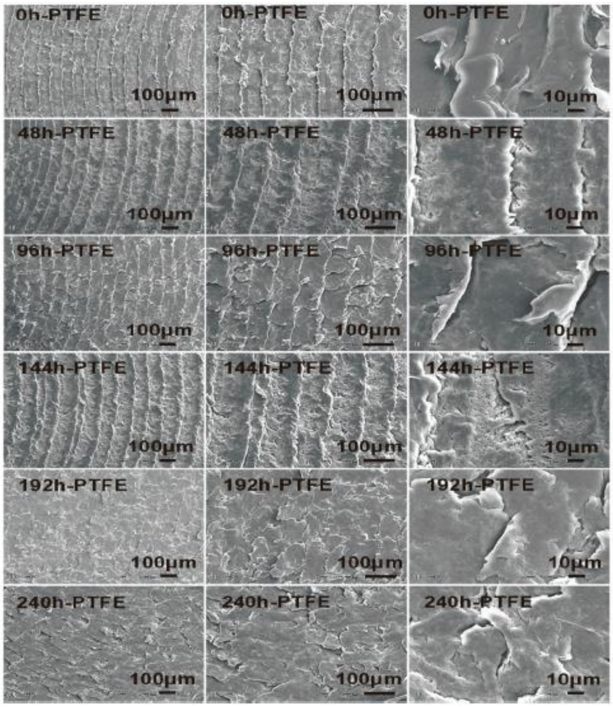


Figure 21: SEM results of aged PTFE at 120 °C

Moreover, El Aidani et al. [66] observed crack initiation at the 9 days and 16 days mark during thermal aging of an e-PTFE/Nomex moisture membrame at 275 °C. Kun et al. [17] concluded a decrease in tensile strength of 50% after 26 days of thermal aging at 315 °C for PTFE samples.

Lastly, a study reviewed by Chinh et al. [53], the importance of selecting appropriate degradation indicators was highlighted. For PTFE coolant hoses, parameters such as hardness and elongation at break are more effective indicators of degradation than tensile strength alone, as noted in multiple studies. These findings align with those of Lee's work on fluorocarbon elastomers, where hardness proved to be a more reliable indicator of aging [51]. Moreover, failure prediction also relies on statistical modelling. For example, both Nelson [49] and Lee [51] described the Weibull distribution as an effective tool for life data analysis. The Weibull model supports a large range of failure modes, from early-life failures (infant mortality) to wear-out failures typical of aged materials. Weibull plots allow for the visualization of failure probabilities over time and the derivation of confidence intervals, aiding in the validation of life prediction models. Figure 22 shows an example from Lee et al. [51] with the use of a Weibull plot to show the results of elongation at break of different samples under accelerated aging. In detail; it shows the cumulative failure rate of samples over time under different accelerated aging temperatures. Each curve represents the progression of failure probability at a specific temperature, with higher temperatures leading to earlier failures. The data shows the time-to-failure dependence on temperature, supporting the use of accelerated life models such as the Arrhenius model.

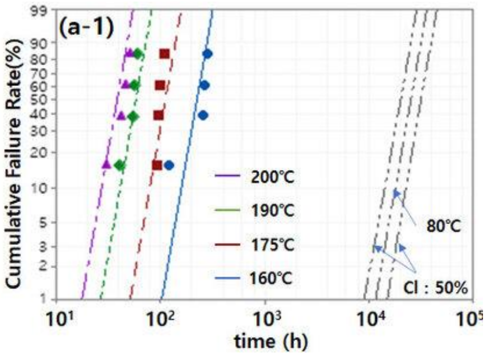


Figure 22: Weibull plot to predict lifetime

Ruz et al. [54] provided an excellent review paper regarding the state of the art for accelerated testing in fluid power pitch systems, including accelerated testing in hose assemblies. A review by Plota et al. [55] presents an overview of the environmental factors affecting the degradation of polymeric materials, which can be seen in Figure 23 for overview, and highlights the differences in degradation processes for various polymers. Polymer chain scission is one of the key degradation processes in polymers, involving depolymerization, destruction, and degradation that lead to a reduction in molecular weight. However, as mentioned before, PTFE stands out due to its exceptional chemical stability and high resistance to these processes. Under typical conditions, PTFE retains its molecular structure, but when exposed to extreme temperatures exceeding 400°C, it can undergo thermal degradation. This process involves the breakage of C-F bonds, resulting in the formation of free radicals, which are highly reactive species that contribute to structural breakdown. Despite being less prone to oxidative damage compared to elastomers, prolonged exposure to elevated temperatures can cause embrittlement and a gradual loss of mechanical properties, particularly in long-term applications

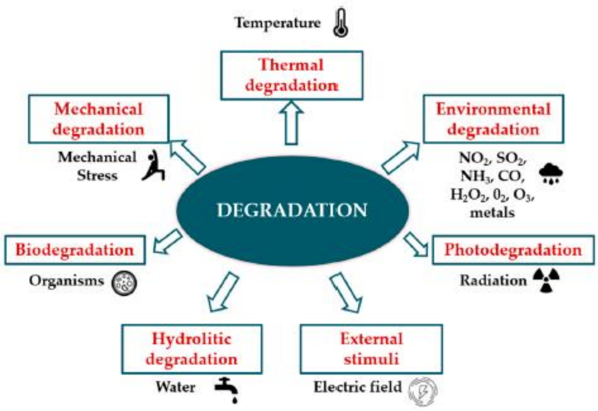


Figure 23: Degradation processes in polymers

Accelerated lifetime testing is also applied for measuring reliability in rubber hose assemblies [56], [57]. The same Arrhenius model approach is used here in order to predict remaining useful life. Brown in "Practical Guide to the Assessment of the Useful Life of Rubbers" [2] describes the importance of simulating operational conditions to avoid introducing unrealistic failure mechanisms. Factors such as exposure to coolant fluids, environmental humidity, and mechanical vibrations must be included into the test design to ensure results that reflect real-world use. Additionally, ADT studies involving rubber-based hoses emphasize that while some degradation mechanisms, such as chemical swelling, are less significant for PTFE, stress cracking and creep remain critical concerns.

In summary, accelerated testing and lifetime prediction for PTFE coolant hoses necessitate a systematic approach that integrates ALT for failure time analysis and ADT for monitoring gradual degradation. The combination of the Arrhenius model for temperature-dependent aging and a Weibull distribution for statistical analysis helps in understanding hose performance and informing maintenance schedules.

3. Failure Analysis

This chapter presents the failure analysis conducted during the early phase of this thesis project. The objective of this analysis was to identify the most critical failure modes and mechanisms that could potentially affect the performance of PTFE coolant hoses. To achieve this, expert interviews were conducted, and relevant literature was reviewed.

Focusing on the SMART-S Mk2 radar system, four different types of PTFE hoses are used in the above-deck equipment. A key distinction must be made between the hoses that are exposed to the external environment and those that are sheltered within the system. The exposed hoses are located on the outside of the antenna system and are subjected to harsher environmental conditions, such as salt-laden air, UV radiation, rain, and fluctuating temperatures. In contrast, the sheltered hoses are positioned inside the antenna assembly, where they are protected from external stressors. This internal space is also climate-controlled, preventing exposure to potentially degrading factors such as salt-laden air and extreme heat cycles. Figure [redacted] provides a schematic overview of the above-deck equipment, clearly indicating the positions of both the exposed and sheltered hoses. This distinction between hose placement is crucial for understanding the differences in operational lifespan and failure risk due to environmental exposure.

Figure 24 and Figure 25 shows pictures of the Goodridge G-Line Ultra 860 exposed hose and the Goodridge G-Flex 711 sheltered hose respectively. Both hose types are manufactured using anti-static PTFE with the help of carbon additives.

The exposed hoses G-Line 860 features a helically wound high tensile 316 stainless steel coil, located between the external convolutions of the smooth bore PTFE hose liner. This feature increases burst pressures, vacuum resistance and kink resistance. Additionally a stainless-steel outer braid is added, offering the highest level of protection from abrasion, tighter bend radius and higher temperature resistance. On the other hand, the sheltered hoses G-Flex 711 is the lightest hose in the Goodridge range. The G-Flex range features a fully convoluted (inside and outside surface), carbon impregnated, anti-static PTFE liner; wrapped in an Aramid fibre braid [19].

Figure 24: Goodridge G-Line Ultra 860

Figure 25: Goodridge G-Flex 711

Table 1 shows the specified allowable working loads for the different utilized hoses taken from the data sheet of the Goodridge parts catalogue [19].

Table 1: Goodridge hoses allowable working conditions

Hose	Location	Allowable pressure	Allowable temperature working range
1. Goodridge G-Line Ultra 960 Dash 12	Sheltered	Pwork = 105 bar Pburst = 315 bar	-40 °C … +180 °C
2. Goodridge G-Flex 711 Dash 06	Sheltered	Pwork = 45 bar Pburst = 180 bar	-40 °C … +180 °C
3. Goodridge G-Line Ultra 860 Dash 08	Exposed	Pwork = 122 bar Pburst = 367 bar	-73 °C …+260 °C

4. Goodridge G-Line Ultra 860 Dash 12	Exposed	Pwork = 105 bar Pburst = 315 bar	-73 °C …+260 °C

Although it may seem intuitive to assume the exposed hoses to fail first due to the harsher environmental loads they endure, the sheltered hoses should also be regarded as critical components. A failure of the sheltered hoses could result in coolant fluid leaking directly onto the sensitive electronic components housed within the antenna assembly, potentially causing significant disruptions or damage. Moreover, cleaning spilled coolant fluid from the sheltered hoses is considerably more challenging compared to the exposed hoses. Therefore, the impact of sheltered hose failure extends beyond simple leakage and includes the potential for prolonged system downtime and maintenance difficulties.

3.1 Loads

The governing loads on the hoses (exposed and sheltered) can be divided in three main load types; *mechanical, thermal and chemical.* Note that only the contextual loads are listed here from the real operating conditions and environments for naval applications. In other applications, PTFE hoses could be subjected significantly more loads like vibrations, UV radiation, pressure impulses etcetera. The exerted loads on the sheltered hoses inside the antenna assembly can be seen in Table 2.

Table 2: Loads on the sheltered hoses

SHELTERED HOSES	
Mechanical loads:	1. Pressure: 6 bar (no pulsation, no severe fluctuations) 2. Kinking: bending load, critical at outer bend. Max bending load exceeded at min. bending radius 3. Twisting: torsional load.
Thermal loads:	1. Temperature Setpoint T1: 20 °C 2. Temperature Setpoint T2: 30 °C 3. Temperature when CU is OFF in cold environment, worst case: 0 °C 4. Temperature when CU is OFF in warm environment, worst case: +43 °C
Chemical loads:	1. Coolant fluid inhibitor (Dowcal) 2. Fluid contamination (parts of metal, glass, caustic soda)

For the exposed hoses, one additional load type is present and the temperature loads are greater in magnitude. These additions and differences are colored in red text. All exerted loads on the exposed hoses are depicted in Table 3.

Table 3: Loads on the exposed hoses

EXPOSED HOSES	
Mechanical loads:	1. Pressure: 6 bar (no pulsation, no severe fluctuations) 2. Kink: bending load, critical at outer bend. Max bending load exceeded at min. bending radius 3. Twist: torsional load
Thermal loads:	1. Temperature Setpoint T1: 20 °C 2. Temperature Setpoint T2: 30 °C 3. Temperature when CU is OFF in cold environment, worst case: -30 °C 4. Temperature when CU is OFF in warm environment, worst case: +71 °C
Chemical loads:	1. Coolant fluid inhibitor (Dowcal)

	2. Fluid contamination (parts of metal, glass, caustic soda) 3. Salt concentration: 1-100 ug/m3

From the collected load data, it can be seen that the thermal loads are higher for the exposed hoses when the Cooling Unit (CU) is turned off. This is due to the fact that the sheltered hoses still experience a flow of conditioned air inside the antenna when the CU is turned off. This air conditioning system needs to be turned on at all times for performance and safety reasons. It is insightful to see that the sheltered hoses will therefore never experience a temperature below 0 °C when the CU system is shut off, while the exposed hoses could in this instance obtain the same temperature as the outside environment (-30 °C in worst case cold environment). The same is true when the CU is turned off and the hoses are in a warm environment. The exposed hoses could then in worst case obtain[1] 71 °C.

Next, the operational temperature loads and pressure loads were compared to the specifications of the hoses provided by the data sheets from Goodridge (Table 1). A mission profile graph is created to visualize the differences. Figure 30 presents the temperature range for the exposed PTFE hoses, highlighting the differences when the cooling unit (CU) is turned on and off. Figure 31 shows the similar thing for the sheltered PTFE hoses. Finally, Figure 32 compares the maximum burst pressure and operational pressure of both exposed and sheltered hoses, demonstrating the extreme differences between operational and burst pressures.

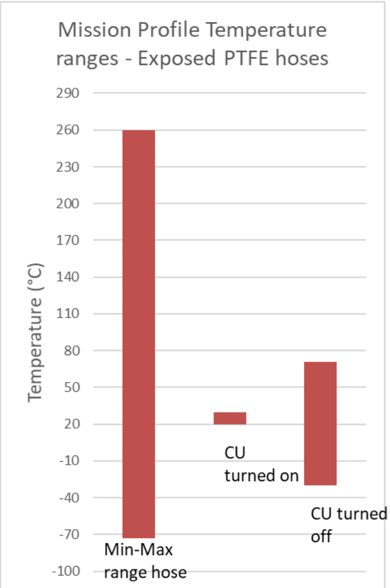


Figure 26: Mission profile - Temperature loads on: exposed hoses,

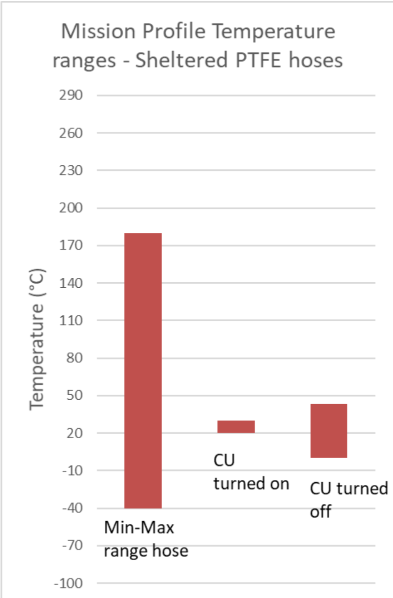


Figure 27: Mission profile - Temperature loads on: sheltered hoses

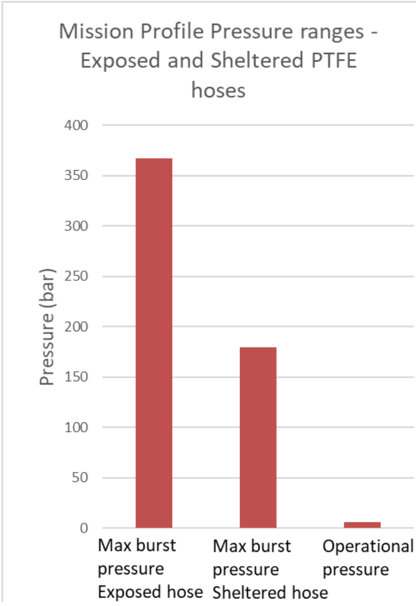


Figure 28: Pressure load mission profile of exposed and sheltered hoses

[1] This includes the addition of worst case maximum solar radiation of 1120 W/m^2

From this comparison it can be seen that the dynamic pressure inside the cooling system of the SMART-S Mk2 is significantly below the maximum burst pressures of the hoses. Therefore we can conclude that the pressure load will not be a critical degradation factor for the hoses.

The same neglect holds for when the CU is turned on; a temperature fluctuation between 20 °C and 30 °C will assumedly not degrade the hose when its allowable operating range is specified between -73 °C and +260 °C for the exposed hoses. However, if the CU system is turned off, temperature values can become extreme and therefore begin to be more critical in terms of degradation. It is thus considered that temperature is to be a critical degradation agent and to use these temperature values in the design of the experimental part. It was also assumed that the exposed hoses will always contain a lower lifetime compared to the sheltered hoses. This is due to the most critical fact that the exposed hose could experience temperatures (-30 °C), closer to the lower temperature limit (-73 °C), where the PTFE material can become more brittle and lose flexibility.

The remaining operational loads mentioned in Table 3 and 4 are evaluated during the next two sections.

3.2 Fault Tree Analysis (FTA)

From literature, expert interviews and calculations the Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) were constructed. These analysis methods help in the determination of the critical failure modes and mechanisms pre- or postmortem. To start, the function of a hose was described; ‘’to maintain pressure, transport fluid and provide flexibility’’. The most general failure mode for a hose that leads to a functional failure is leaking [34], [44], [6], [47]. While on a lower level, the failure mode embrittlement, is another functional failure mode in terms of providing flexibility [44], [38]. Embrittlement is also known as ‘’taking set’’.

First the FTA was constructed. It includes all failure mechanisms and causes that a typical PTFE hose could experience while not necessarily judging the severity and probability of occurrence in the research application. The FTA provides a helpful distinction in the top-down failure mechanisms and causes. This is realized with the help of classifying each cause or failure mechanism as a human error, a avoidable overload or unavoidable overload. For example, kinking of the hose can be treated as a cause that is induced by a maintainer or operator (human error) by handling the hose in a wrong way. Cracking of the PTFE inner liner, on the other hand, can be treated as an unavoidable load because unavoidable vibrations of the frigate diesel engine, could propagate through the ship’s structures and consequently through the hose.

The FTA can be seen in Figure 29. Breaking down the FTA; the top level is the most probable and critical failure mode; leaking of the hose. The hose can only start leaking when the weakest part that holds the fluid together, fails. This is indicated by damaged PTFE material. This damage can be initiated by cracking or thinning of the PTFE layer. The consequent failure mechanisms show the last level in circles and the legend indicates the load type. A damaged braid could also lead to hose leaking in the end, since damage to the braid will ensure that the hose assembly loses structural integrity. This means that locally, the PTFE inner layer will not receive the aid of strength from the outer braiding and thus a local weak point for the PTFE material could occur, resulting in cracking. A damaged braid has multiple lower level failure mechanisms that could be the cause of failure.

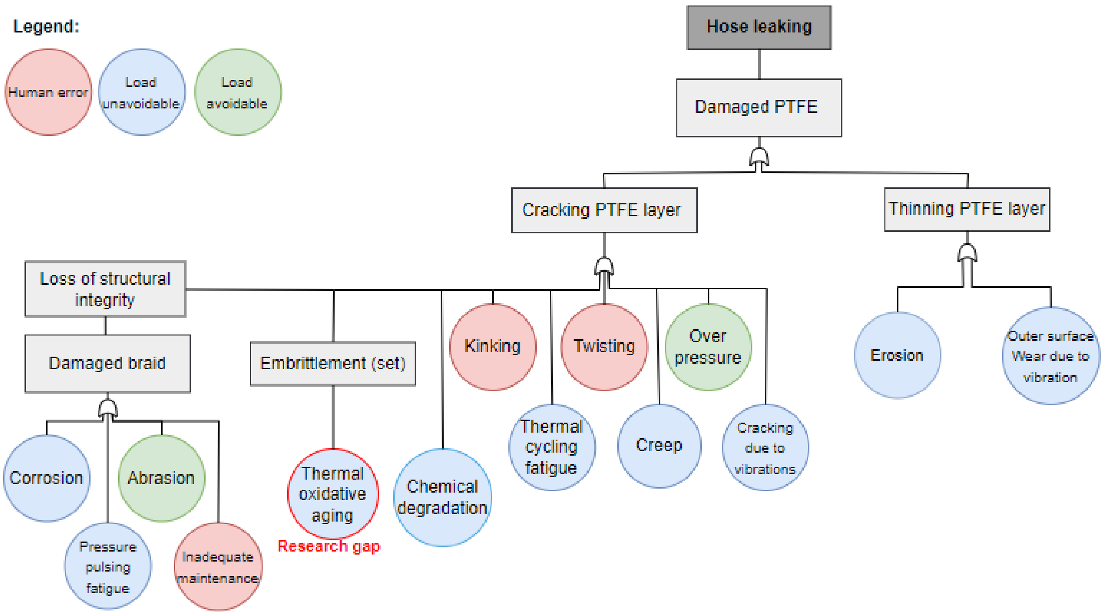


Figure 29: Fault Tree Analysis

Lastly, the FTA figure indicates thermal oxidative aging is the unexplored research gaps with respect to the application in PTFE hoses specifically.

3.3 Failure Mode and Effects Analysis (FMEA)

The FMEA helps in the categorization and qualification of the failure mechanisms and causes. The same causes from the FTA are listed in the FMEA while each was given a score from 1-10 on severity, occurrence and detectability. The full FMEA diagram can be seen in Appendix B.

Analysis of the FMEA resulted in the fact that *Thermal Oxidative Aging* is the main failure mechanisms that could degrade the PTFE hose in the operational context from Thales. Thermal oxidative aging[2] refers to the gradual deterioration of polymer materials due to prolonged exposure to elevated temperatures and an oxidative environment. This process is considered unavoidable and uncontrollable in long-term service conditions. Thermal aging occurs as the polymer chains within the PTFE material undergo chain scission, a process in which the long molecular chains break into shorter fragments [58], [59], [60]. Chain scission weakens the overall molecular structure of the material, leading to a gradual loss of mechanical strength and flexibility. When PTFE is exposed to high temperatures in the presence of oxygen, the chemical bonds in the polymer backbone are attacked, causing oxidative degradation [59]. This process is exacerbated by static positioning, where mechanical stresses become concentrated in specific areas, making the material more prone to cracking and deformation.

One of the most prominent characteristics of an aged PTFE hose is the phenomenon of taking set, where the hose becomes brittle and retains its deformed shape instead of returning to its original form. This loss of flexibility represents a functional failure of the hose, which is expected to provide flexibility within the cooling system.

[2] In the remainder of this thesis, this will be referred to as thermal aging

The failure mechanism *''Chemical degradation''* presented a similar high score on the FMEA to thermal aging. And since the problem with *''Corrosion''* and *''Erosion''* are already present for the Thales hoses; the reason for not focusing on these failure mechanisms is as follows.

Chemical degradation refers to the deterioration of a material caused by chemical reactions with substances in its environment, potentially leading to weakened mechanical properties, cracking, or even structural failure. Extensive literature and material data indicate that PTFE is highly resistant and shows excellent compatibility with respect to ethylene glycol [61], [62]; the main ingredient in Dowcal used in the coolant systems of Thales. The high level of chemical inertness makes it unlikely that PTFE will undergo significant degradation when exposed to the coolant. Therefore, the likelihood that chemical degradation would lead to hose failure is considered negligible. Discussions with Thales' material specialist further confirmed these findings.

Corrosion; existing confidential test data was provided by Goodridge, including the results of a salt spray test performed in accordance with ASTM B117-11. It indicated that the stainless steel braiding of the hose showed no observable corrosion damage. The only notable observation from the test was the appearance of small stains at the hose fitting ends, rather than any structural degradation of the braiding itself. Furthermore, operational feedback, as described in the section 1.3., indicates that the braiding of the exposed hoses sometimes develops surface rust during service in naval environments. However, this rust is typically a cosmetic issue and can be cleaned off during regular maintenance or overhauls without compromising the hose's structural integrity. No cases of hose leakage have ever been attributed to corrosion of the stainless steel braiding and is therefore excluded for analysis.

Erosion refers, in this case, to contamination particles inside the Dowcal coolant fluid. The particles flow through the hose and consequently wears out the inner surface. Thales mentioned previous issues with coolant fluid contamination containing parts of metal, glass, caustic soda and the inhibitor ingredients (Boron Potassium Oxide (B4K2O7) Tetra Hydrate). For example, extensive analyses of the composition of operational Dowcal coolant fluids show particles of Iron (Fe), Bromine (Br) which could lead to wear. Figure 30 shows an example of sharp metal parts inside the Dowcal coolant fluid.

Thales already conducted an experiment in which contaminated coolant fluid was forces through a hose set and later analyzed with surface morphology measurement equipment. This resulted in the same crack formation as for a 10-years operational reference hose which was analyzed in 5.2. However, documentation is unavailable.

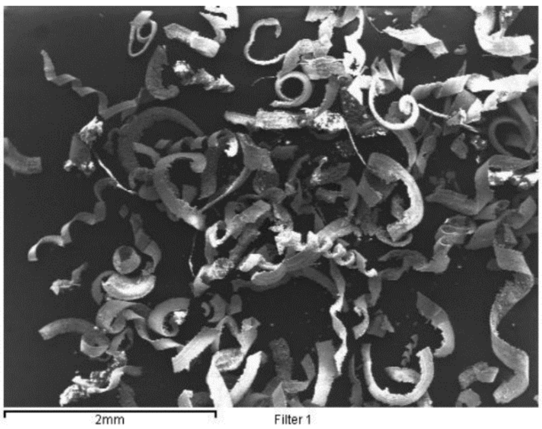


Figure 30: SEM picture of sharp metal parts inside operational Dowcal coolant fluid

A comprehensive overview of all failure mechanisms considered in the FTA and FMEA are described in Appendix B.

3.4 Failure analysis results

The failure analysis, consisting of the evaluation of operational loads, Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA), concludes that leakage is the most critical failure mode for PTFE coolant hoses. Leakage is typically initiated by the formation of microcracks in the PTFE inner liner. These microcracks result from thermal aging, a gradual degradation process caused by prolonged exposure to both high and low temperatures, an oxygen-rich environment, and mechanical stress from being held in a fixed position. Figure 31 below shows the degradation mechanism of the atom bonds during aging. It shows that the carbon-fluoride bonds tend to break into smaller chains due to chain scissions.

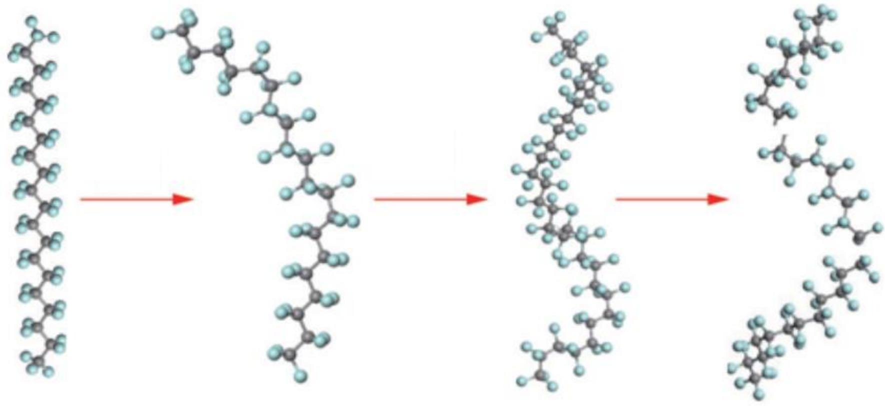


Figure 31: Aging process of PTFE atom bonds

This analysis highlights the importance of considering thermal influences when assessing the long-term reliability of the hoses. To accurately characterize the degradation behavior and quantify the expected service life of the PTFE hoses, an accelerated test program is required. The primary focus should be an accelerated temperature test designed to simulate the temperature effects that occur during operation. The experimental methods in the next chapter outline the design of this accelerated testing approach.

4. Experimental methods - Accelerated Tests

This chapter outlines the experimental methods used to investigate the degradation and lifespan of PTFE coolant hoses under accelerated aging conditions. The tests are designed to simulate long-term thermal exposure and assess the material's properties before- and after aging.

4.1 Introduction

Designing an accelerated test program is essential for determining the lifetime and degradation behavior of materials or products. The test must ensure that the critical aging processes are triggered and measured within a shorter timeframe, while still representing the real operating conditions of the hoses. Building on the findings from previous research, this study focused on creating an experimental approach specific to the harsh maritime environment. By following the principles of Brown [2] and Nelson [49], this research aimed to provide a clear understanding of the degradation behavior of PTFE hoses and come up with reliable estimates of their lifespan in operational conditions.

The literature review already explains a lot about accelerated testing utilized by other scholars. The basic concept of accelerated testing is to increase the levels of the degradation agents [2]. This is easily obtained for environmental factors, for example raising the temperature or the intensity of radiation. When acceleration is produced by increasing the level of the degradation agent, it is generally achieved by applying a constant (elevated) level. The alternative to this is to increase the frequency at which it is applied. This can be achieved in various ways. For temperature, a high level may be applied continuously where in service it is variable.

In this study of PTFE coolant hoses, it was essential to come up with a suitable testing approach to evaluate the degradation behaviour of the hoses. While Accelerated Life Testing (ALT) is typically used to assess the time-to-failure by pushing the material or component to extreme conditions, this approach was found impractical in this research. The primary reason for this was the high reliability and over-dimensioning of the currently used PTFE hoses, making it unlikely that they would fail within a reasonable testing timeframe, noting that failure in this case is classified as leakage. Additionally, resource limitations played a significant role: the number of hoses available for destructive testing was restricted due to their high cost. Furthermore, the available Thales testing equipment was limited to a pump, capable of building pressure up to only 16 bar. This was an insufficiently high pressure to check for leaks before and after the aging process. These constraints forced an alternative approach focused on measurable degradation characteristics rather than complete failure. Therefore, Accelerated Degradation Testing (ADT) was selected as an alternative approach to systematically study the degradation behaviour rather than complete failure.

In the literature review, the distinctions between ALT and ADT were already discussed, highlighting the following key differences:

- ALT focuses on determining the time until complete failure, collecting time-to-failure data to predict the life expectancy or reliability.
- ADT measures the progressive degradation of specific performance parameters under accelerated conditions to predict when the product will no longer meet its intended specifications or performance level.

Objective of the Experimental Tests

1. To identify and verify the critical failure modes and mechanisms of PTFE hoses used in the Thales cooling systems.

2. To gather relevant data that could be used to predict their lifetime.

To achieve this, it was necessary to first identify the primary degradation agents responsible for hose degradation. The failure analysis identified temperature as the foremost degradation agent, contributing to thermal aging. Therefore, temperature was the only tested degradation agent during this research.

Two distinct test programs were designed and executed to assess the degradation behaviour of the PTFE hoses:

Test 1: Temperature Cycling Test. This test was conducted to simulate thermal fatigue, a potential failure mechanism from repeated temperature changes. Temperature cycling is a common qualification method used by Thales to evaluate the robustness of their components and systems, since in operational context, these are subjected to temperature changes when located in hot or cold environments. Temperature cycling induces stress from thermal expansion and contraction, which can lead to fatigue damage.

Although preliminary calculations indicated that hose degradation due to thermal cycling was not expected to be highly severe, this test was performed to verify whether any observable degradation occurred. Although test 1 remains not the primary focus of this research, it still provided valuable insights into the susceptibility of the hoses to thermal fatigue and helped map the overall degradation behaviour.

Test 2: Constant Temperature Stress Loading Test. The second and most crucial test focused on inducing thermal aging by exposing the hoses to constant elevated temperatures. This test was designed to evaluate the thermal stability of the PTFE material and to determine whether long-term exposure to heat would lead to significant changes in material properties. By focusing on thermal aging as a failure mechanism, this test aimed to track changes in key performance parameters, such as tensile strength, hardness, burst pressure and more.

In summary, this experimental program utilized both temperature cycling and constant temperature stress loading to evaluate the degradation behaviour of PTFE hoses. The findings from these tests contribute to mapping the degradation profile and provide essential data for estimating lifetime.

4.2 Experimental Setups and Methods

4.2.1 Analysis methods:

Microscopic analysis (SEM):
A microscopic analysis using a SEM machine provides a way to understand a sample surface's topography. This analysis could indicate cracks, voids, and possible change in microstructure due to thermal effects. SEM analysis is short for Scanning Electron Microscopy analysis. This spectroscopy technique is a form of high-resolution surface imaging that uses the principle of light microscopy. SEM analysis scans the sample being tested with a focused electron beam to produce a high-resolution image of its surface. SEM analysis is fast, non-disruptive, non-destructive and accurate.

The microscopic analysis were executed under room-temperature environments and data was collected by scanning the PTFE samples manually and searching for cracks, or discontinuities etceterara. After that, a High-Definition photo was taken and saved on the computer. Three most suitable enlargements have been chosen to use for each sample: 50x, 400x and 1600x. One PTFE sample per specific aging temperature and duration was analyzed. Samples were cut from the region in which the smallest radial bend took place. This ensures a region that contains the highest chance of observable cracks/degradation. The SEM analysis was outsourced to partner company DEON. Figure 32 shows the SEM machine used from Thermoscientific Axia.

Figure 32: Microscopic SEM analysis machine: Thermocientific Axia

The parameter(s) to be monitored, before- and after accelerated aging, using the SEM are: Presence of cracks, cuts, discontinuities, voids and any other form of surface degradation.

DSC:
For thermal analysis, Differential Scanning Calorimetry (DSC) was used. It measures the heat flow associated with phase transitions in materials as a function of temperature. For thermally aged PTFE samples, DSC can help analyze degradation by identifying changes in crystallinity since degradation may alter the crystallinity of PTFE, which affects its melting temperature and enthalpy of fusion, or by detecting oxidation or decomposition. If the PTFE has undergone chemical changes, these may be evident through shifts in endothermic or exothermic peaks. Comparing the onset of melting or degradation temperatures between aged and unaged samples helps evaluate changes in thermal properties due to aging.

The analysis were executed under room-temperature environments and data was collected by turning on the DSC to let it start the heating and cooling cycle. After that, a plot has been generated and saved on the computer. One PTFE sample per specific aging temperature and duration was analyzed. Samples were cut from random locations of the hose as they should not interfere with the DSC results. The DSC analysis was outsourced to partner company DEON. Figure 33 shows the DSC machine used from Netzsch.

Figure 33: DSC machine: Netzsch

The parameter(s) to be monitored, before- and after accelerated aging, using DSC is: Melting temperature.

Tensile test:
For the mechanical analysis, the tensile test is one of the most powerful analysis tools to determine mechanical deterioration. For example, a change in elongation at break for the damaged hose could be an indication of reduction in mechanical properties. For this research, two types of tensile tests were executed.

1. Hose cut sample tensile tests:

Dumbbell shaped hose samples were cut and tested in a small tensile test bench that was available at Thales. Each test run contained at least five hose samples tested in the tensile test. The displacement rate of the test bench was set to 200 mm/min. The samples were clamped tight using hand force so that they did not show signs of slip. The distance between the tensile clamps was set at 70 mm. Before the test was started, each sample was measured using a calliper on smallest width and length. All samples failed in the rejuvenated area of the sample, that is where the width of the sample is the smallest. The test bench used is the Mecmesin Multitest 2,5 dv, depicted in Figure 34 and contains a maximum tensile force of 2500 N. Figure 35 shows an example of how the hose samples were clamped during setup.

Figure 34: Tensile test setup

Figure 35: PTFE sample clamping

2. Functional hose tensile tests:

In this test, a full diameter hose has been tested by outsourcing it at partner company DEON. This test was set up in order to compare tensile results the dumbbell cut PTFE samples. A special clamping tool was designed and used in order to prevent the functional hose from slipping. A clamping force of 50 bar was used and a strain rate of 203 mm/min. The test bench used is depicted in Figure 36.

Figure 36: Tensile test setup; heavy

The two types of tensile tests were executed under room-temperature environments. Data was collected by sampling data points of the test bench in Force vs. Displacement values. This raw data was later translated to Stress vs. Strain pots.

The parameter(s) to be monitored, before and after accelerated aging, using the tensile test are: plastic modulus, maximum stress, maximum elongation.

Hardness test:
The hardness of PTFE is typically measured in Shore D and according to method ASTM D2440 [63]. A change in hardness values for damaged PTFE samples could also indicate a reduction in mechanical properties. In detail, it could give an indication of the severity of brittleness. Figure 37 shows the measurement equipment used. For each aging setpoint, a minimum of five hardness values have been collected from randomly cut hose samples.

Figure 37: Hardness measurement device

The analysis were executed under room-temperature environments and data was collected by writing down the hardness values for the specific aging setpoint samples. Results showed an average error of +- 1 Shore D for basically all tested samples.

The parameter(s) to be monitored, before and after accelerated aging, using the hardness test is: Hardness

Burst tests:
The burst or leak test was the only destructive test method used in this research. Since destructive testing is expensive, the test was to be designed in a well-thought manner. Four Goodridge G-Line 860 Dash-12 hoses have been tested on leakage and burst values and in accordance with ISO 1402; Hydrostatic testing of rubber and plastic hoses. The test has been outsourced and was executed at Eriks Hydraulics in Roermond. The student was present during the execution of the test. Note that each aging setpoint only contains the testing of one hose.

The burst pressure for these hoses is specified by Goodridge to be 315 bar. Consequently, the test was designed to reach 500 bar with a buildup pressure of 2,5 bar per second. The hoses were connected with the applicable torque settings specified by HSV-P-6031. Each hose was tested individually and put inside the protected burst test room. Figure 38 and Figure 39 shows the test room and the connected hose setup respectively.

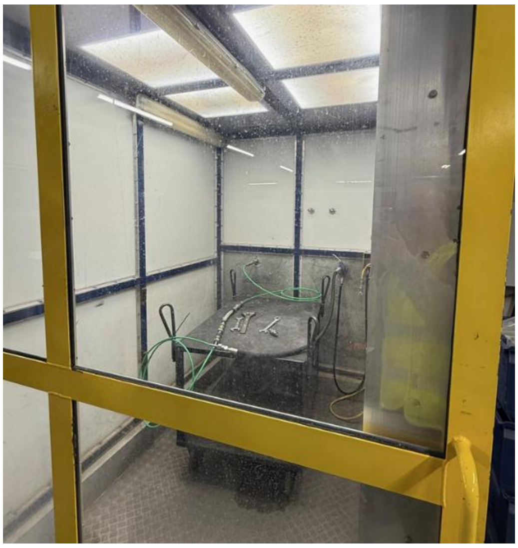


Figure 38: Burst pressure room

Figure 39: Burst pressure test setup

The parameter(s) to be monitored, before- and after accelerated aging, using the burst test are: Leak pressure and burst pressure.

4.2.2 Research setups:

Heat generation:
The temperature & humidity chamber depicted in Figure 40 was used to induce temperature cycling for test 1. Classified as the Espec ARG 860, containing a temperature range of -75 °C to + 180 °C, heat up rate of 6.0 K/min, allowable heat load of 4500 W and a capacity of 680 L. Maximum measurement uncertainty of this equipment is 1,02 °C

A smaller and more simple temperature oven, depicted in Figure 41, was used for generating a constant elevated temperature level regarding test 2. The Heraeus oven is a product from Kendro Laboratory Products with a maximum temperature setpoint of 250 °C and a output power of 1,22 kW.

Figure 40: Temperature & humidity chamber

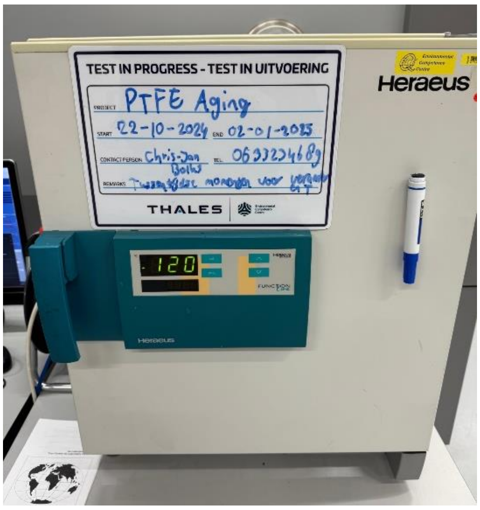


Figure 41: Thales oven

Hoses and Samples:

Table 4 shows an overview of all the hose types that were utilized during test 1 and test 2. Note that the pictures do not yet show the final form of sample preparation.

Table 4: Hose types and sample configuration names used in the experimental parts

Hose type	Employment	Generic Sample name	Features	Picture
Goodridge G-Flex 711 Dash 12	Tensile, SEM, DSC	G711	Convulated bore & outer surface, aramid braiding, sheltered hose	
Goodridge G-Flex 711 Dash 10	Tensile, SEM, DSC	G711-REF-DH	Convulated bore & outer surface, aramid braiding, sheltered hose	
Goodridge G-Line Ultra 860 Dash 12	Tensile, SEM, DSC	G860	Smooth bore, convulated outer surface, SS braiding, SS helical wire reinforcement, exposed hose	
Goodridge G-Line Ultra 860 Dash 12	Burst pressure test	G860-Burst	Smooth bore, convulated outer surface, SS braiding, SS helical wire reinforcement, exposed hose	
Goodridge G-Line XF 811 Dash 08	Tensile, SEM, DSC	G811	Smooth bore, convulated outer surface, SS braiding, exposed hose	
ERIKS Eriflon F511 Dash 06 [64]	Tensile	Eriks	Convulated bore & outer surface, SS braiding, not used in Thales equipment	

Special attention should be upon the G711-REF DH hoses. Since these consists of a reference hose set taken from the inside of an antenna assembly in which these hoses were positioned for 10 years. These hoses thus induced degradation from operational loads during 10 years and are very helpful in comparing them to the accelerated aged hose samples. Figure 42 shows a figure of the as-received REF-DH hose.

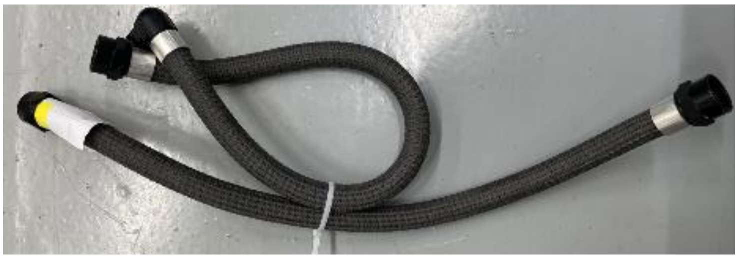


Figure 42: G711 REF-DH hose; 10 years operational life

A total of 150 samples have been used for analysis. A designed sample sequence overview in Excel offers a clear view of each sample with its corresponding aging temperature and duration. The sequence list of all samples used can be found in Appendix C.

Sample preparation:

Since four different analysis methods were employed, various types of samples had to be prepared accordingly. The preparation of PTFE hose samples began with the careful removal of the outer braiding without damaging the PTFE inner liner. The stainless steel braiding was required more effort to remove compared to the aramid braiding. Once the braiding was removed, the inner PTFE liner was isolated for further sample preparation. For the tensile test, cutting the PTFE liner lengthwise into rejuvenated/dumbbell shaped test specimens was necessary to ensure that the samples failed in the middle of the sample. Cutting these rejuvenated tensile samples proved to be the most difficult step due to the precision needed and the use of a surgical knife. This process often resulted in inconsistent sample widths, affecting the uniformity of the tensile test specimens. An example of the before and after cutting of the hose samples can be seen in Figure 43.

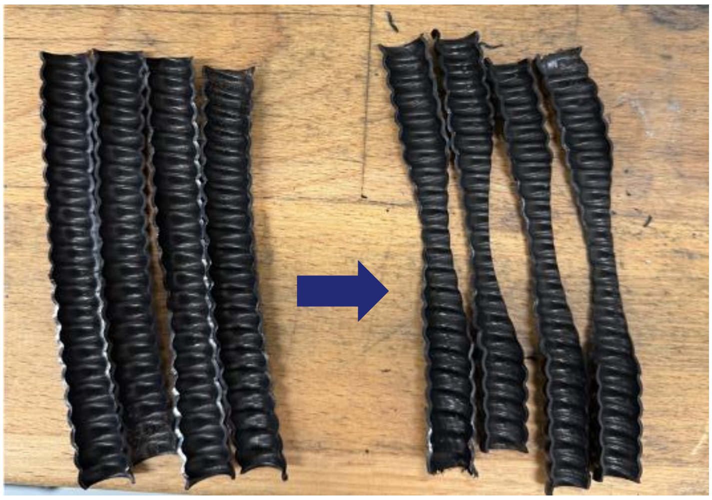


Figure 43: Sample preperation - cutting for tensile tests

For SEM, DSC, and hardness testing, smaller samples were required. Samples for the SEM analysis were cut into 10x10 mm shapes to meet the requirements of the respective tests. Figure 44 shows an example of the hose samples pasted on mounting pads for SEM analysis. DSC samples needed to be cut in a similar way compared to the SEM samples, but now with a dimension of roughly 2x2 mm. Lastly, the hardness samples did not require a maximum dimension except for the thickness. The ASTM D2440 requires a minimal sample thickness of 3 mm. Therefore, two hose sample thicknesses needed to be placed on top of each other in order to guarantee proper measurement values. Figure 45 shows the stacking of the two samples.

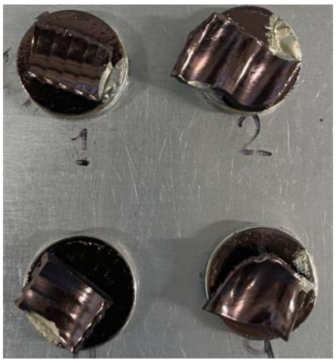


Figure 44: PTFE samples inside the SEM machine

Figure 45: Sample setup for hardness measurements

4.3 Accelerated test design

4.3.1 Test #1 Temperature cycling

The temperature cycling test was designed as part of the "Accelerated Test Design" framework to simulate the thermal cyclic stresses experienced by PTFE hoses during operation. By using operational temperature cycling data, the required number of cycles necessary to replicate the expected fatigue damage within a shorter timeframe was calculated. These calculations were performed using the life cycle aging calculation sheet provided by Thales. This document uses a modified version of the typical Miner's rule. In fatigue analysis, the accumulation of damage due to cyclic loading is often described using Miner's Rule, which states that total damage (D) is the sum of individual cycle contributions. Traditionally, this model is applied to mechanical fatigue, where damage is a function of stress cycles. However, for temperature-induced fatigue, a similar cumulative damage approach can be used, as thermal expansion and contraction induce stress within the material.

To account for the effect of temperature variations, an empirical acceleration factor is introduced. The Thales model assumes an acceleration stress factor of 2 for every 10°C increase in temperature relative to normal environmental conditions, a principle commonly applied to electronic equipment in temperature-based reliability testing (e.g. by Thales). It follows an approximation of the Arrhenius equation, which describes temperature-dependent degradation. Instead of directly using stress levels, the acceleration factor is thus defined as 2^x. This allows temperature fluctuations to be incorporated into the damage accumulation model in a simplified but effective manner.

By integrating this empirical factor into Miner's Rule, the damage equation due to temperature is redefined as:

$$D = n * 2^{x}$$

With D being the number of cycles that the component experiences in operation, n the number of cycles needed in the accelerated test, 2^x being the acceleration factor and x being further defined using the following equation:

$$x = \frac{(\Delta T_2 - \Delta T_1)}{10}$$

In here, ΔT_2 is the range in accelerated test temperatures and ΔT_1 is the range in operational temperatures.

The sheltered PTFE hoses are – in worst case - subjected to either 0 °C (cold environment) or 43 °C (hot environment). Thus, ΔT_1 of 43 °C. To simulate the thermal stress experienced over a lifetime of 30 years, the operational temperature range was taken as a worst-case scenario. Meaning that the Cooling Unit is shut off for 240 days per year. The operational number of cycles (D) can be simply calculated using:

D = years * days * cycle change per day

Thus, for 30 Years → D= 30 * 240 * 1= 7200 cycles

For the temperature range in the accelerated test, the following was selected: cycling between -10 °C and 130°C, Thus, ΔT_2 = 140°C. These values can then be used to calculate x.

$$x = \frac{(140 - 43)}{10} = 9{,}7$$

Finally, a life cycle test for 30 years, in which the cooling system is turned off 240 days per year (worst case) can be brought down to cycles (n) needed from thermal fatigue damage:

$$\mathrm{n} = \frac{\mathrm{D}}{2^x} = \frac{7200}{2^{9{,}7}} = 8.6\ cycles$$

The amount of cycles needed is rounded up to 9 cycles.

The temperature cycling test was designed using three Goodridge G-Flex 711 PTFE hoses. These hoses, positioned within the radar antenna system, are categorized as sheltered components. Other parameters that were defined for the test design include a general consideration for the heating and cooling rate, set at 15°C per minute, and a 2-hour soak period at both the hot and cold setpoints. This configuration results in a total duration of 39 hours for the total test. The hoses were put in a fixed position inside the temperature cabinet with the help of a tie wrap so that a minimum outer bend radius is achieved in the middle of the hose. This creates a region that can be analyzed for potential cracks. Figure 46 shows the two hoses inside the chamber with the addition of thermocouples to monitor the temperature of the hose wall and of the environment.

Figure 46: Temperature cycling test setup; hoses placed inside

The schematic design of the temperature cycling test is depicted in Figure 47. It shows that three hoses are used for this test; hose #1 will be used as an ''as-new'' hose which is un-aged. The other two hoses are subjected to the calculated 9 cycles. After the first temperature cycling test, Hose #2 was subjected to an additional cycling test of 9 cycles and within the same accelerated temperature cycling range. In this way, change in degradation for different type of cycles could be analyzed. It should be noted that Hose #2 now theoretically receives damages induced from simulating 60 years of thermal cycling in operation (18 cycles).

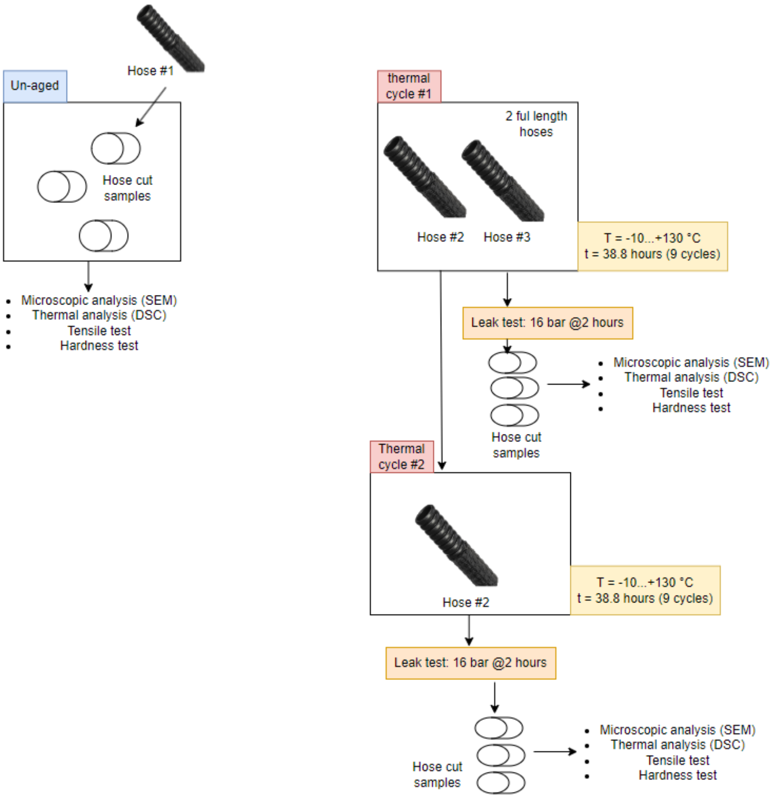


Figure 47: Test #1 design

A pressure tightness or leak test was executed before- and after the cycling test to verify externally if visible degradation took place. The leak test was executed at 16 bar for a duration of two hours with demi water. Operational Dowcal could not be used due to safety reasons[3]. The external leak test indicated no signs of leakage, sweating or other anomalies. This concludes that no sufficient degradation occurred for the 9 and 18 cycles hoses. Therefore, internal analysis of the PTFE material is needed as will be discussed in the next chapter.

4.3.2 Test #2 Constant temperature

The second test involved subjecting the PTFE hoses to constant stress under elevated temperatures to simulate long-term thermal aging. This approach aimed to accelerate the thermal aging process and evaluate the material's degradation behavior. To ensure that the test parameters led to measurable and observable degradation, a sensitivity analysis was conducted. The analysis involved systematically selecting a starting temperature and different aging durations and evaluating how each variation affected the material properties. This analysis was

[3] Dowcal is a hazardous fluid, especially when pressurized, and should be treated with care handling and protection

crucial in determining the appropriate aging temperatures and exposure durations required to induce noticeable changes in the material properties for the final test program.

Sensitivity test: The selected temperature setpoint for constant stress loading depended on the maximum limit of the Heraeus oven at Thales (250 °C). With the information of the academic papers described in the Literature review 2.3, the sensitivity test was started. An aging temperature of 250 °C was chosen with an duration of 72 hours (3 days). A total of 12 samples were analyzed using a tensile test, including 5 unaged samples. A total of 8 samples have been analyzed using SEM and DSC analysis. All samples were analyzed at DEON. The conclusion after analysis is that there was no significant change in morphology according to the SEM analysis, no significant change in thermal properties according to DSC analysis. Lastly, no reliable results were drawn from the tensile test and significant changes in tensile strength, elongation at break or plastic modulus of the aged and unaged samples could not be seen.

The sensitivity test insisted that aging durations need to be greater than 72 hours in order to observe and measure degradation from the PTFE samples using the measurement equipment.

Constant temperature test design: The next step was to design the constant temperature test program. The test program in schematic overview is depicted in Figure 48. To capture a range of potential degradation behaviors, three different temperature setpoints were employed and for each setpoint, aging exposures of 12 days, 18 days, and 24 days were used:

1. 120°C (low) - 12, 18, 24 days
2. 180°C (medium) - 12, 18, 24 days
3. 250°C (high) - 12, 18, 24 days

These durations were hypothesized to be sufficient to observe measurable degradation in the material's mechanical and thermal properties. Throughout the aging process, samples were removed from the oven after each set duration for subsequent analysis. Control samples, referred to as "unaged" samples, were not subjected to any thermal exposure and were prepared directly for the previously mentioned analysis methods (tensile testing, SEM, DSC, and hardness testing).

It must be noted that the PTFE hoses were not placed in the oven in their final prepared form for tensile testing or other sample-specific analyses. Instead, the samples were placed in the oven as full-diameter PTFE inner liners. This approach was necessary to prevent the pre-cut samples from deforming drastically under high temperatures, which could interfere with their usability for post-aging measurements. By aging the hoses in their original shape, the risk of heat-induced warping or shrinkage during the aging process was minimized. This setup ensured that the samples retained their structural integrity for accurate post-aging evaluation.

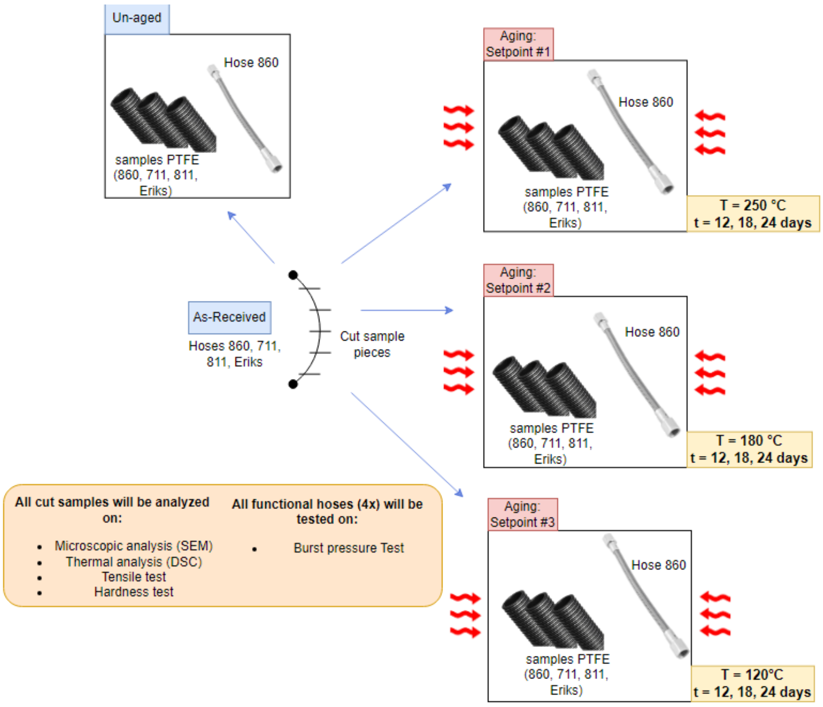


Figure 48: Test #2 design

Figure 49 shows the inside of the small oven during aging at 250 °C, with different hose samples inside. Next to the stripped PTFE inner liner samples, the three fully functional G860 hoses were placed inside (including braiding and crimped fittings). These were utilized during the burst pressure test at Eriks Roermond. In the end, the constant temperature test took a total of 48 days to complete.

Figure 49: Test #2 aging setup inside the Thales oven

5. Results

This chapter describes the results from the different analysis methods used to quantify the magnitude of PTFE hose degradation. The analysis methods are divided into different sections. The first section concerns the mechanical analysis, which includes the tensile test, hardness test and burst pressure test. The next section touches upon morphological analysis; microscopic analysis using the SEM. The third section presents the results of the thermal analysis; using the DSC analysis. This chapter will finally be concluded by interpreting all the results and uses a lifetime prediction model to make a statement about the useful life of the PTFE coolant hoses used in Thales equipment.

5.1 Mechanical analysis:

Tensile Test:

Only the tensile test results for the PTFE hoses that were cut and prepared in rejuvenated samples are described here (Eriks hose cut samples and G711 hose cut samples). The remaining results of other hose sample tensile tests and the full-diameter hose tensile tests are shown in Appendix D.

Eriks hoses:

The Eriks hose samples; their availability was higher in terms of sample resources compared to the Goodridge samples. This allowed for the generation of the largest tensile data. Figure 50 shows the stress-strain plot of seven unaged Eriks samples. The stress-strain curves exhibit typical behavior for polymeric materials: A linear elastic region at the start (approximate strain ≤ 0,1). A yield point followed by a plastic deformation region with a certain plastic modulus. The change of slope from the plastic region to the next is classified as strain hardening up until the ultimate failure point (elongation at break). This general trend or shape of the plot generally returns in every other test run (e.g. 120 °C – 12d etc.). Furthermore, key observations that reoccur for all tested hose samples and types are: The strain at failure varies significantly between samples. Some samples fail at much lower strains (+-1,5) compared to others (+-2,2). The maximum stress also varies between samples, ranging from +-35 MPa to +-45 MPa. The reason for these variations are likely the result of cutting challenges introducing micro-cracks or imperfections, inherent material inconsistencies due to manufacturing, residual stresses from preparation, and potential deviations in testing conditions.

Figure 51 show the stress-strain plot of aged Eriks samples at 250 °C-18 days. It already shows that maximum stress and strain are lower compared to the unaged Eriks samples, but still a significant variation can be seen.

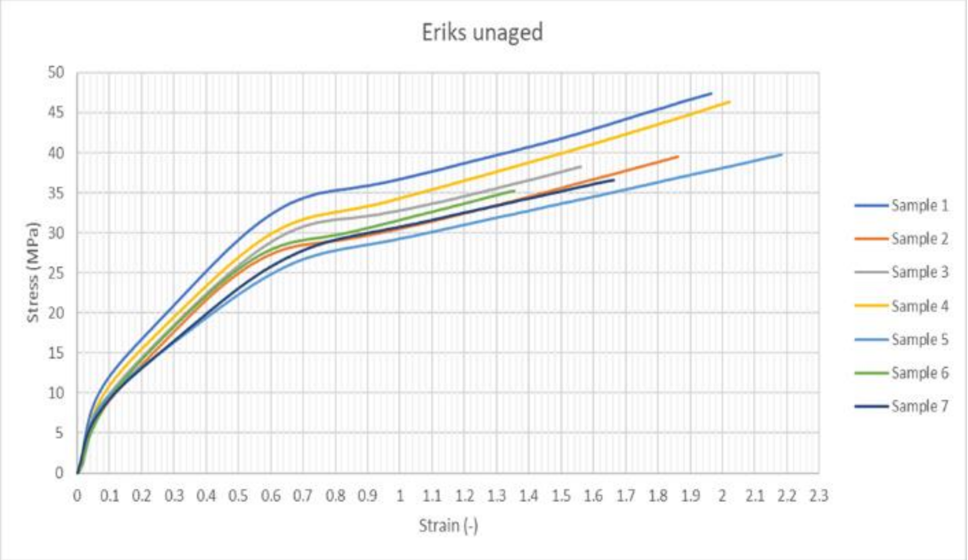


Figure 50: Stress-strain plot Eriks unaged hose samples

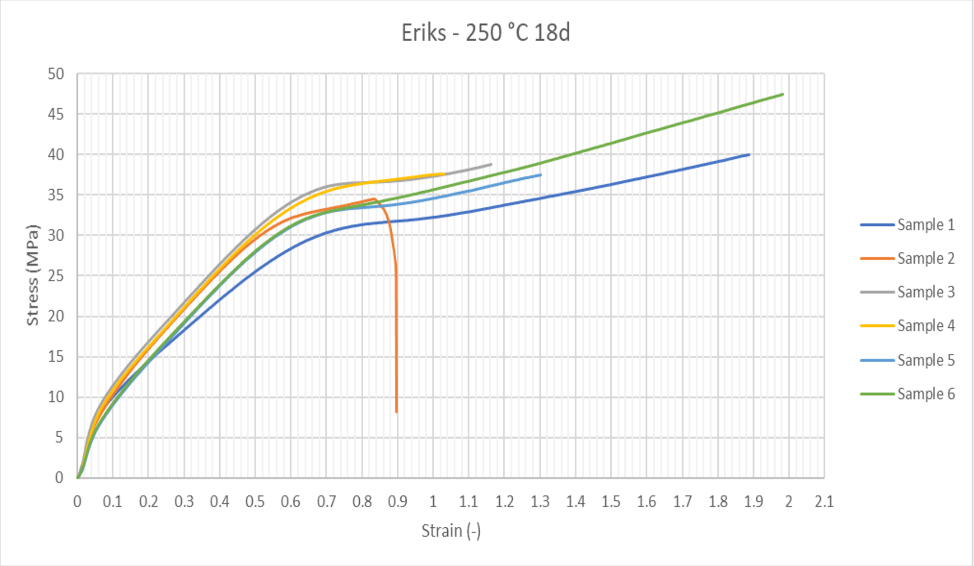


Figure 51: Stress-strain plot Eriks 250°C-18d hose samples

Using the stress-strain data from all aged samples, an average stress-strain plot was constructed, as shown in the Figure 52. Each line represents the average behavior of the Eriks hose samples at a specific aging temperature and duration. Prominent outliers from the raw stress-strain plot data (e.g. Figure 54 and 55) were filtered out while designing the average line plots. The graph focuses on the plastic modulus region, excluding the observations of maximum stress and strain. In the plot, the average stress-strain curves for all aged samples show a shift upward and exhibit a steeper slope compared to the unaged sample. This suggests an increase in stiffness within the plastic deformation region due to aging. This behavior could be due to thermal aging effects, such as crosslinking or changes in the polymer's microstructure, which reduce chain mobility and increase resistance to deformation. However, it is important to note that there does not appear to be a clear correlation between the degree of shift and the aging temperature or duration. While the general trend shows that all aged samples are positioned more upward and left-shifted compared to the unaged sample, the extent of this shift does not consistently increase with higher or more extreme aging conditions.

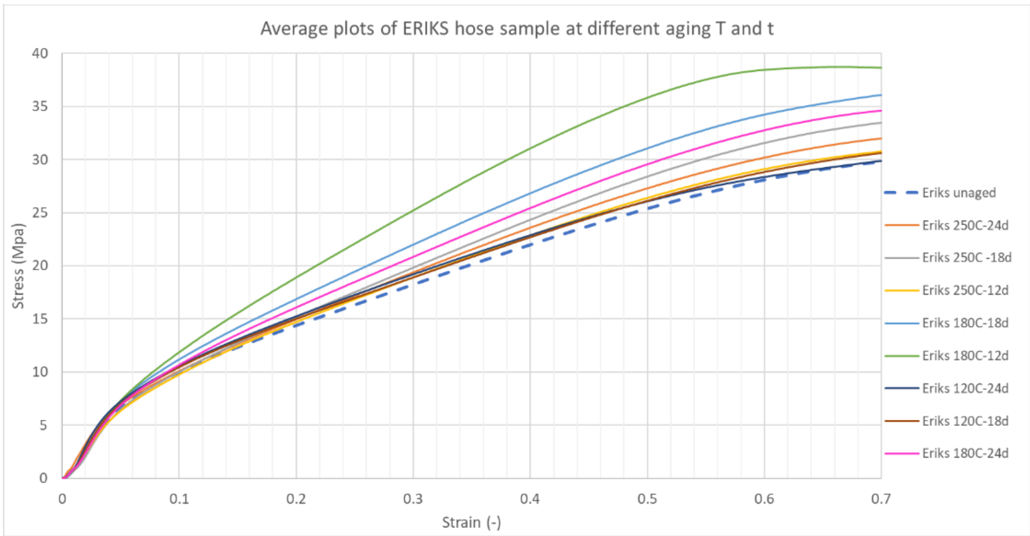


Figure 52: Average stress-strain plots ERIKS hoses

To verify this statement regarding an increase in stiffness in the plastic region, the error bandwidth of the average lines are plotted (see Figure 53 for example). If error bandwidths are clearly separated, then this indicates a statistically significant difference between the stress-strain behavior of the two conditions. In this case, the shift in the plastic modulus or the overall stiffness of the material can be confidently attributed to the aging effects (e.g., temperature, duration) rather than sample-to-sample variability or experimental error.

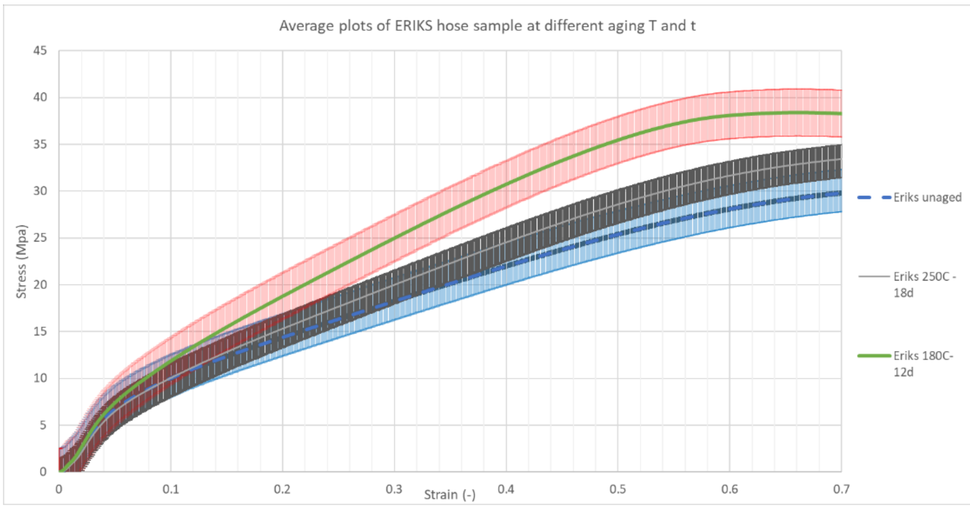


Figure 53: Error bandwidth plot of ERIKS hose samples unaged vs. 180 °C-12d

Next, focusing on the results from the average stress-strain plots and looking at maximum strain and stress. This is presented with the help of column plots.

Maximum strain (Figure 54) decreases significantly after aging, with the unaged samples showing the highest strain (+-175%). Aging reduces strain to +-100–125%, except for the 120°C-24d condition, which stands out as an outlier with a higher strain (+-125%) and large variability.

Maximum stress (Figure 55) generally stabilizes around +-35–40 MPa for most aged conditions, but a slight increase (+-45 MPa) is observed for 120°C aging. However, the large variability in the 120°C-24d condition limits the reliability of this result. At higher aging temperatures, stress values stabilize or slightly decrease, indicating degradation.

The cloud plot (Figure 56) highlights the overall trends, with the unaged sample being an outlier due to its higher strain and moderate stress. Almost all aged samples contain lower strain and stress values, showing a general trend that aging indeed does decrease maximum stress and strain. However, the 120°C-24d condition deviates due to its high variability.

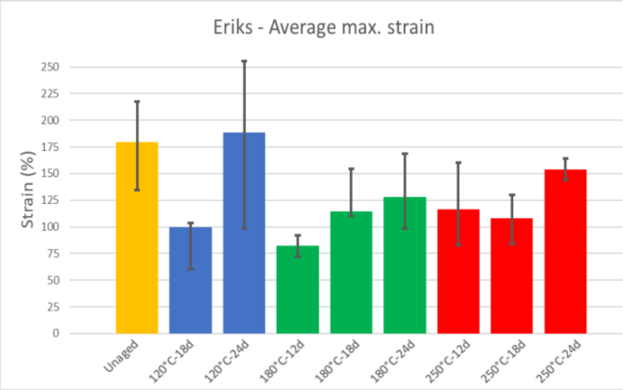


Figure 54: plot - Eriks Average max. strain

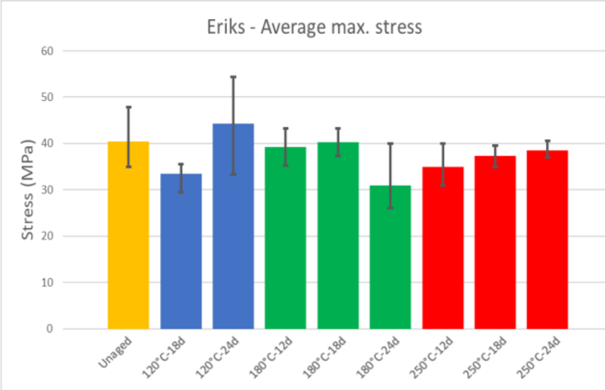


Figure 55: plot - Eriks Average max. stress

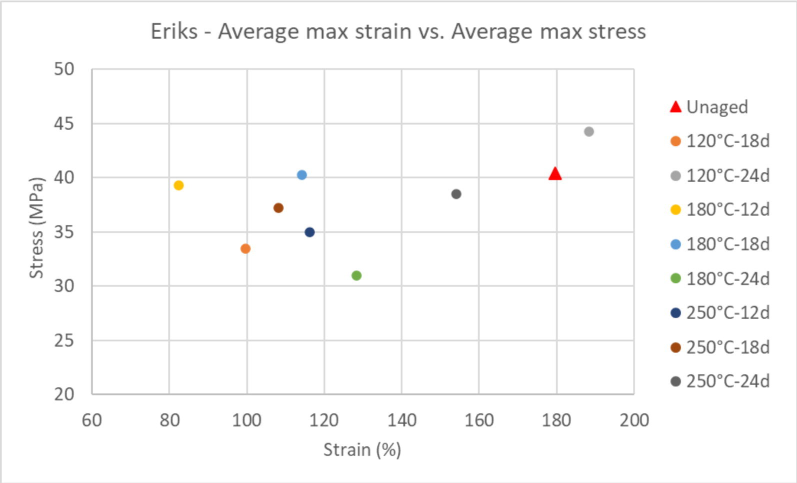


Figure 56: plot - Eriks average max strain vs. stress

However, no clear linear or exponential trend could be observed for the decrease in max. strain and max. stress as aging duration or aging temperature increases. In other words, the extent of this decrease is not consistent with higher or more extreme aging conditions. This acknowledgement is very important as it limits the possibilities for lifetime predictions.

In summary, the main findings:

- Aging reduces ductility (maximum strain), but the 120°C-24d condition shows unusual recovery with high variability.
- Maximum stress slightly increases with low aging at 120°C, but stabilizes or decreases with higher temperatures.
- Aged samples cluster at lower strain and stress values, with the unaged sample as an outlier due to its high ductility.

Goodridge 711 (G711):

The Goodridge 711 hose cut samples exhibit interesting trends in their mechanical properties, particularly when comparing unaged samples, the reference hose from 10-years operational use (REF DH), and hoses subjected to the cyclic loading test. Testing the G711 hose samples was the most insightful since it contains the reference hose from operational use that can be analyzed on degradation parameters.

Particularly the strain hardening region shows a distinct separation of the reference hose and the unaged hose Figure 57. The corresponding column plots and clout plots can be found in Figure 58, Figure 59 and Figure 60. The maximum strain results further highlight these differences. The unaged samples exhibit an average maximum strain of +-240%, with significant variability. The REF DH hose shows a notable reduction in strain (+-170%), likely reflecting long-term aging and operational stress during its service life. However, the cyclically loaded samples display strain values closer to the unaged sample, particularly after 9 cycles, suggesting that short-term cyclic loading may not immediately compromise ductility. The 9 cycles hose samples even indicate a slight increase in terms of maximum strain. However, after 18 cycles, maximum stress and strain slightly decreases, indicating the onset of fatigue effects with prolonged cycling.

The maximum stress results show a more consistent trend across all samples, with values being around +-40 MPa. The unaged sample maintains the highest stress (+-45 MPa), while the REF DH and cyclically loaded samples display a marginal reduction in stress (+-35–40 MPa). This indicates that both long-term use and cyclic loading cause minor reductions in the material's ultimate strength, though the effect is less pronounced compared to the changes in strain.

In summary, the main findings were:

- The REF DH hose, after 10 years of service, exhibits a slight decrease in maximum stress but more significant decrease in maximum strain, indicating degradation over time.
- Cyclic loading causes further softening and a slight decrease in ductility, especially after prolonged cycling (18 cycles).
- Maximum stress is only marginally affected by long-term use or cyclic loading, suggesting the material retains much of its strength despite aging or mechanical fatigue.

Figure 57: Average stress-strain plot G711 hoses

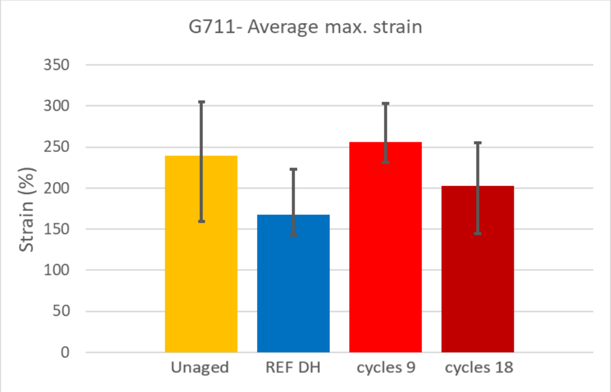


Figure 58: plot- G711 hoses max. strain

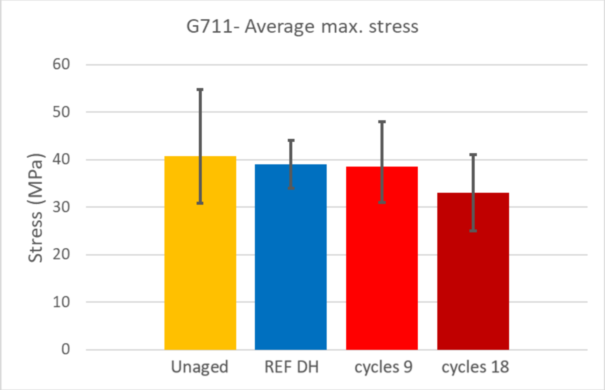


Figure 59: plot- G711 hoses max. stress

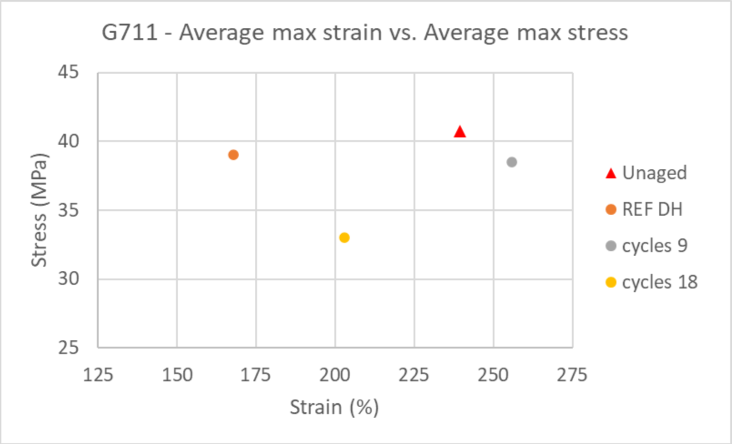


Figure 60; plot - G711 hoses average stress vs. strain

Hardness Test:

Figure 61 shows a column graph representation of the Eriks hose samples tested on hardness. It shows the hardness values for the unaged hose and the aged hoses from the constant temperature test. The result shows that hardness increases for all aged hoses, with a maximum increase of 20,8% for age setpoint 250 °C-24d compared to the unaged hose samples.

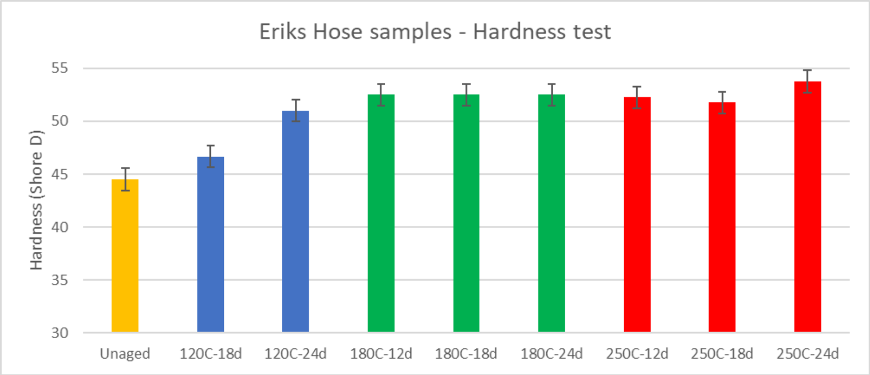


Figure 61: plot - Hardness test ERIKS hose samples

Furthermore, Figure 62 shows a column graph representation of the Goodridge 711 hose samples tested on hardness. It shows the hardness values for the unaged hose, the aged hoses from the constant temperature test, the aged hoses from the temperature cycling test and also includes the reference hose REF DH again. The results shows that hardness increases for all aged hoses, with a maximum increase of 18,2% for age setpoint 250 °C-24d compared to the unaged hose samples. Secondly, hardness increased for the operational reference hose REF DH with 17,1% indicating a quite significant state of embrittlement after operational use. Lastly, the temperature cycling test increased the hardness of the 9-cycle hoses with only 8,3%, while the 18-cycle hoses increased with 18,8%.

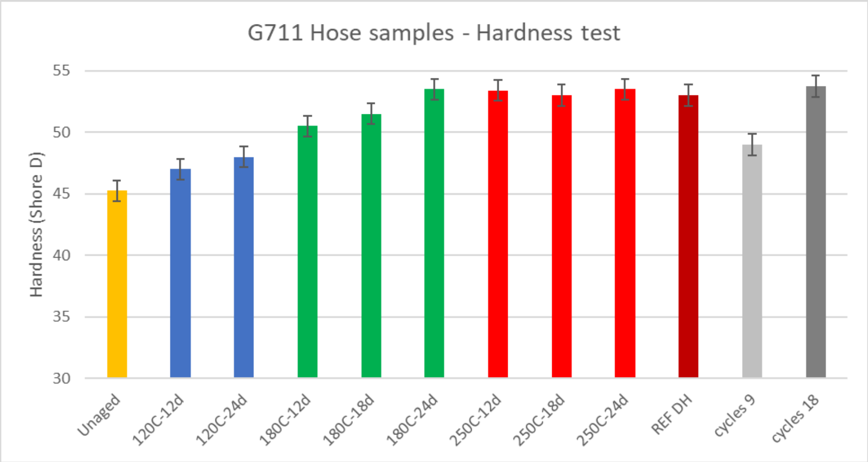


Figure 62: plot - Hardness test G711 hose samples

Both charts show that the hardness of PTFE hoses increases with thermal aging. The unaged sample has the lowest hardness, serving as the baseline. At 120°C, the hardness increases compared to the unaged sample, indicating initial structural changes. Aging at 180°C results in a further increase in hardness, suggesting accelerated material embrittlement. At 250°C, the highest hardness values are observed, with only slight differences between 18 and 24 days, indicating the material is reaching a thermal equilibrium. The reference hose from 10 years in operation shows similar hardness values compared to the range between 180 °C 24-d and 250 °C-24d. The same holds for the 9-cycle hoses, showing similar properties compared to the 120 °C-24d aged samples. However, the 18-cycle hoses tend to show a rapid increase in hardness, reaching the same values as the high range of aged samples (250°C-12d…24d).

Main observations were:

- Overall Trend: Hardness consistently increases with higher aging temperatures and longer durations. This implies that thermal aging leads to progressive material stiffening or embrittlement.
- Saturation Effect: Beyond a certain point (e.g., 180°C, 24 days), the increase in hardness is minimal, suggesting that the material properties are nearing their thermal degradation limits or equilibrium state.

Burst/Leak test:

The burst/leak tests conducted at Eriks Roermond revealed surprising insights into the performance of the Goodridge G-Line Ultra 860 Dash 12 (exposed) hoses. The goal of this test was to gain data on the failure mode and degradation behaviour in terms of burst pressure performance of the hoses before and after accelerated aging. The gathered data regarding change in burst pressure could be utilized in the lifetime prediction model for these hoses. It was hypothesized that the tests would result in the following failure mode: burst in the middle of the hose and that aged hoses show a clear decrease in performance level regarding burst pressure. However, the results presented the couplings as the weakest link in the system.

The tested hoses should withstand a burst pressure of 315 bar according to their specifications. Surprisingly, not a single hose—neither unaged nor aged—reached this expected threshold. In every test run, failure occurred not in the middle of the hose, but at the coupling side where the hose meets the fitting. The coupling relies on the ferrule to grip the hose tightly, exerting a constant compressive force on the stainless-steel braiding and the PTFE liner. However, PTFE has a characteristic, tending to creep under pressure, especially at higher temperatures. This could mean that the tight grip of the ferrule on the hose slowly weakens as the PTFE flows. Aging the hoses at 250°C likely increased this effect. The heat increased the likelihood of the PTFE material creeping, reducing the effective grip of the coupling.

In summary, key observations were as follows:

1. Failure Points:
   - In all cases, the failure occurred at the coupling/fitting rather than the middle of the hose.
   - This highlights the coupling as the weakest component in the assembly rather than the hose material itself.
2. Pressure at Leakage:
   - Unaged Hose: 132 bar.
   - 250°C for 12 Days: 109 bar.
   - 250°C for 18 Days: 150 bar. (potential outlier)
   - 250°C for 24 Days: 71 bar, burst at 180 bar (at the coupling).

Appendix E shows the raw data of the executed burst tests in pressure vs. time graphs. Concluded from the leak pressure values, it can be stated that an increase in aging duration lowers the maximum pressure at leak. Figure 63 shows the moment of failure regarding the unaged hose. Importantly, the three remaining aged hoses did not show such an explosive leak failure but rather an easier, slow leak.

Figure 63: Screenshot of moment of failure during the burst pressure test - unaged G860 hose

The results indicate that thermal aging at 250°C influences the integrity of the fittings more than the hose material. Small differences in crimping pressure, slight variations in the wall thickness of the PTFE liner, or inconsistencies in the density of the stainless-steel braiding can all influence the strength of the coupling. The high aging temperature likely affects the PTFE's creep behaviour, making it more prone to deformation and reducing the retention force of the fitting.

Analysis of Coupling Weakness:

Since the ferrule's teeth primarily grip the steel braiding rather than the PTFE directly, even minor variations in material thickness can cause differences in how securely the hose is held. Moreover, industry standards specify the diameter of the hoses but do not set strict tolerances for the wall thickness. This means that the quality and precision of the PTFE material become crucial factors in determining whether a hose can approach its specified burst pressure. Figure 64 and Figure 65 show the post-mortem photos of the G860 250 °C-24d hose that had its fitting removed after burst.

Figure 64: G860- 250C-24d Coupling removed after burst

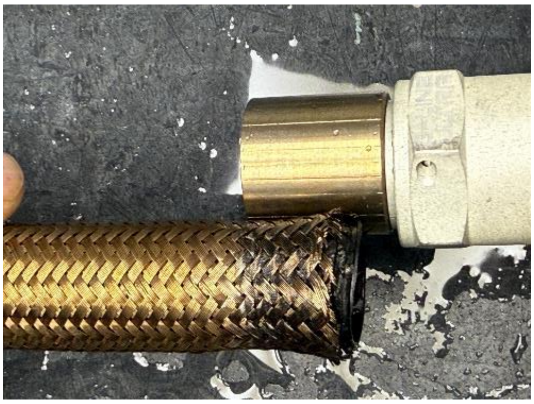


Figure 65: G860 - 250C-24d post-mortem photos

The burst test provided valuable insights, but it also highlights the challenges of testing assemblies where multiple factors come into play. While the hoses themselves may be capable of higher burst pressures, the fittings introduce a vulnerability that can mask the hose's true performance. This finding suggests that to improve reliability, focus must be not just on the hose material but on the entire assembly, particularly the couplings.

Ultimately, the tests demonstrated that high temperatures and pressures put more strain on the couplings than anticipated. The interaction between the PTFE's creep behaviour and the gripping force of the ferrule defines the hose's performance under extreme conditions. Furthermore, thermal aging at 250 °C and for increasing aging durations indicates a decrease in performance level; leak-pressure. With the help of this data, a lifetime prediction model is constructed and described in paragraph 5.4.

5.2 Morphological analysis:

Microscopic Analysis (SEM):

In this section, only the SEM results of the Goodridge 711 hose samples are presented. During the research, Goodridge 860 hose samples were also analyzed. The SEM results of these can be seen in Appendix F.

The 10-years reference hose showed the most interesting morphological results. Notably, it was the only sample to exhibit obvious cracking on the inside surface of the hose, as shown in the SEM image at 50X and 400X magnification (Table 5 and Table 6 respectively).

Table 5: 50x magnification SEM photos REF DH hose

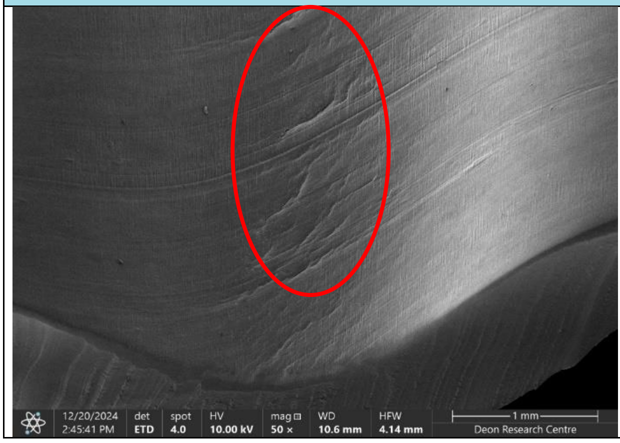
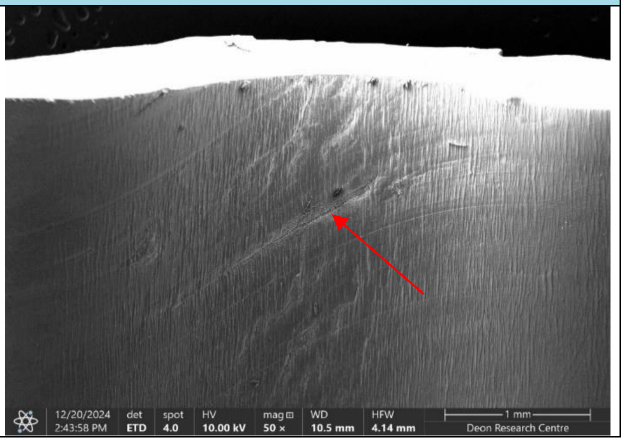
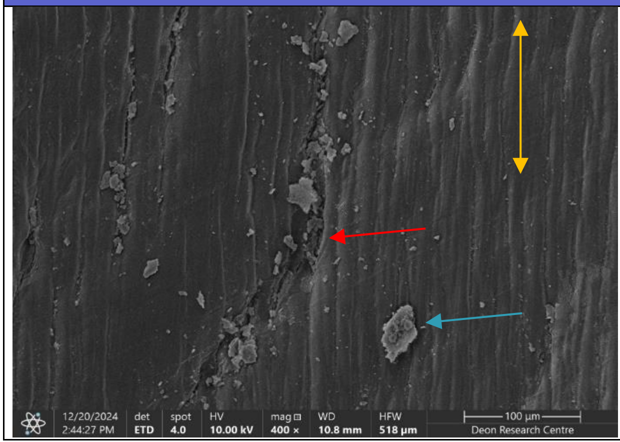
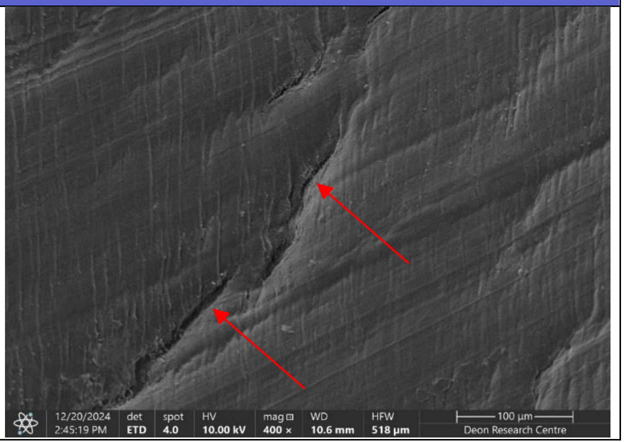
50X	
	

Table 6: 400x magnification SEM photos REF DH hose

400X	
	

To clarify, the red circled area and the red arrow point out specific regions where cracks can be observed at a low magnification of 50X already. Furthermore, the 400X magnification pictures show the obvious appearance of these cracks (red arrows). The yellow double-sided arrow represents a recurring pattern in all analyzed hose samples, which seems to be directional marks from the manufacturing process. The blue arrow highlights dried up residue from the Dowcal coolant fluid that was present in these hoses for 10 years. Figure 66 shows the white residue that could be seen when cutting open the hoses.

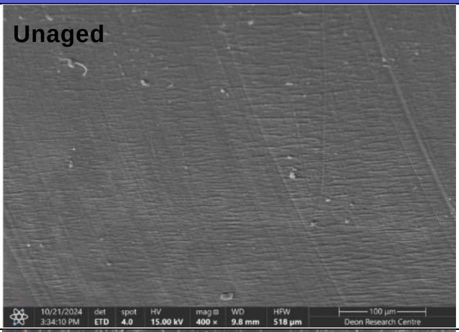
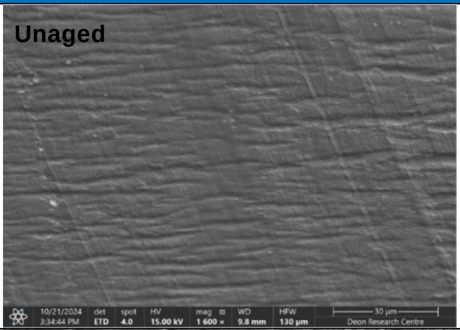
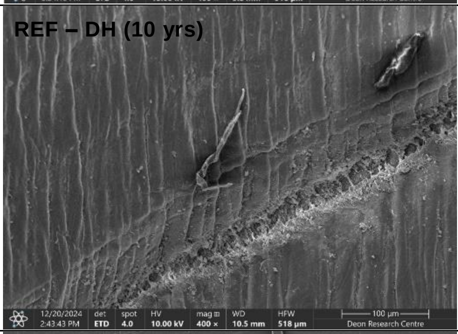
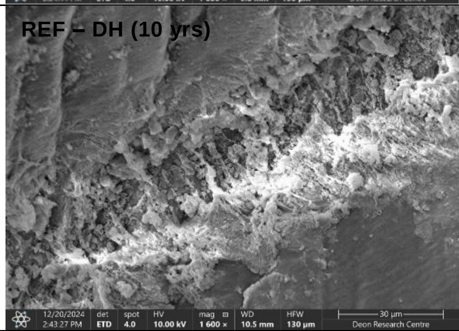
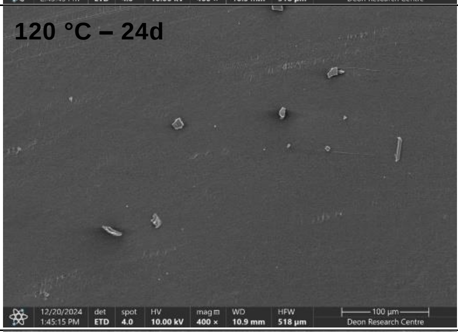
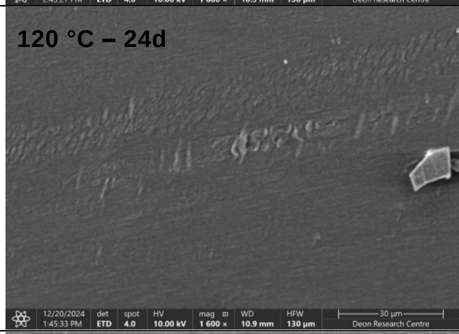
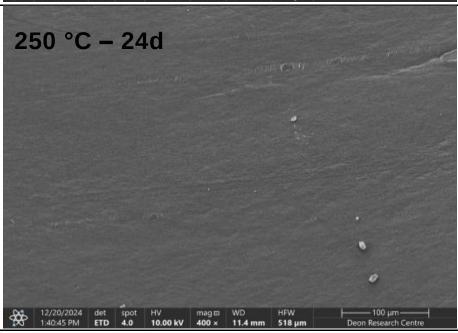
Figure 66: Inside surface of the G711 REF DH hose - Dowcal residue

These cracks likely formed due to the prolonged exposure to the coolant fluid Dowcal over its 10-year operational lifetime. The fluid may have caused chemical interactions or erosion from fluid contamination with the material, contributing to microstructural degradation over time. Another factor to consider is the possibility of human error during the hose's operational or maintenance history, which could have introduced additional stress or damage that contributed to the observed cracks. For example, improper installation, excessive bending, or other handling errors may have created weak points, making the hose more susceptible to cracking over time.

In contrast, Table 7 on the next page shows the SEM results for potential degradation trend for the thermally aged hoses, subjected to controlled conditions at 120°C, 180°C, and 250°C for 24 days. The trend showed no obvious cracking in the SEM images for all accelerated aged hose samples. To elaborate, the aged samples at 250 °C-24d show no pronounced difference in surface degradation compared to the unaged hose samples. This suggests that the controlled thermal aging processes may not fully replicate the combined effects of real-life operational stressors, such as exposure to the coolant fluid, cyclic pressure fluctuations, or environmental conditions experienced by the REF DH hose. These findings highlight the complexity of real-life aging mechanisms compared to laboratory simulations.

Appendix F also includes the SEM results from the temperature cycling test regarding the hoses subjected to 9- and 18 cycles. The results showed that no cracking or signs of degradation could be found for these hoses.

Table 7: SEM results G711 hose samples, 400x and 1600x magnifications

400x	1600x
	
	
	
	
	

5.3 Thermal analysis:

DSC Results:

The DSC analysis (Figure 67) shows that the melting temperatures of PTFE samples aged at 120°C, 180°C, and 240°C for 24 days are quite similar, with minimal variation in peak melting points. This suggests that the thermal properties of the PTFE hoses, such as their melting behaviour, remain largely unaffected by aging under these conditions..

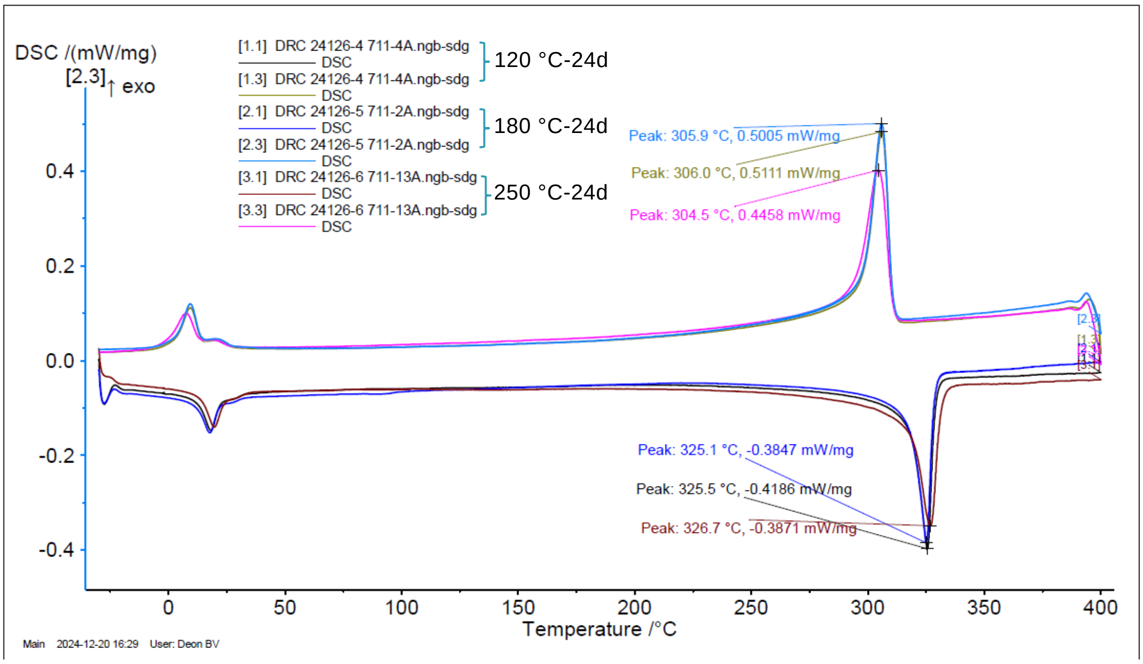


Figure 67: DSC results of G711 hose samples 120C, 180C, 250C at 24d

Furthermore, the unaged samples showed a melting temperature peak at 304,9 °C, which is still an insignificant difference compared to the maximum aged sample of 250 °C -24d. Lastly, the REF-DH hose samples presented a melting temperature of 304,2 °C, which again is an insignificant change compared to the unaged samples.

These results indicate that aging did not significantly influence the thermal stability of the material, supporting the idea that PTFE maintains its thermal characteristics even after prolonged exposure to elevated temperatures.

5.4 Lifetime prediction

Burst pressure model:

The objective of this study is to determine the lifetime of PTFE coolant hoses used in naval environments. The hoses were subjected to thermal aging at elevated temperatures followed by mechanical failure testing under increasing pressure until leakage occurred. The provided dataset included failure pressures for hoses aged for 0 days (unaged), 12 days, and 24 days at 250°C, explained in 5.1.

This paragraph includes the fit of a stress-life model as an approach to predict lifetime. The burst test involved step-stress loading under pressure, while thermal aging was performed in an oven beforehand. Failure was defined as the pressure at which leakage occurred.

The Arrhenius model is commonly used for materials subjected to thermal degradation, where reaction rates accelerate with temperature. However, this model assumes that failure is driven by degradation processes directly linked to time-to-failure measurements. In this study, the hoses were pre-aged thermally and then tested mechanically, separating the aging process from the stress application. Furthermore, the burst pressure test dataset lacks time-to-failure measurements during thermal aging, making the Arrhenius model unsuitable for this analysis.

A fitted stress-life model was selected due to its ability to describe the relationship between failure stress and aging time. The model is expressed as either a linear or exponential approximation. To fit the stress-life model to the experimental burst pressure data (Appendix E), extrapolation methods were used.

Figure 68 shows the graph illustrating the stress-life model fit. The graph shows the relationship between failure pressure and aging time. The red points represent the burst pressure experimental data (unaged, 12-day aged, and 24-day aged hoses). The dashed green curve represents the linear model fit, showing a linear decline in failure pressure as aging time increases. The dashed yellow curve represents the exponential model fit. The exponential model assumedly aligns the best with the expected degradation behaviour. In other words, aging time increases exponentially with lower expected failure pressure. The plot shows fitting the data points with linear and exponential model and extrapolates it to operational pressure of 6 bar, which is used in Thales radar systems.

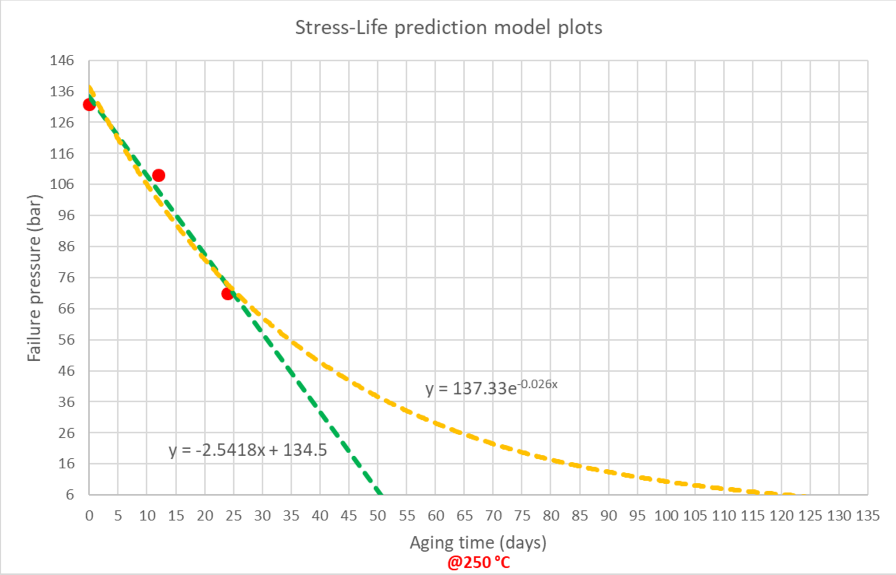


Figure 68: Stress-Life model plots of the burst pressure test results

Using the extrapolation fitted equations for linear and exponential respectively, the expected aging time (x) can be found by substituting the operational failure pressure of 6 bar for (y):

$$6 = -2{,}5418 * x + 134{,}5$$

$$6 = 137.33 * e^{-0{,}026*x}$$

This results in an aging time (x) of 50,55 days for the linear model and 120,41 days for the exponential model.

However, the calculated aging time life's corresponds to the operational pressure of 6 bar while aged at 250°C. Since the operational temperature is rather 30 °C (see Failure analysis; Loads 3.1), the life prediction at 6 bar could be considered conservative if the temperature is much lower than the aging temperature (250 °C). In other words, at 30 °C, the thermal degradation rate is significantly slower than at 250 °C. Therefore, the degradation process at 30 °C is much less severe, meaning the hose lasts significantly longer and thus further corrections were made.

Temperature Correction via Arrhenius Model:

To adjust for the lower operational temperature effects, the stress-life model is combined with an Arrhenius-type factor for temperature dependency. The corrected failure time (tf) can be calculated via:

$$tf_{corrected} = tf * AF$$

In traditional reliability tests, the relation between AF (Acceleration Factor) and Ea (Activation Energy) is found by using the Arrhenius model.

$$AF = e^{\frac{E_a}{R}\left(\frac{1}{T_{operational}} - \frac{1}{T_{aging}}\right)}$$

The activation energy represents the energy barrier that must be overcome for the degradation reactions to occur in the PTFE material. In this study, no specific value for Ea has been found as it needs the ALT approach (measuring time-to-failure), which was not feasible (see 4.1.).

An alternative way of calculating AF is used. With the help of the 10-years reference hose REF DH, it was found that aging of 250°C-24d shows the closest similar properties regarding stress, strain and hardness compared to REF DH. Therefore, AF can be calculated by dividing the time it took for the REF DH hose to reach these property values, by the time it took at 250°C at an accelerated test time of 24 days. This results in an AF of 152,08 (Activation energy of 30,1 kJ/mol). In other words, it means that the accelerated aging process at 250°C is 152 times faster than at 30°C to reach the same material properties.

Another way to find a proper value for AF is by revisiting the Thales temperature cycling calculation sheet, it was stated that they utilize an acceleration factor of 2 for every 10°C increase. In this case, that would result in an AF of 4194304 (Ea = 91 kJ/mol). This shows that degradation rate is 4194304 times slower at 30°C compared to 250°C.

Data in literature regarding thermal degradation of PTFE also utilizes these ranges. Values for Ea range from 40-60 kJ/mol for wear by thermoactivation mechanisms [67]. On the extremes, the strongest C-F bonds of PTFE begin to break at around 400-500 kJ/mol. But at this point, the PTFE hose would already have lost it integrity and leak would have already occurred.

Table 8 presents the results of the corrected failure time (tf) using the conservative, low bound AF of 152,08 (activation energy of 30,1 kJ/mol). This would result in a predicted hose failure time of +-21 years regarding the linear model and +-50 years regarding the exponential model.

Table 8: Life prediction in years for the different models

Model	Tf (years)	Tf_corrected (years)
Linear	0,138 (50,55 days)	21,05
Exponential	0,330 (120,41 days)	50,14

It is expected that the PTFE hoses follow an exponential behaviour regarding degradation affecting failure pressure. Thus it shows that time to failure of the hose under operational conditions of 6 bar and 30°C is roughly 50 years. Naturally, finding a more exact value for Ea will result in a better prediction for tf with lower variability.

Alternatively, attempts have been made regarding extrapolation methods to predict degradation properties after certain years. It utilizes the measured mechanical properties of the unaged hose and the reference 10-years operational hose. The method should be treated with caution as such a small dataset is used. Therefore, no confident conclusions could be drawn from this method. Appendix G presents the extrapolation method and explains the limitations.

6. Discussions and limitations

This chapter discusses the results and mentions the limitations that were found during this research. The descriptions are divided per specific subject that needs discussion.

Failure Data:

- In terms of limitations, no company data is available regarding previous coolant hose failures. This means that during the operational life of a typical radar (30-35 years), no hose failure occurred. There have only been reports of problems with the couplings and rust on the stainless steel braiding of the hose.

Thermal Aging Focus

- The research focused exclusively on thermal aging of PTFE hoses. While this approach provides insight into thermal degradation mechanisms, it does not account for the combined effects of chemical, mechanical, and environmental stresses encountered in operational conditions.
- The thermal aging tests were conducted at elevated temperatures to accelerate degradation. However, the activation energy (Ea) used in the Arrhenius-based life prediction model needs better accuracy. Additional tests, such as prolonged aging at intermediate temperatures, are necessary to refine the Ea and improve the reliability of lifetime predictions.

Accelerated Aging Test Limitations

- The heat aging oven used in this study was limited to a maximum temperature of 250°C. This may have restricted the extent of aging effects observed, as higher temperatures could potentially yield more prominent degradation results. Consequently, could this result in more prominent observations of a certain degradation trend when aging temperatures and durations increase.
- The burst pressure test for hoses only included a single sample per data point. This introduces significant variability and limits statistical confidence in the results. A larger sample size would give more robust data to support conclusions about the degradation trends.

Environmental and Operational Considerations

- Cold environments and their effects on PTFE hoses remain unexplored. It is unclear whether such conditions could exacerbate degradation, particularly through thermal cycling-induced stress or embrittlement.
- Chemical interactions and fluid contaminations between Dowcal fluid and the PTFE liner during thermal cycling are not well understood. While no cracks were observed in the accelerated aging tests, real-life exposure to coolant fluids and temperature cycling may introduce additional degradation mechanisms. An example of this is perfectly presented by the reference hose REF DH, which was the only hose which showed presence of microcracks compared the accelerated aging samples.

Mechanical Analysis Observations

- For all hose types, aging overall reduces ductility (maximum strain), decreases maximum stress, causes increase in hardness, however reaching a plateau and causes increased stiffness in the plastic deformation region. However, no consistent correlation was found between aging conditions and the degree of degradation, complicating trend analysis.

- The variability in results (e.g., 120°C-24d condition) underscores the potential need for larger sample sizes and improved test controls. It also indicates that no prominent trend in mechanical properties can be observed
- From the burst pressure test, the findings suggest that coupling failure, not hose material degradation, is the primary factor limiting the operational lifespan of the assembly. This shifts the focus from hose material properties to coupling design improvements for long-term performance.

Morphological Analysis

- SEM analysis revealed no cracking in thermally aged hoses, even at 250°C for 24 days. In contrast, the reference hose exhibited cracks likely caused by long-term exposure to coolant fluid and operational stress.
- These findings emphasize that thermal aging alone does not fully replicate real-life degradation, indicating a need for combined stress simulations.

Interpretation of Lifetime Prediction Models

- The stress-life model provided a baseline prediction for the operational lifetime of PTFE hoses. However, the limited dataset, the approximation for exponential behaviour and a rough estimation for the acceleration factor (AF) reduces confidence in the model's accuracy.
- The predicted lifetime only accounts for temperature as the degradation agent and uses mechanical burst pressure testing to verify change in performance levels.
- The Arrhenius correction for temperature effects produced widely varying acceleration factors (AFs), depending on the assumptions used. The lower bound (AF = 152) suggests realistic conservative estimates, while the higher bound implies almost infinite lifetime for the hoses.
- The lack of clear degradation trends in mechanical properties further complicates the use of predictive models based on these tests. The findings from the reference hose offer some insights but remain limited due to the small dataset.
- The high predicted lifetime of the coolant hoses emphasizes the criticality of human error induced failures. Wrong handling or installation of the hoses could potentially be more critical regarding its lifetime.

7. Conclusions and recommendations

This thesis investigated the degradation behaviour, failure mechanisms, and lifetime prediction of PTFE coolant hoses used in Thales radar systems under thermal aging conditions. While the results provide valuable insights, key limitations in the testing and analysis methods were acknowledged.

Thermal aging is induced by focussing on accelerated temperature test approaches. Temperature stresses were selected with a constant and cycling approach. Thermal aging leads to increased stiffness and hardness in the PTFE material, reducing its ductility. However, the study did not establish a clear linear or exponential relationship between aging conditions and mechanical property degradation, which limits the direct applicability of predictive lifetime models.

One of the most significant findings of this research is that coupling failure due to PTFE material degradation, represents the primary limitation in the operational lifespan of PTFE hoses. Burst pressure tests consistently showed failures occurring at the coupling rather than in the middle of the hose. Thermal aging further exacerbated this issue, weakening the PTFE-coupling interface and reducing burst pressure. A trend reduction in performance levels could be observed with increasing aging magnitude. With the help of the burst pressure test, a lifetime prediction model could be fitted.

Lifetime prediction using a stress-life model, combined with Arrhenius-based temperature corrections, provided an estimated operational lifetime of 50 years at 6 bar and 30°C. However, the limited data of the burst pressure results, coupled with uncertainties in activation energy calculations, reduces the confidence in this estimate. Additionally, the analysis of a reference hose that had been in service for 10 years revealed degradation patterns that were not replicated in the controlled thermal aging tests as morphological analysis revealed no visible surface cracks in the thermally aged hoses. This suggests that thermal aging alone may not fully replicate real-life degradation mechanisms. Thus, operational factors, such as chemical interactions with coolant fluids, cyclic loading, and environmental conditions, play a crucial role in long-term hose degradation, necessitating further investigation.

In the end, this study demonstrates that the lifetime of the PTFE coolant hoses in application for Thales is roughly 50 years. This approximation is based on thermal aging effects being the dominant failure mechanism. However, the results of this research indicate that the degradation behaviour of PTFE coolant hoses is not primarily influenced by thermal aging, but also fluid effects, and coupling performance. Thereby, the main research question ‘’What is the lifetime and degradation behaviour of PTFE coolant hoses?’’ is addressed. The findings of this study are expected to contribute to the development and optimization of Thales’ replacement policies for PTFE coolant hoses. Figure [redacted] concludes the findings in operational context for Thales. It shows that a typical end of life for a radar system is around 30-35 years. During this lifecycle, overhauls take place roughly every 10-12 years. Alignment of the overhaul activities with hose replacement was stated to be efficient in the beginning of this study. However, the results of the study does not indicate that the hoses (exposed or sheltered) are expected to fail before 30-35 years. They rather do not need replacement during overhaul as they outlive the typical lifetime of a radar system. In other words, it suggests that the hoses are never to be replaced since the expected lifetime is roughly 50 years. Naturally, this only holds true if the hoses show no sign of significant degradation due to other effects (kinking, wrong installation etc.) that is to be observed during the health checks every one or two years. The figure also presents the other critical activities that align with the radar overhaul period.

Recommendations:

No guarantee can be given for the estimated 50 years lifetime of the PTFE hoses. The actual lifetime of PTFE hoses in operational conditions may be significantly longer due to lower degradation rates (AF) at the low operational temperatures. On the other hand, the estimated lifetime could also be shorter due to other effects (kinking, wrong installation, erosion). These effects are not studied during this research and could be a continuation to find a more detailed prediction for the lifetime of PTFE hoses. Future research could focus on larger sample sizes, intermediate aging temperatures, and combined chemical, mechanical, and thermal stress tests to better simulate real-life conditions. Improvements in coupling design and manufacturing precision are also essential.

This study provides a foundational understanding of PTFE hose degradation in naval radar systems, highlighting both the material's resilience and the assembly's vulnerabilities. While the findings offer preliminary insights into lifetime performance, further research is required to fully quantify and optimize hose reliability in operational environments.

8. Bibliography

[1] Wikipedia, “Thales Group,” https://en.wikipedia.org/wiki/Thales_Group.

[2] R. P. Brown, *Practical Guide to the Assessment of the Useful Life of Rubbers*. Rapra Technology Limited, 2001. Accessed: Dec. 31, 2024. [Online]. Available: https://www.smithers.com/home

[3] Wikipedia, “SMART-S Mk2,” https://en.wikipedia.org/wiki/SMART-S_Mk2.

[4] All Hose & Valves, “What are the Different Types of Industrial Hoses?,” https://www.allhose.com.au/different-types-of-industrial-hoses/.

[5] I. Proco Products, “Why Braided Pipe Connectors Are the Best Option for Vibration Control,” https://empoweringpumps.com/proco-why-braided-pipe-connectors-are-the-best-option-for-vibration-control/.

[6] Eleena Aqmal Binti Ab Rahim, “Simulation Study on Braided Hose Failure in Major Equipment at PETRONAS Carigali Sdn Bhd (PCSB),” Universiti Teknologi PETRONAS, 2015.

[7] Tony Fluid, “Composition and Application of Flexible Metal Hose,” https://www.tonyfluid.com/article/composition-and-application-of-flexible-metal-hose.html.

[8] Wikipedia, “Metal hose,” https://en.wikipedia.org/wiki/Metal_hose?

[9] Precision Hose & Expansion Joints, “STRIPWOUND METAL HOSE BY PRECISION HOSE & EXPANSION JOINTS,” https://www.precisionhose.com/products/stripwound-metal-hose/.

[10] Qianli, “Light duty Annular Corrugated Flexible Hose,” https://www.stainlesssteelbraidedhose.com/annularcorrugated/low-pressure-hose.html.

[11] Velon, “How to Understand Hose Performance from Basic Parameters,” https://www.velonhose.com/News/how-to-understand-hose-performance-from-basic-parameters.

[12] Wikipedia, “Polytetrafluoroethylene,” https://en.wikipedia.org/wiki/Polytetrafluoroethylene.

[13] Kingdaflex, “PTFE Hose: The Things You Need to Know About PTFE Hose,” https://kingdaflex.com/ptfe-hose/.

[14] Chemours, “The History of Teflon™ Fluoropolymers,” https://www.teflon.com/en/news-events/history.

[15] Hoseflex, “PTFE HOSE.” [Online]. Available: www.hoseflex.com

[16] E. Dhanumalayan and G. M. Joshi, “Performance properties and applications of polytetrafluoroethylene (PTFE)—a review,” *Adv Compos Hybrid Mater*, vol. 1, no. 2, pp. 247–268, Jun. 2018, doi: 10.1007/s42114-018-0023-8.

[17] W. U. Kun, fan Yaqin, shen Qian, miao Zhuang, and zhou Cheng, “Study on aging state and life prediction of PTFE seals for nuclear power stations (China）,” *CHINA PLASTICS*, Oct. 2022.

[18] Eaton, “Aeroquip performance hoses,” https://www.eaton.com/sg/en-us/catalog/hose-tubing-fittings-and-connectors/performance-racing-hoses.html.

[19] Goodridge, “Goodridge Parts Catalogue,” 2020.

[20] M. Taherzadehboroujeni, R. Kalhor, G. B. Fahs, R. B. Moore, and S. W. Case, “Accelerated testing method to estimate the long-term hydrostatic strength of semi-crystalline plastic pipes,” *Polym Eng Sci*, vol. 60, no. 5, pp. 879–888, May 2020, doi: 10.1002/pen.25087.

[21] U. Schulte, “A vision becomes true-50 years of pipes made from High Density Polyethylene,” 1953.

[22] D.G. Collingwood M.A. and A.M.I.Mech.E., “An Introduction to P.T.F.E. Hose: A Description of the Development and Production of Palmer Fluoroflex Polytetrafluoroethylene Hose for Aircraft Hydraulic Systems,” *Aircraft Engineering and Aerospace Technology*, Jan. 1963.

[23] Research and Markets, “PTFE Market by Form, Application, End Use Industry and Region - Global Forecast to 2029,” Aug. 2024.

[24] Wikipedia, “Per- and polyfluoroalkyl substances,” https://en.wikipedia.org/wiki/Per-_and_polyfluoroalkyl_substances?

[25] Juliana Montoya, “Advances in PTFE Recycling,” https://www.plasticsengineering.org/2024/08/advances-in-ptfe-recycling-006350/.

[26] H. B. Mayya, D. Pai, V. M. Kini, and N. H. Padmaraj, “Effect of Marine Environmental Conditions on Physical and Mechanical Properties of Fiber-Reinforced Composites—A Review,” Jun. 01, 2021, *Springer*. doi: 10.1007/s40032-021-00676-w.

[27] Seven Seas Machinery L.L.C., “How Climate Conditions Affect: Marine Equipment Maintenance,” https://ssmachin.com/marine-equipment-maintenance/.

[28] F. Barutzki, I. Tamura, M. Kuramasu, and S. Kaneko, “PROTECTION OF PIPING SYSTEMS AGAINST OPERATIONAL VIBRATION AND SEISMIC EXCITATION BY MEANS OF VISCOELASTIC FLUID DAMPERS,” *17th World Conference on Earthquake Engineering,* vol. 17, no. 2, Sep. 2020.

[29] F. Kai, S. Zhiyong, P. Ming, W. Yadong, and D. Chaohui, “Life prediction method for aviation steel wire reinforced fluoroplastic hose under impulse load,” *NOISE AND VIBRATION CONTROL*, vol. 43, Apr. 2023, doi: 10.3969/j.issn.1006-1355.2023.02.044.

[30] F. Kai, S. Zhiyong, G. Kai, W. Yadong, and D. Zhaohui, “Numerical Study on the Reliability of PTFE Hose in Aeroengine,” *NOISE AND VIBRATION CONTROL*, vol. 44, Apr. 2024, doi: 10.3969/j.issn.1006-1355.2024.02.033.

[31] Y. V Sytyi, M. M. Gudimov, A. I. Soshko, A. N. Tynnyi, and N. G. Kalinin, “INVESTIGATION OF CRACKING OF TEFLON HOSES,” 1970.

[32] J. Yao, X. Li, Y. Ren, M. Li, S. Yang, and D. Wang, “An Analytical Model for The Capacitance of Stainless Steel Braided Reinforced Teflon Aviation Hoses,” *International Journal of Pressure Vessels and Piping*, Mar. 2023, doi: 10.21203/rs.3.rs-2658651/v1.

[33] Z. Longchao, L. Xinhao, Y. Jing, Y. Shuai, and Z. Qianrui, “Study on pressure pulsation characteristics of aviation stainless steel braided hose; Chinese,” *Machine tool & hydraulics*, vol. 51, no. 14, Jul. 2023.

[34] X. Wang, S. Xi, and Y. Chen, “A dangerous type of failure mode of aircraft PTFE hose assembly and reliability measures,” in *Proceedings of 2012 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering, ICQR2MSE 2012*, 2012, pp. 1309–1313. doi: 10.1109/ICQR2MSE.2012.6246462.

[35] R. M. Schisla, S. C. Ernst, and P. N. Lodal, “Case history: PTFE-lined pipe failure,” *Process Safety Progress*, vol. 21, no. 1, p. 26, 2002, doi: 10.1002/prs.680210107.

[36] B. Gao, A. Zhang, K. Lu, and H. Y. Liu, “Failure analysis of polytetrafluoroethylene lined pipe under thermal shock,” *International Journal of Pressure Vessels and Piping*, vol. 201, Feb. 2023, doi: 10.1016/j.ijpvp.2022.104871.

[37] G. Joseph, “Chlorine transfer hose failure,” in *Journal of Hazardous Materials*, Nov. 2004, pp. 119–125. doi: 10.1016/j.jhazmat.2004.06.010.

[38] WMT, “Frequently Asked Questions about hose assemblies,” https://www.wmtonline.eu/en/products/hose-assemblies/hose-assemblies-faq/.

[39] Parker Hannifin, “Off the shelf PTFE Hose Assemblies.” Accessed: Jan. 05, 2025. [Online]. Available: https://www.parker.com/content/dam/Parker-com/Literature/Stratoflex-Products-Division/SPD_-PTFE-Hose-Assemblies-(OTS).pdf

[40] XU Yijun, “Preliminary Study of structural integrity requirements for aero engine ducts (CHINES; Translated),” *Aero Engine*, vol. 3, pp. 53–62, 1994.

[41] Forum member, “Teflon Hoses , proof that they are ‘on condition,’” Feb. 13, 2023, *MooneySpace*.

[42] Forum member, “Stainless steel hose life expectancy?”

[43] Australian Government - Civil Aviation Safety Authorithies, “AIRWORTHINESS BULLETIN: Flexible Hose Assemblies - Maintenance Practices,” May 2015.

[44] Textron Lycoming and FAA Approved, “Aeroquip Service Bulletin No. AA135,” May 1993.

[45] J. R. Cho, Y. H. Yoon, C. W. Seo, and Y. G. Kim, “Fatigue life assessment of fabric braided composite rubber hose in complicated large deformation cyclic motion,” *Finite Elements in Analysis and Design*, vol. 100, pp. 65–76, Aug. 2015, doi: 10.1016/j.finel.2015.03.002.

[46] S. B. Kwak and N. S. Choi, “Micro-damage formation of a rubber hose assembly for automotive hydraulic brakes under a durability test,” *Eng Fail Anal*, vol. 16, no. 4, pp. 1262–1269, Jun. 2009, doi: 10.1016/j.engfailanal.2008.08.009.

[47] H.-E. Kim, Y.-B. Lee, and Y.-I. Kwon, “Life Prediction of High Pressure Hydraulic Hose Assemblies by the Impulse Test,” *Corrosion sciende and technology*, vol. 3, pp. 209–215, 2044.

[48] Wikipedia, “Accelerated life testing,” https://en.wikipedia.org/wiki/Accelerated_life_testing.

[49] W. B. Nelson, *Accelerated Testing - Statistical Models, Test Plans, and Data Analysis*. John Wiley & Sons Inc., 1990.

[50] J. A. . McLinn, *Practical accelerated life testing.* Reliability Division, ASQ, 2000.

[51] P. C. Lee *et al.*, “Durability and Service Life Prediction of Fluorocarbon Elastomer under Thermal Environments,” *Polymers (Basel)*, vol. 14, no. 10, May 2022, doi: 10.3390/polym14102047.

[52] D. H. Collins, “Accelerated Test Methods for Reliability Prediction.” [Online]. Available: www.lanl.gov/orgs/adtsc/publications.php

[53] N. T. Chinh and T. Hoang, “LIFE-TIME PREDICTION FOR POLYMER MATERIALS,” Oct. 26, 2021, *Publishing House of Natural Science and Technology, VAST*. doi: 10.15625/2525-2518/59/5/16057.

[54] D. M. C. Ruz, H. C. Pedersen, J. Liniger, M. Bhola, and G. Wrat, “A Review of State of the Art for Accelerated Testing in Fluid Power Pitch Systems,” May 30, 2024. doi: 10.20944/preprints202405.2070.v1.

[55] A. Plota and A. Masek, “Lifetime prediction methods for degradable polymeric materials—a short review,” Oct. 02, 2020, *MDPI AG*. doi: 10.3390/ma13204507.

[56] S.-B. Kwak, N.-S. Choi, B.-S. Kang, and S.-M. Shin, “Characteristic Accelerated Aging Assessment for Coolant Rubber Hose of Automotive Radiator,” *Department of Mechanical Engineering, Hanyang University*, May 2006.

[57] S. W. Han, S. B. Kwak, and N. S. Choi, “Accelerated life prediction of ethylene-propylene diene monomer rubber subjected to combined degradation,” *Transactions of the Korean Society of Mechanical Engineers, A*, vol. 38, no. 5, pp. 505–511, 2014, doi: 10.3795/ksme-a.2014.38.5.505.

[58] X. L. Huang, J. Martinez-Vega, and D. Malec, “Morphological evolution of polytetrafluoroethylene in extreme temperature conditions for aerospace applications,” *J Appl Polym Sci*, vol. 131, no. 3, Feb. 2014, doi: 10.1002/app.39841.

[59] V. Henri, E. Dantras, C. Lacabanne, A. Dieudonne, and F. Koliatene, “Thermal ageing of PTFE in the melted state: Influence of interdiffusion on the physicochemical structure,” *Polym Degrad Stab*, vol. 171, Jan. 2020, doi: 10.1016/j.polymdegradstab.2019.109053.

[60] F. Qu *et al.*, “Effect of thermal oxidative ageing on the molecular structure and tribological properties of polytetrafluoroethylene,” *Tribol Int*, vol. 188, Oct. 2023, doi: 10.1016/j.triboint.2023.108850.

[61] CP Lab Safety, “PTFE and Teflon Chemical Compatibility,” https://www.calpaclab.com/teflon-ptfe-compatibility/.

[62] Polyfluor, “Chemical resistance PTFE,” https://www.polyfluor.nl/en/chemical-resistance/ptfe/.

[63] The plastic shop, “Virgin PTFE - Detailed Technical Information,” https://www.theplasticshop.co.uk/ptfe-technical-information.html.

[64] Eriks, “Slang Eriflon F511 AS,” https://shop.eriks.nl.

[65] M. Meyer, “PTFE-A Fascinating Polymer Investigated by Advanced Thermal Analysis Techniques.” [Online]. Available: www.netzsch.com

[66] R. El Aidani, P. I. Dolez, and T. Vu-Khanh, “Effect of thermal aging on the mechanical and barrier properties of an e-PTFE/Nomex® moisture membrane used in firefighters' protective suits,” *J Appl Polym Sci*, vol. 121, no. 5, pp. 3101–3110, Sep. 2011, doi: 10.1002/app.33991.

[67] V. A. Smurugov, A. I. Senatrev, V. G. Savkin, V. V Biran, and A. I. Sviridyonok, “On PTFE transfer and thermoactivation mechanism of wear,” 1992.

[68] V. Laan, “Engineering Analysis Report; Cooling and Drying system Smart-S Mk2 Naval 3D Search Radar,” Hengelo.

Appendix A

Figure 1 displays the total literature review matrix that has been strategically used.

		Degradation agent researched												Analysis used	
Reference	Material	Static Pressure	Pressure pulsing	Static Temperature	Temperature cycling	Vibrations	Static Bending radii / Shapes	Cyclic large deformations	Chemical degradation	Ozone	Salt	ECD	Oxygen aging	Tensile / strain tests	Microscopic analysis
Lee et al. (1)	N.A. (no access)	x		x											
Kim et al (2)	Rubber	x	x					x							
Kwak et al. (3)	Rubber			x					x	x		x	x	x	
Kwak et al. (4)	Rubber			x									x	x	x
Wook et al. (5)	Rubber			x								x		x	
Kai et al. (6)	PTFE	x	x	x		x	x								x
Cho et al. (7)	Rubber							x						x	
Eleena Aqmal (8)	PTFE	x					x								
Sytyi et al. (9)	PTFE				x										x
Gao et al. (10)	PTFE			x	x									x	x
Yao et al. (11)	PTFE	x												x	
Drumond et al. (12)	PTFE	x				x	x		x						
Taherzadehboroujeni et al. (13)	HDPE	x		x										x	x
Cho et al. (14)	Rubber							x							
Longchao et al. (15)	PTFE		x			x									
Zhou et al. (16)	Rubber	x													
Kai et al. (17)	PTFE & rubber	x	x											x	
Entwistle (18)	Rubber	x												x	
Lee et al. (19)	Rubber			x										x	x
Kwak et al. (20)	Rubber		x					x							x
Hachemi et al. (21)	Steel													x	
Lee et al. (22)	Rubber		x												x

Figure 1: Literature review matrix

Appendix B

Figure 2 shows the full FMEA diagram. Thermal aging is located within the red cell, indicating the highest RPN score.

Component	Function	Sub-component	Potential failure mode	Potential failure effects	SEV	Potential causes	OCC	Current process controls	DET	RPN
			In what ways can the item fail?	*What is the impact if the failure mode is not prevented or corrected?*	*10*	*How could the failure mode occur?*	*10*	*What are the existing controls that either prevent the failure mode from occurring or detect it should it occur?*	*10*	***1000***
Hose	*Pressure maintenance, fluid transport and flexibility*	**Fibre braiding**	Fracture	Loss of structural integrity	4	Corrosion	10	Use different material or clean the hose	5	200
		Fibre braiding	Fracture	Loss of structural integrity	7	Inadequate maintenance	6	Follow maintenance periods and manuals	3	126
		Fibre braiding	Fracture	Loss of structural integrity	8	Pressure pulsing fatigue	2	Gradual pressure change	5	80
		Fibre braiding	Fracture	Loss of structural integrity	8	Abrasion	2	Use abrasion sleeve or fixed adapters	4	64
		Fibre braiding	Fracture	Loss of structural integrity	8	Surface wear due to vibration	2	Use dampening fasteners	6	96
		PTFE inner liner	Leaking	Fluid pressure loss	8	Kinking	4	Follow installation guidelines and handle with care	9	288
		PTFE inner liner	Leaking	Fluid pressure loss	8	Twisting	4	Follow installation guidelines and handle with care	9	288
		PTFE inner liner	Leaking	Fluid pressure loss	8	Overpressure	2	Use pressure relief valve and pressure alarming sensors	3	48
		PTFE inner liner	Leaking	Fluid pressure loss	8	Thermal cycling fatigue	3	Allow for gradual temperature change	10	240
		PTFE inner liner	Leaking	Fluid pressure loss	8	Creep	3	Avoid long subjection to high temperatures	10	240
		PTFE inner liner	Leaking	Fluid pressure loss	8	Chemical degradation	4	Check for chemical compatibility	10	320
		PTFE inner liner	Leaking	Fluid pressure loss	8	Erosion	4	Filter contaminations inside the fluid	10	320
		PTFE inner liner	Leaking	Fluid pressure loss	9	Cracking due to vibrations	2	Use dampening fasteners	8	144
		PTFE inner liner	Embrittlement (set)	Cracking and loss of flexibility	8	Aging	10	Check for flexibilty at scheduled health checks	8	640

Figure 2: FMEA

FMEA descriptions of the different failure causes:

1. Chemical degradation: In pristine state, PTFE is highly resistant to chemical attack according to literature and manufacturers. In this context, chemical degradation includes the propagation of already existing cracks. The degradation is induced by factors like: contamination of the Dowcal100E and its inhibitor ingredients. In pristine states these factors should not affect the PTFE material.
2. Corrosion: The Stainless Steel braiding offers high level of protection from abrasion, tighter bend radius and higher temperature resistance. Though, the salt air environment at sea could induce corrosion processes to occur. This failure mechanism already occurs within the systems of Thales, especially for the exposed hoses. However, it is not considered as critical, since this failure mechanism is more easily visible and treatable compared to inner cracking of the PTFE for example. When surface corrosion on the hose is detected by the operator or maintainer, it is generally replaced or cleaned.
3. Pressure pulsing fatigue: This is a common failure mechanism within hydraulic systems. Rubber hoses that have to transport high pressure hydraulic oil for cylindrical movements for example, could experience cyclic loading of pressure in their lifetime. This induces cyclic stresses on the hose and results in fatigue.
4. Abrasion: In case the hose experiences cyclic deformations, or is dragged along the floor while handling, it could then induce abrasion wear between the braiding and the contacting solid. Over time this could result in fracture of the braiding and in turn loss of pressure performance of the hose.
5. Inadequate maintenance: In case maintenance actions are ignored or not well performed, it is possible that the hose will degrade faster. Especially when corrosion is ignored, it could result in fracture of the stainless steel braiding.
6. Kinking: Bending a hose beyond its minimum bend radius is treated as kinking. In case of PTFE hoses, it will damage the inner liner of the hose. A kink induces a bending load which will initiate a crack in the ptfe inner layer.
7. Thermal cycling fatigue: Cycling between the extreme outside temperatures will induce a expansion and contraction stress on the hose at the fixed ends and clamps. From calculations it can be concluded that the severity is really low.
8. Twisting: This could be treated as a same problem compared to kinking. However, usually hose manufacturers do not specify a maximum allowable twist. A twist induces a torsional load which will initiate a crack in the ptfe inner layer.
9. Overpressure: The hose manufacturer specifies maximum allowable work pressures and the maximum allowable pressure at which the hose will eventually burst. Pressure surges in highly dynamic application (hydraulics for example), could induce a pressure impulse. several pressure surges accumulated, or a overpressure for a prolonged period of time will cause the ptfe inner liner to crack and burst.
10. Creep: This failure mode is a time dependent process. For a hose that is prolongedly exposed to high pressure and high temperatures. Due to these loading factors, the ptfe material slowly deforms over time.
11. Cracking due to vibrations: Vibrations of the frigate diesel engine could propagate through the structures and also through the hose. It is however a question if this severity is high or not. In any way, prolonged exposure to low- and high frequency vibrations could over time lead to cracking of the ptfe material.
12. Outer surface wear due to vibration: The PTFE inner liner and outer braiding are in contact. This ensures that wear between these two surfaces could happen in case of vibrations. The softer PTFE material is likely to start thinning due to this wear process.

Appendix C

3below shows the complete hose sample sequence list that was constructed in Excel.

Temperature (°C)	Aging duration (days)	Take sample out:
120	12	711-1A
		811-1A-DH
120	18	811-2A_DH
		Eriks-1A
		Eriks-2A
		Eriks-3A
120	24	711-2A
		811-3A_DH
		Eriks-1A-R
		Eriks-2A-R
		Eriks-3A-R
		Eriks-4A
		Eriks-5A
		Eriks-6A
		811-1A-ECC
		811-2A-ECC
		811-3A-ECC
180	12	711-3A
		811-4A-DH
		860-1A
		Eriks-7A
		Eriks-8A
		Eriks-9A
180	18	811-5A_DH
		860-2A
		Eriks-10A
		Eriks-11A
		Eriks-12A
		811-4A-ECC
		811-5A-ECC
		811-6A-ECC
180	24	711-4A
		811-6A_DH
		Erik-13A
		Eriks-14A
		Eriks-15A
		811-7A-ECC
		811-8A-ECC
		811-9A-ECC
		860-3A
		860-4A
		860-5A
		860-6A
250	12	711-5A
		711-6A
		711-7A
		711-8A
		Erik-16A
		Eriks-17A
		Eriks-18A
		811-7A-DH
		811-10A-ECC
		811-11A-ECC
		811-12A-ECC
		860-7A
		860-B1
250	18	711-9A
		711-10A
		711-11A
		711-12A
		Erik-19A
		Eriks-20A
		Eriks-21A
		811-8A_DH
		811-13A-ECC
		811-14A-ECC
		811-15A-ECC
		860-8A
		860-B2
250	24	711-13A
		711-14A
		711-15A
		711-16A
		811-9A_DH
		Erik-22A
		Eriks-23A
		Eriks-24A
		811-16A-ECC
		811-17A-ECC
		811-18A-ECC
		860-9A
		860-10A
		860-11A
		860-12A
		860-B3

Figure 3: Hose samples sequence list for the thermal aging program (Test #2)

For clarification, the hose sample configuration names are explained in Figure 4:

Sample classifications:
Letter A in the sample name refers to an Aged sample
Letter U in the sample name refers to an Unaged sample

- **711:** Refers to the Goodridge G-Flex 711 with convulated inner and outer core. Hose samples will be mainly tested on full diameter tensile test at DEON and SEM/DSC
- **811-DH:** Refers to the Goodridge G-Flex 811 with convulated outer core and smooth inner core. DH refers to the fact that this hose has been received from Den Helder in which it has been stored for 8 years. Hose samples will only be used for SEM/DSC analysis
- **811-ECC**: ECC refers to the fact that this hose has been taken from the storage of the ECC lab at Thales. It seemed that this hose has been stored since 2015 and several tests have been executed. Thus take caution. Hose samples will only be used for Tensile tests (strip cut)
- **860:** Refers to the Goodirdge G-Line Ultra 860 with convulated outer core and smooth bore inner core. These hoses are newly purschased from Teesing and will be used from SEM/DSC and Tensile tests (strip cut)
- **Eriks:** Refers to the Dummy batch delivery from Eriks to Thales. These hoses also contain the roguhly same black PTFE inner liner as the Goodridge 811. The Eriks hoses will be used for Tensile tests only (check if full diameter is doable)
- **Eriks-R:** Refers to the rest of the Eriks dummy batch which contained a slightly different outer core
- **860-B:** Refers to the Goodridge 860 hose again, but this hose will be aged and tested in full assembly mode for burst pressure

Figure 4: Hose samples configuration names -explanation

Appendix D

Goodridge 811 (G811):

G811 samples show a similar average stress-strain plot. The trend shifts upward and a slight increase in slope of the plastic modulus is observed (Figure 5)

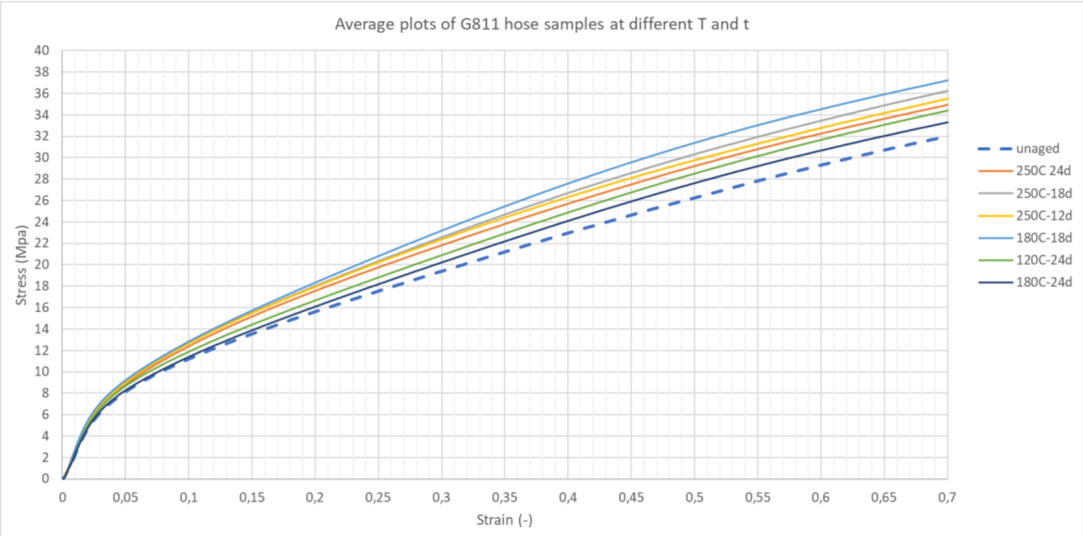


Figure 5: Average stress-strain plot G811 hose samples

The results for the G811 samples show notable variability in both maximum strain and stress, without any consistent trend related to aging temperature or time. The unaged samples present an average maximum strain of +-130% and a maximum stress of +-50 MPa. For aged samples, maximum strain fluctuates, with conditions such as 120°C-24d and 250°C-24d showing slightly higher strain (+-140%) compared to other aging conditions (+-120%). Similarly, maximum stress remains relatively stable across all aging conditions, being around +-45–50 MPa. See Figure 6 and Figure 7 for both column plots.

The cloud plot (Figure) also highlights this randomness, with no pattern linking aging severity to the mechanical properties. While the unaged sample stands out due to its higher strain and stress, the aged samples are scattered, making it impossible to conclude that higher aging temperature or longer exposure leads to a consistent reduction in either strain or stress.

In summary, the key findings were:

- Maximum strain fluctuates across aging conditions, with no consistent decrease observed.
- Maximum stress remains stable regardless of aging temperature or duration.
- No clear relationship exists between aging severity and mechanical properties, suggesting random variability or material resilience.

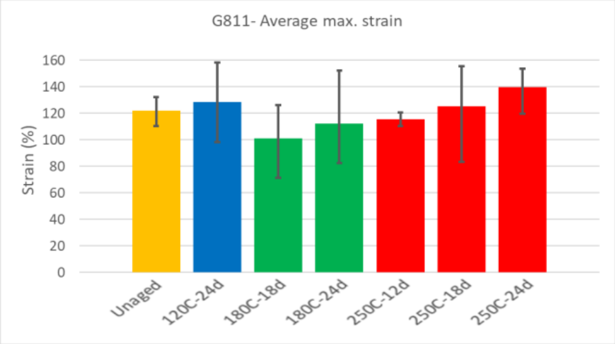


Figure 6: plot - G811 Average max. strain

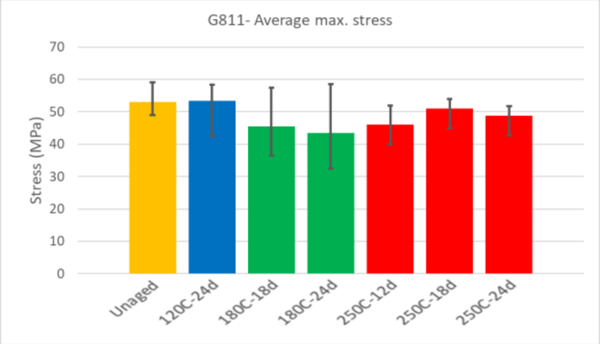


Figure 7: plot - G811 Average max. stress

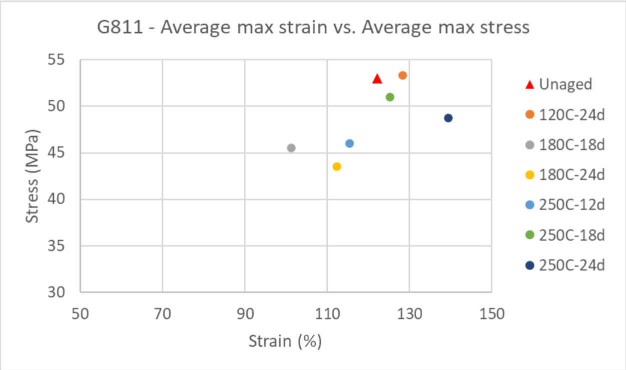


Figure 8: point plot - G811 Average max. strain vs. stress

During the research, a sensitivity tensile test was executed by cutting the PTFE hose samples of the G811 180°C-24d with a consistent minimum sample width. The goal from this was to find if inconsistent sample width resulted in large variations of the stress-strain plots. Figure 9 shows the stress strain plot of G811 180°C-24d hose samples.

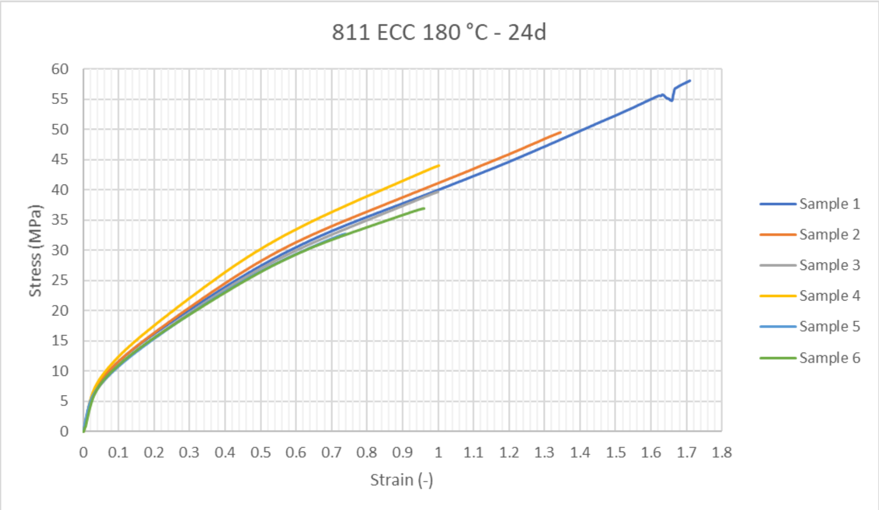


Figure 9: Stress-strain G811 180C-24d

It can be seen that no large variability can be seen in the plastic modulus region. However, maximum stress and maximum strain values tend to vary regardless.

Full-diameter hose tensile test:

The full-diameter hose tensile test was executed at DEON Hengelo. It must be noted that all hoses failed at the clamping region. Figure 10 leftshows how the PTFE hoses were clamped, while Figure 10 right shows the region of failure.

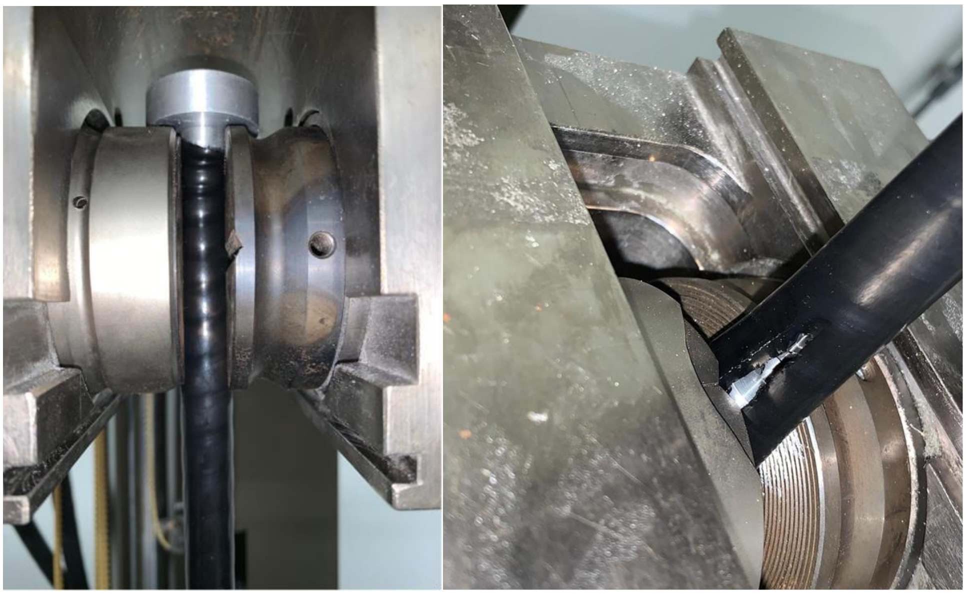


Figure 10: Detailed photo of the full diameter test (clamping left and failure right)

Figure 11 shows the average plots of the full-diameter hose tensile test. The same behaviour can be observed from the ERIKS hose cut hose samples. The slope of the plastic region tends to shift upwards and increase slightly, but no trend is observable in terms of increase in aging duration with increase in this shift.

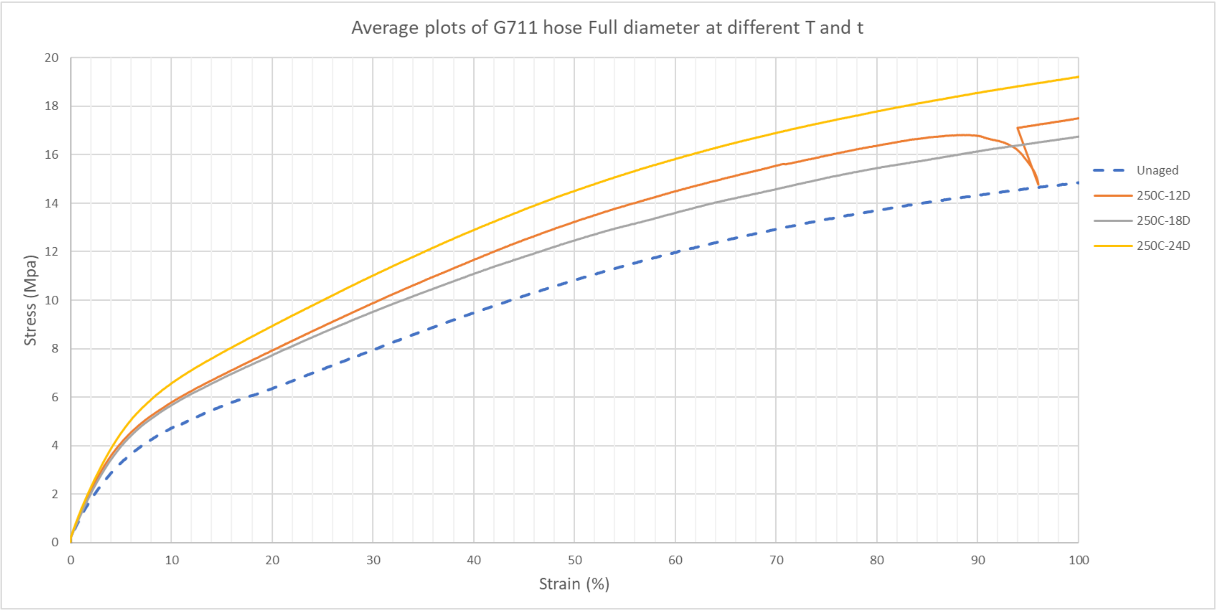


Figure 11: avergae plot full diamter hose tensile test

The values for maximum stress and maximum strain can be seen in Table 1.

711-Ref n = 3	Fmax. N	Stress Max N/mm²	ε Break %
$\bar{x}$	1250,63	21,41	328,99
s	108,60	1,86	-
ν	8,68	8,68	-

744-12D n = 3	Fmax. N	Stress Max N/mm²	ε Break %
$\bar{x}$	1116,19	19,11	133,25
s	101,49	1,74	46,72
ν	9,09	9,09	35,06

Table 1

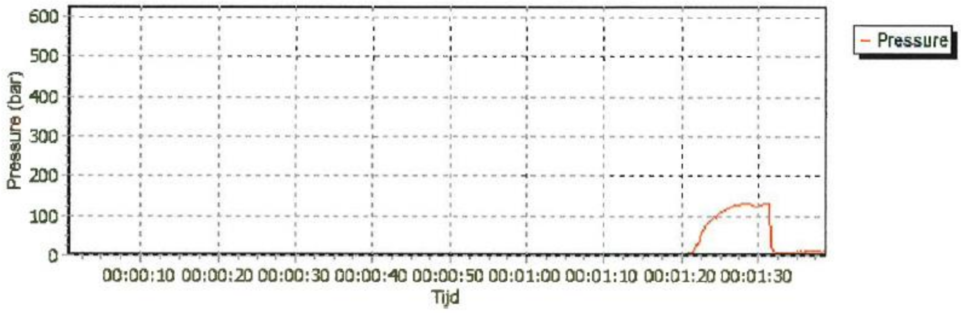
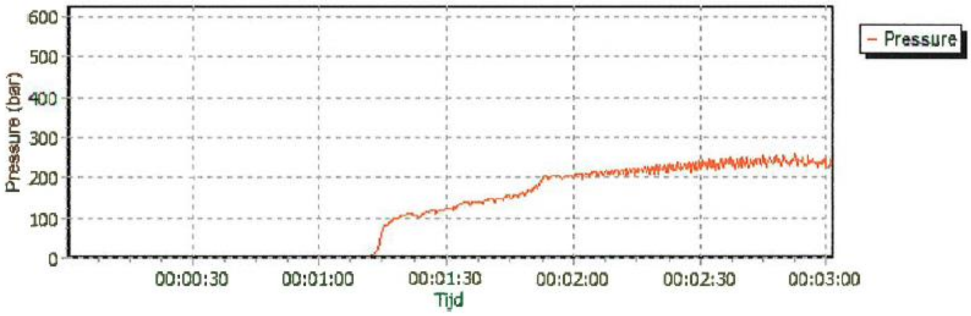
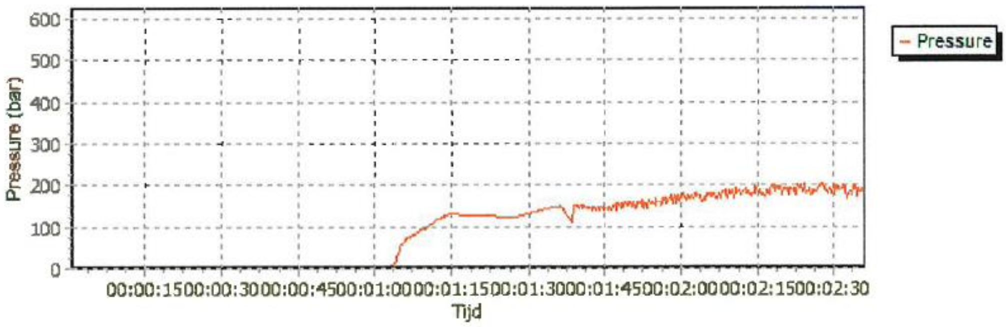
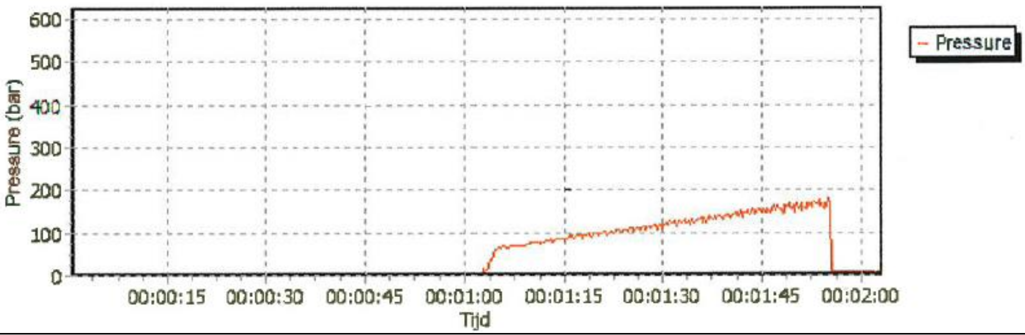
711-18D n = 3	Fmax. N	Stress Max N/mm²	ε Break %
$\bar{x}$	1093,16	18,72	123,06
s	37,76	0,65	-
ν	3,45	3,45	-

711-24D n = 3	Fmax. N	Stress Max N/mm²	ε Break %
$\bar{x}$	1575,56	26,98	319,58
s	109,28	1,87	28,95
ν	6,94	6,94	9,06

Appendix E

Table 2 below shows the raw data from the burst pressure test. It shows time on the x-axis and Pressure in bar on the y-axis.

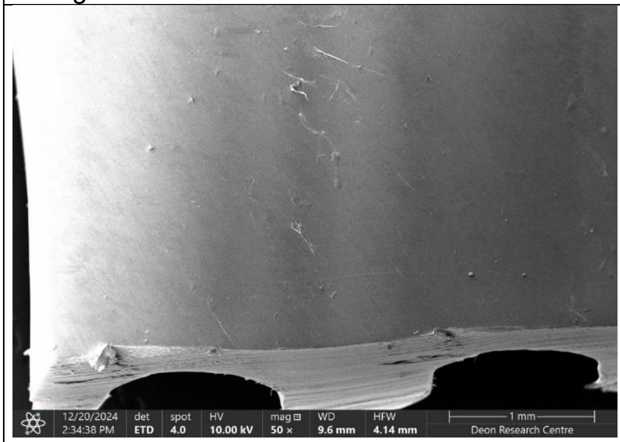
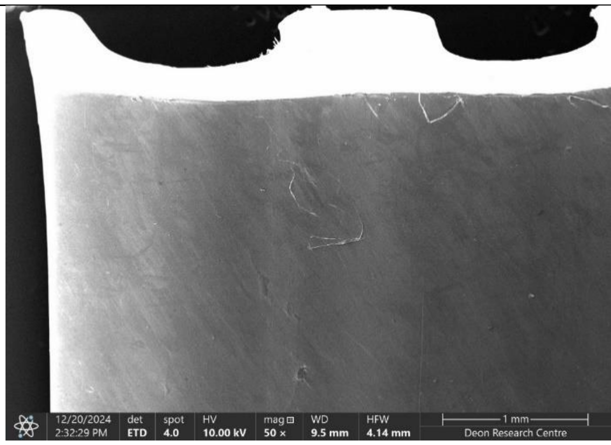
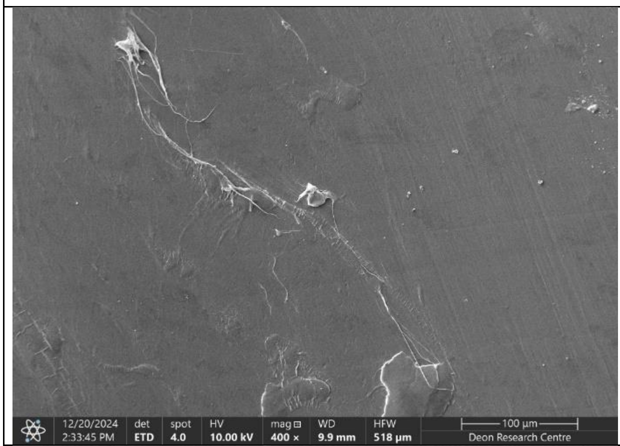
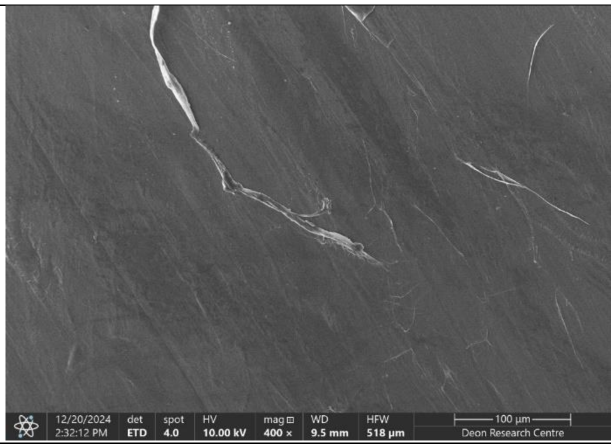
Table 2: Raw data plots of the burst pressure tests

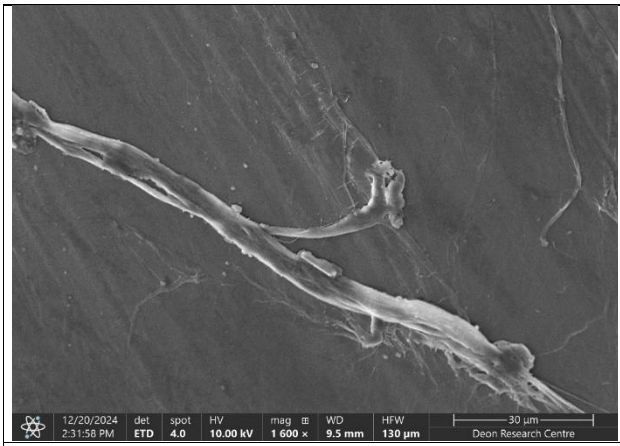
<table>
<tr><td>Unaged</td><td>
</td></tr>
<tr><td>Aged 250C-12d</td><td>
</td></tr>
<tr><td>Aged 250C-18d</td><td>
</td></tr>
<tr><td>Aged 250C-24d</td><td>
</td></tr>
</table>

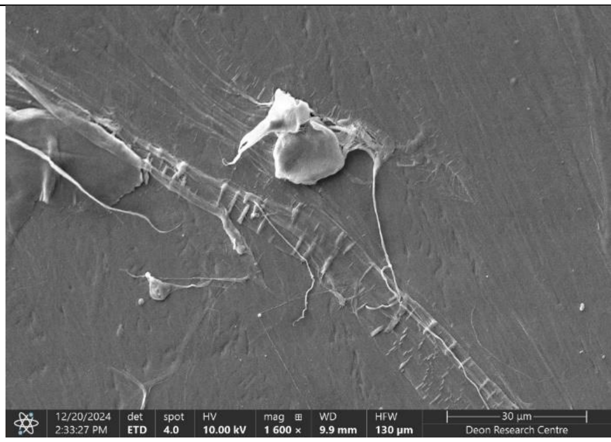
Appendix F

Table 3 shows all SEM pictures from the Goodridge 860 hose samples.

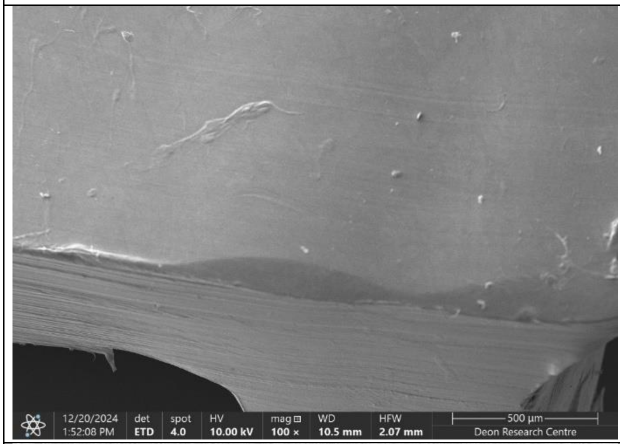
Table 3: SEM picture results of the Goodridge 860 hose samples

Unaged:	
	
	
	


12/20/2024 2:31:58 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 9.5 mm
HFW 130 µm
30 µm
Deon Research Centre

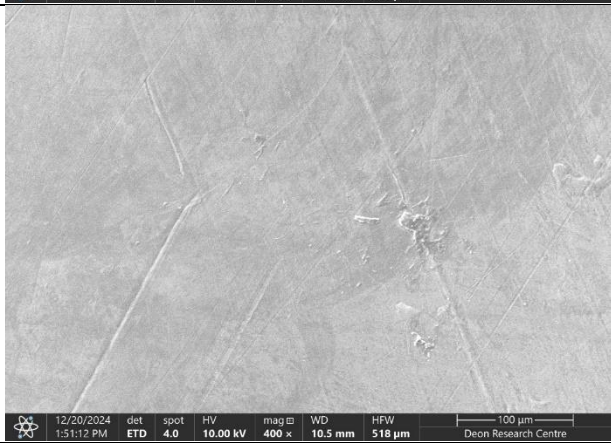

12/20/2024 2:33:27 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 9.9 mm
HFW 130 µm
30 µm
Deon Research Centre

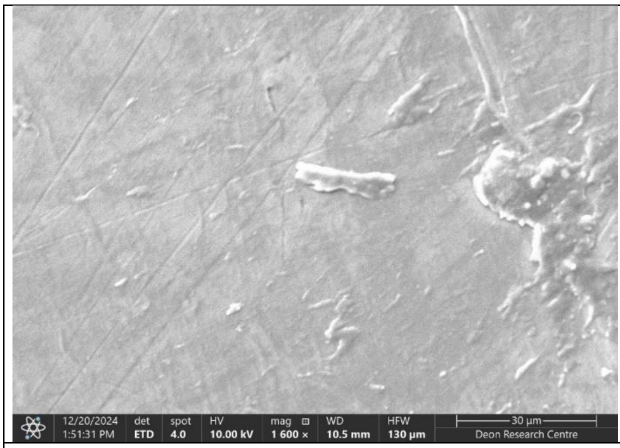
180C-12d

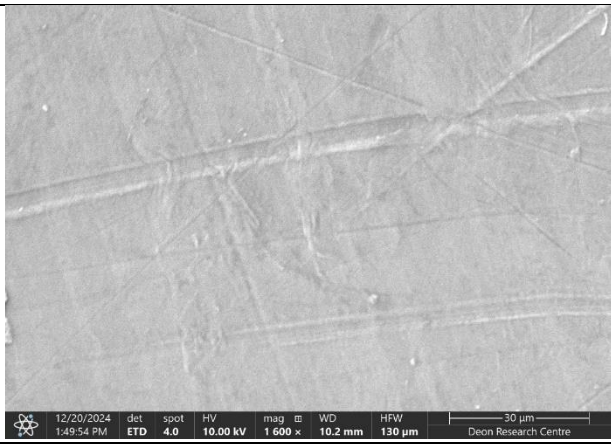

12/20/2024 1:52:08 PM
det ETD
spot 4.0
HV 10.00 kV
mag 100 ×
WD 10.5 mm
HFW 2.07 mm
500 µm
Deon Research Centre


12/20/2024 1:49:27 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre

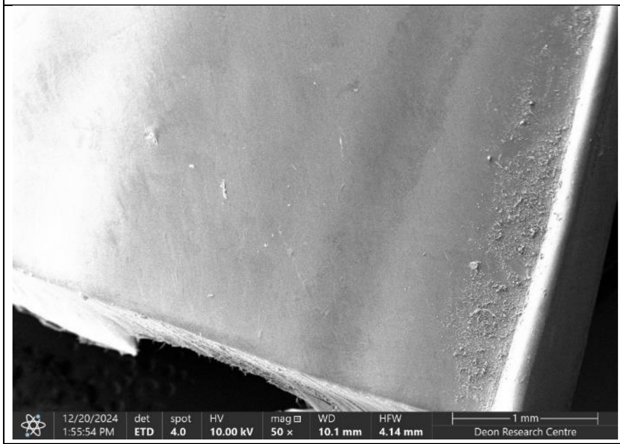

12/20/2024 1:49:27 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre

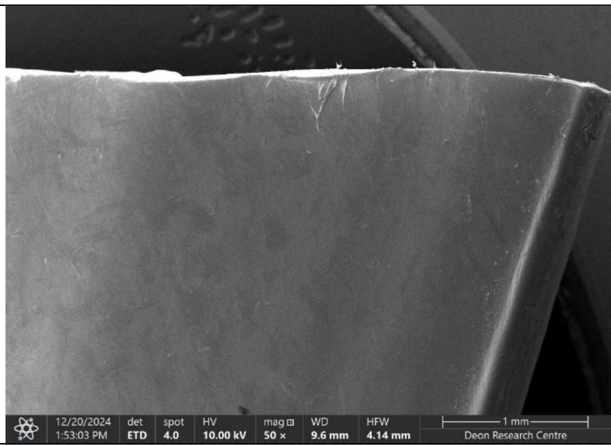

12/20/2024 1:51:12 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.5 mm
HFW 518 µm
100 µm
Deon Research Centre

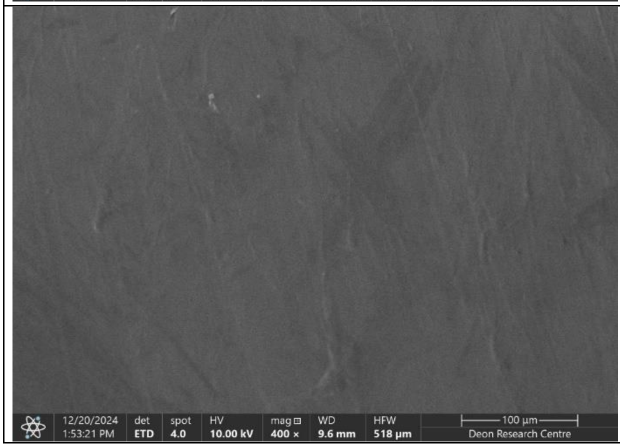

12/20/2024 1:51:31 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.5 mm
HFW 130 µm
30 µm
Deon Research Centre

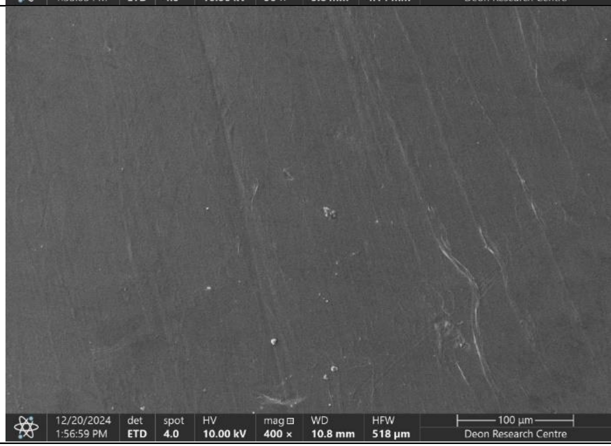

12/20/2024 1:49:54 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.2 mm
HFW 130 µm
30 µm
Deon Research Centre

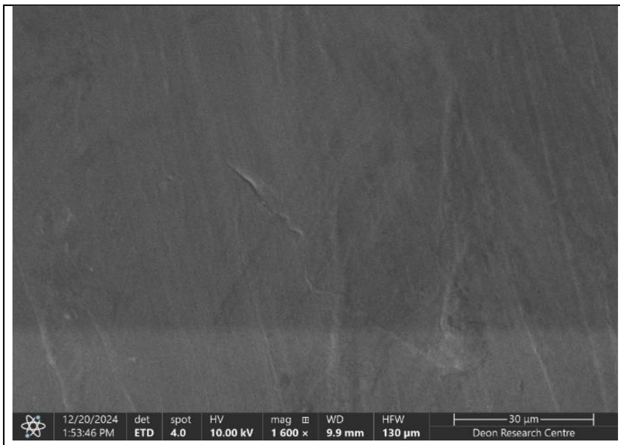
180C-18d

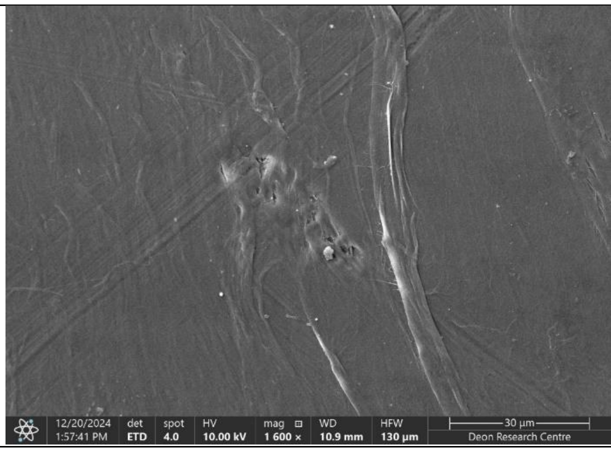

12/20/2024 1:55:54 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 10.1 mm
HFW 4.14 mm
1 mm
Deon Research Centre


12/20/2024 1:53:03 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 9.6 mm
HFW 4.14 mm
1 mm
Deon Research Centre

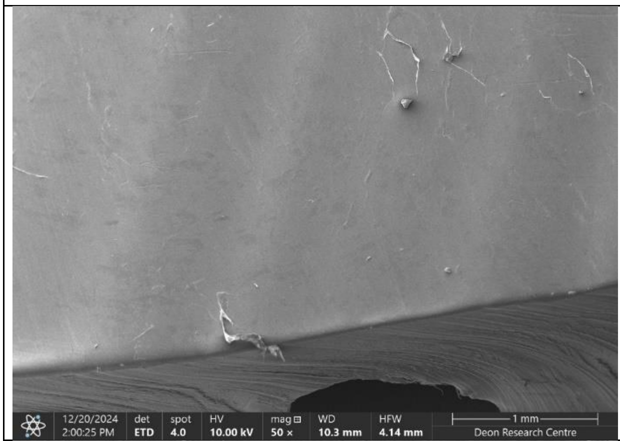

12/20/2024 1:53:21 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 9.6 mm
HFW 518 µm
100 µm
Deon Research Centre


12/20/2024 1:56:59 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.8 mm
HFW 518 µm
100 µm
Deon Research Centre

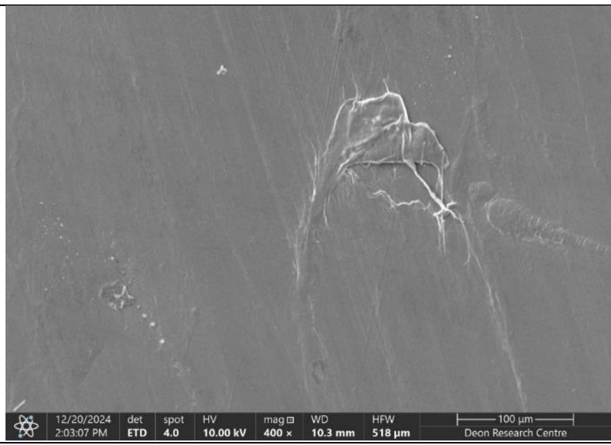

12/20/2024 1:53:46 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 9.9 mm
HFW 130 µm
30 µm
Deon Research Centre

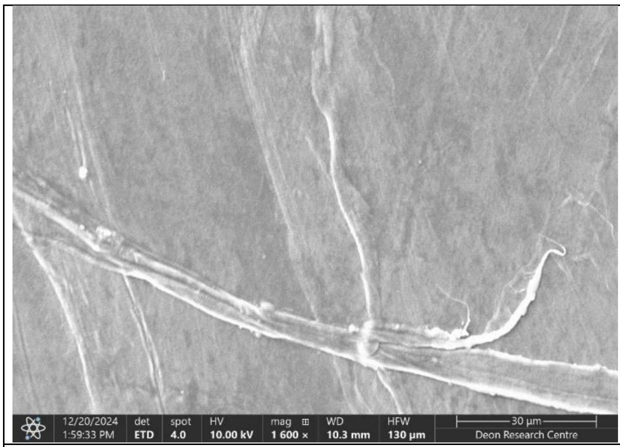

12/20/2024 1:57:41 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.9 mm
HFW 130 µm
30 µm
Deon Research Centre

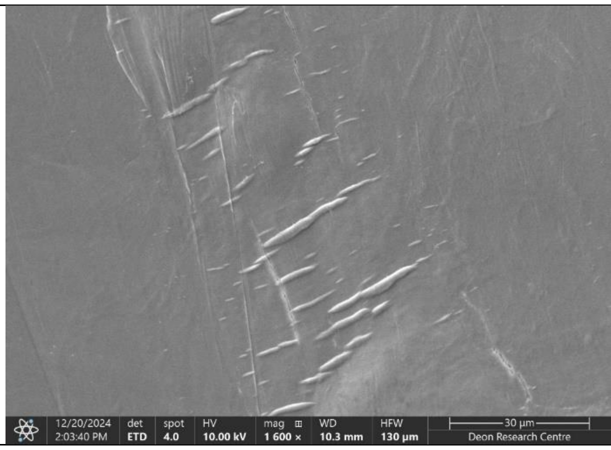
180C-24d


12/20/2024 2:00:25 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 10.3 mm
HFW 4.14 mm
1 mm
Deon Research Centre

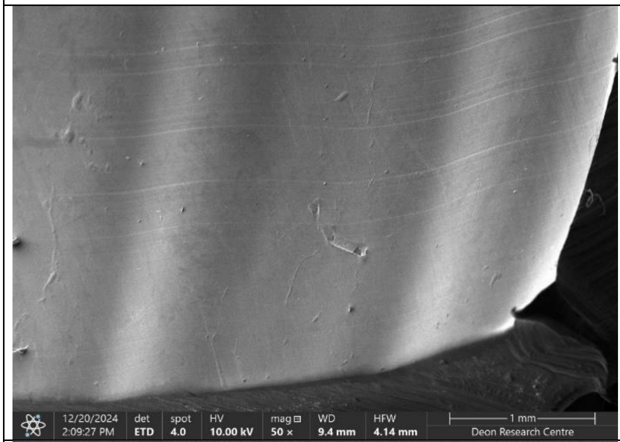

12/20/2024 1:59:14 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre

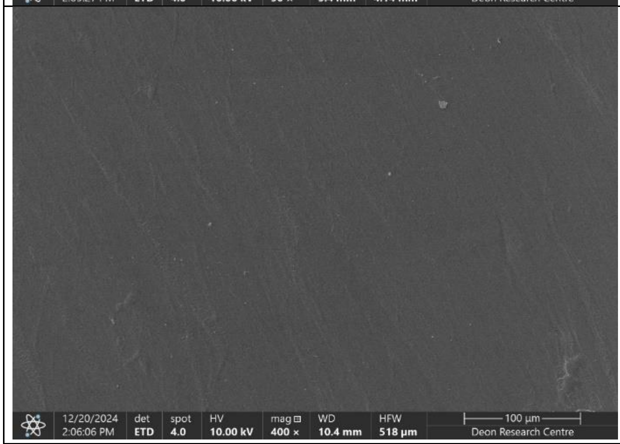

12/20/2024 2:03:07 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.3 mm
HFW 518 µm
100 µm
Deon Research Centre

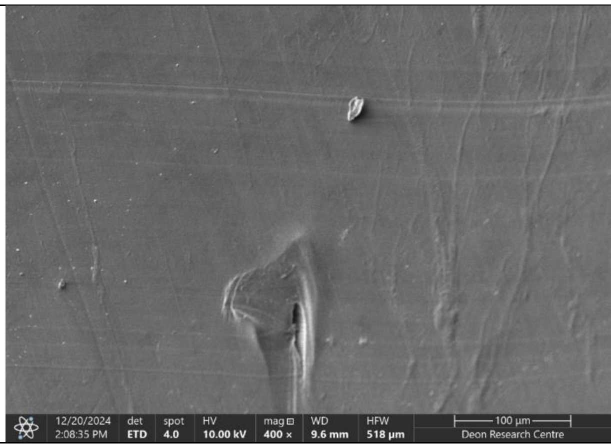

12/20/2024 1:59:33 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.3 mm
HFW 130 µm
30 µm
Deon Research Centre

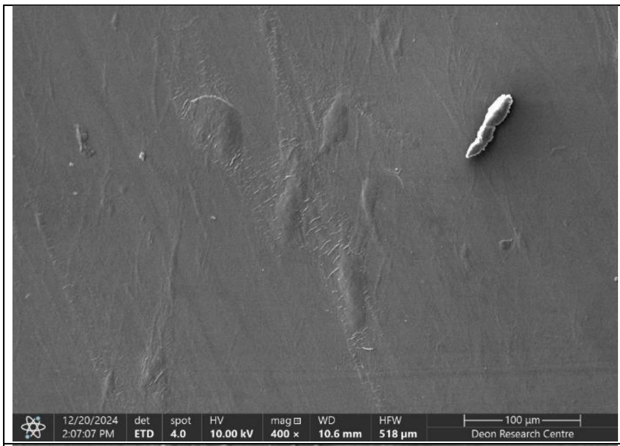

12/20/2024 2:03:40 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.3 mm
HFW 130 µm
30 µm
Deon Research Centre

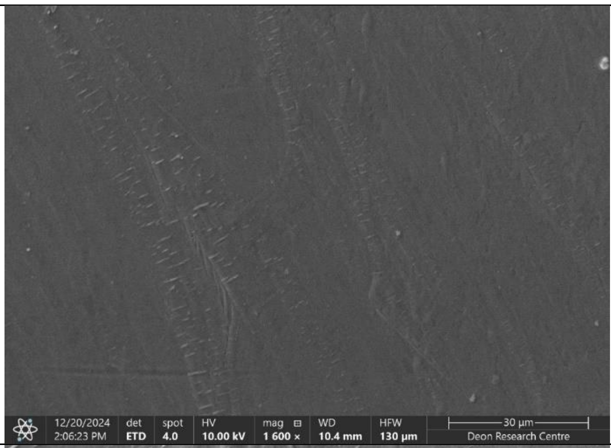
250C-12d

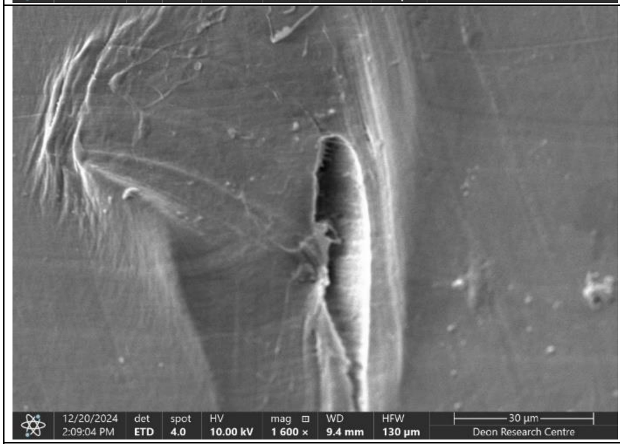

12/20/2024 2:09:27 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 9.4 mm
HFW 4.14 mm
1 mm
Deon Research Centre

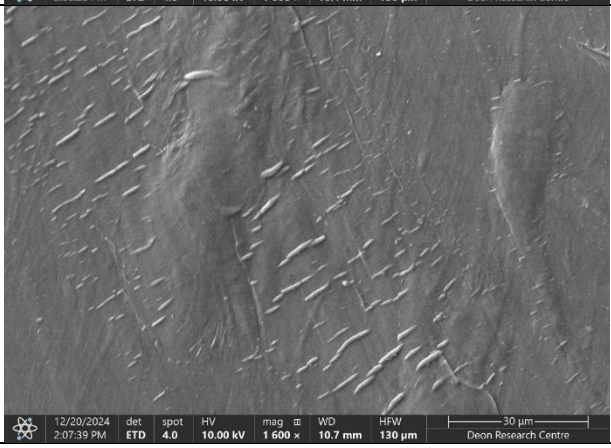

12/20/2024 2:06:06 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.4 mm
HFW 518 µm
100 µm
Deon Research Centre


12/20/2024 2:08:35 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 9.6 mm
HFW 518 µm
100 µm
Deon Research Centre

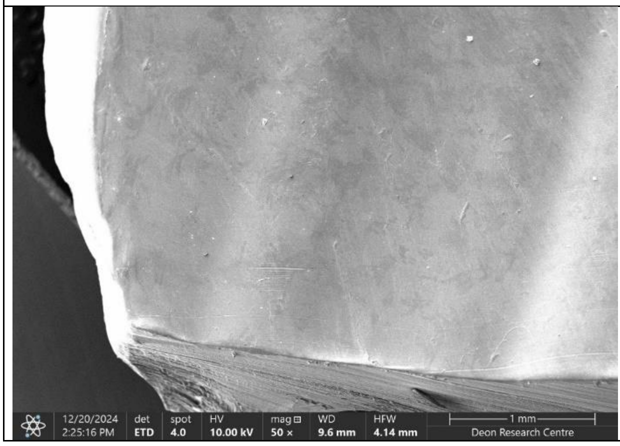

12/20/2024 2:07:07 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.6 mm
HFW 518 µm
100 µm
Deon Research Centre

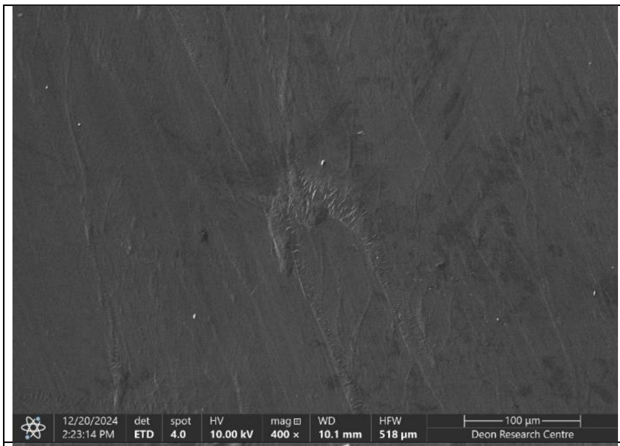

12/20/2024 2:06:23 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.4 mm
HFW 130 µm
30 µm
Deon Research Centre

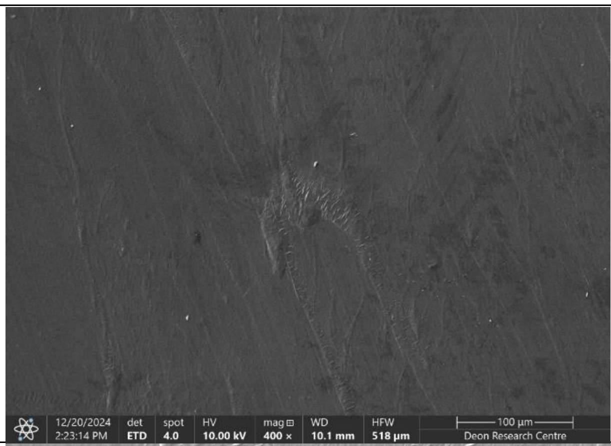

12/20/2024 2:09:04 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 9.4 mm
HFW 130 µm
30 µm
Deon Research Centre

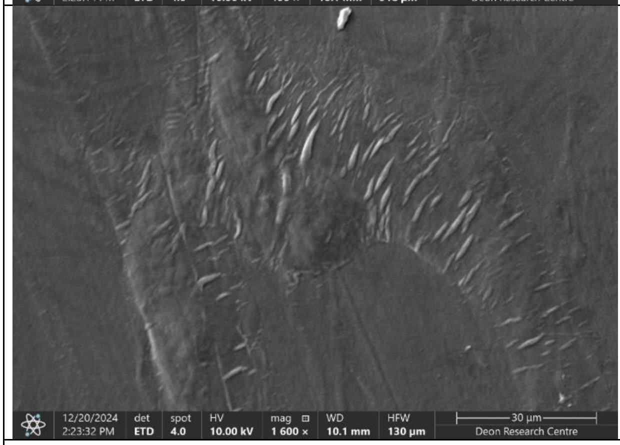

12/20/2024 2:07:39 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.7 mm
HFW 130 µm
30 µm
Deon Research Centre

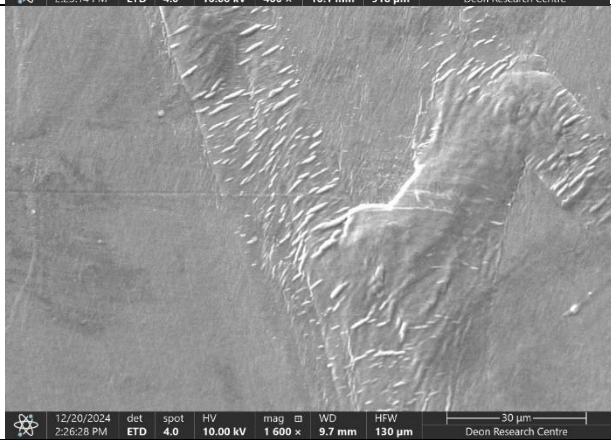
250C-18d


12/20/2024 2:25:16 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 9.6 mm
HFW 4.14 mm
1 mm
Deon Research Centre

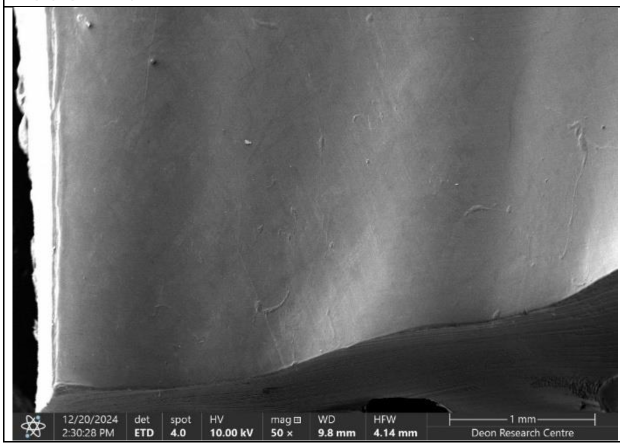

12/20/2024 2:23:14 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre

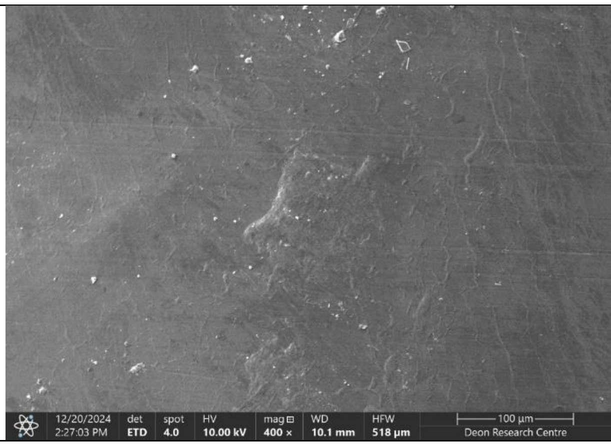

12/20/2024 2:23:14 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre

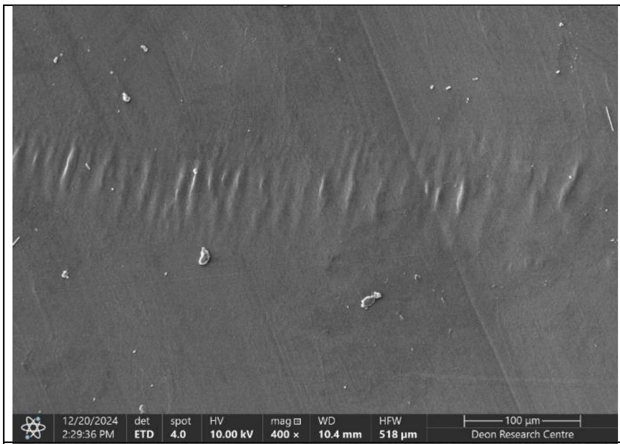

12/20/2024 2:23:32 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.1 mm
HFW 130 µm
30 µm
Deon Research Centre

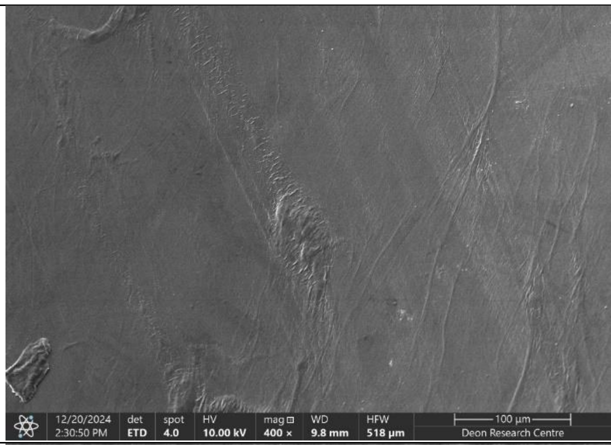

12/20/2024 2:26:28 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 9.7 mm
HFW 130 µm
30 µm
Deon Research Centre

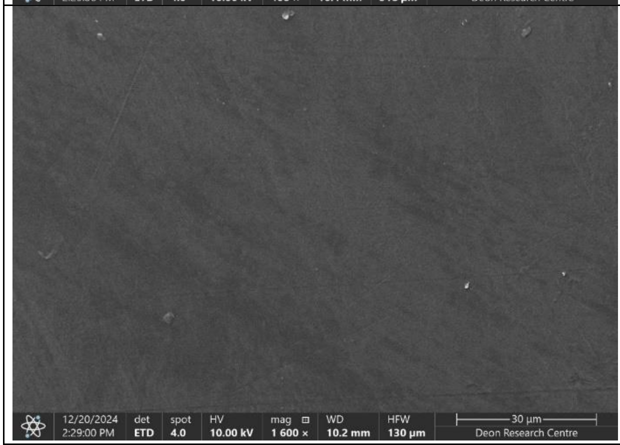
250C-24d


12/20/2024 2:30:28 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 9.8 mm
HFW 4.14 mm
1 mm
Deon Research Centre


12/20/2024 2:27:03 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.1 mm
HFW 518 µm
100 µm
Deon Research Centre







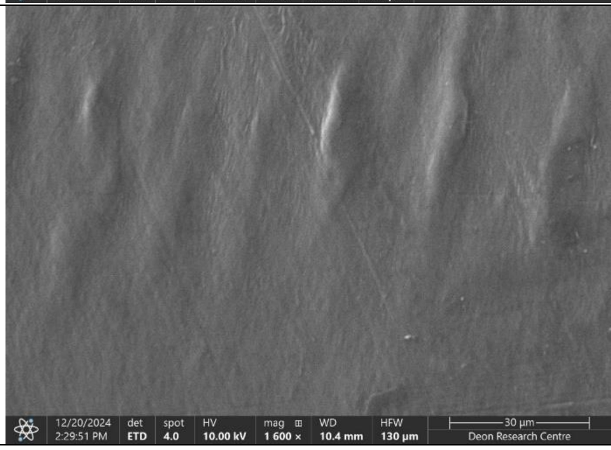
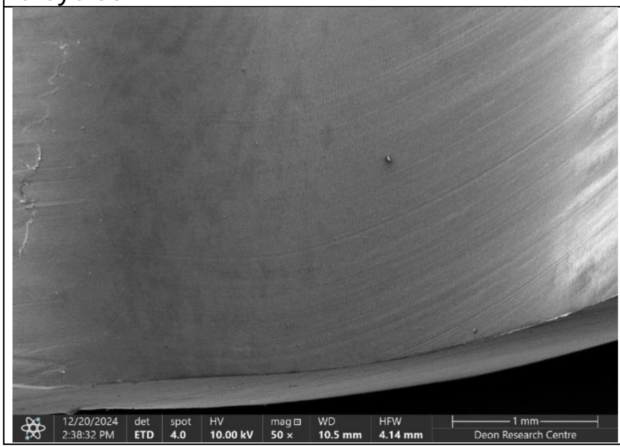
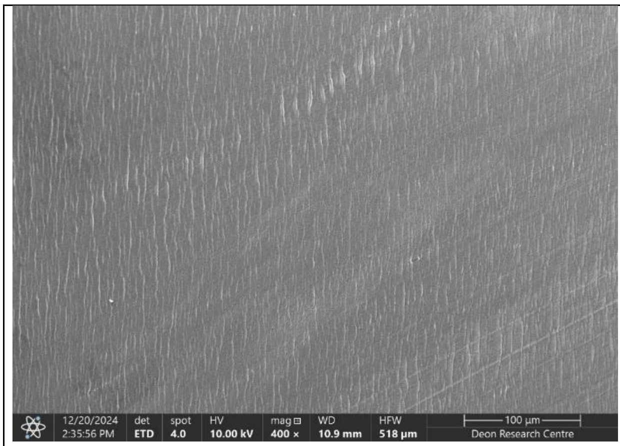


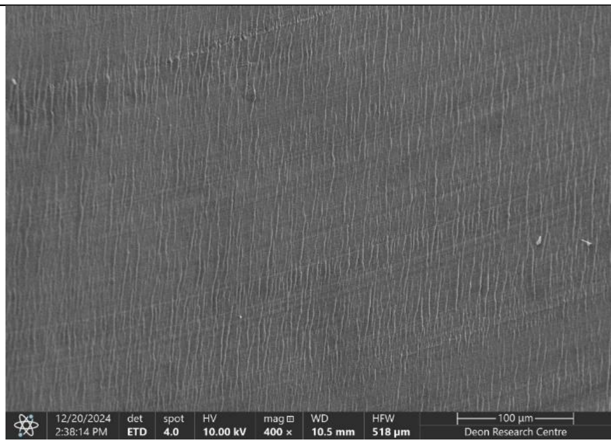
Table 4 shows the SEM pictures from the temperature cycling test. Goodridge G-Flex 711 hoses.

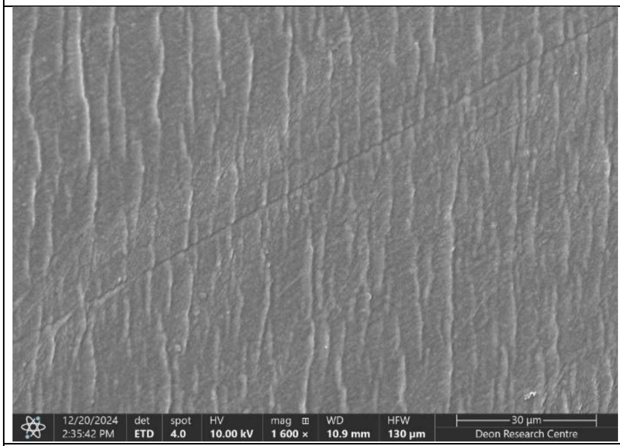
Table 4: SEM results of Test #1 - 9 & 18 cycles

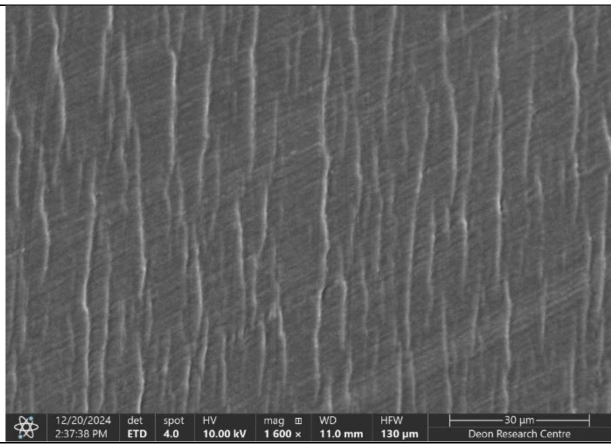
9 cycles	



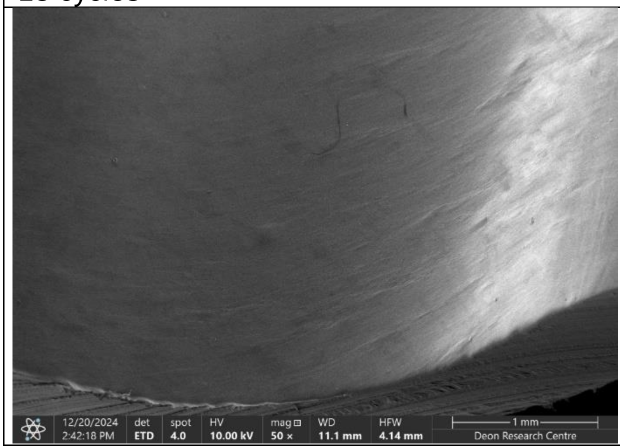

12/20/2024 2:35:56 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.9 mm
HFW 518 µm
100 µm
Deon Research Centre

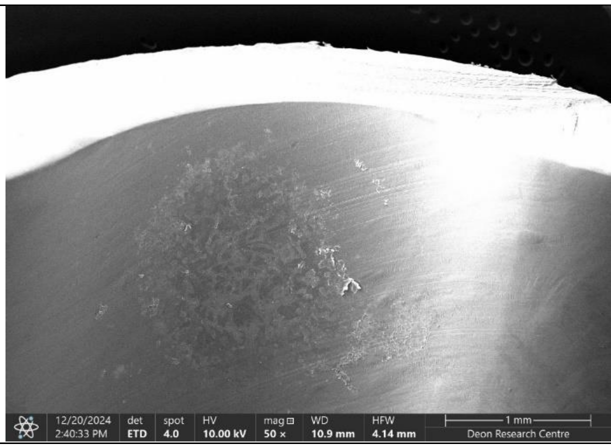

12/20/2024 2:38:14 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.5 mm
HFW 518 µm
100 µm
Deon Research Centre

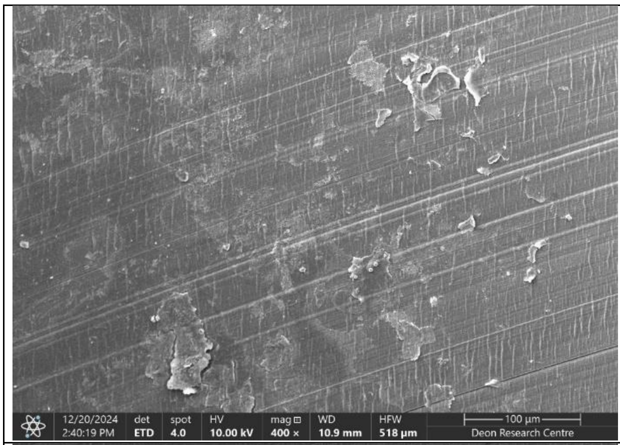

12/20/2024 2:35:42 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.9 mm
HFW 130 µm
30 µm
Deon Research Centre

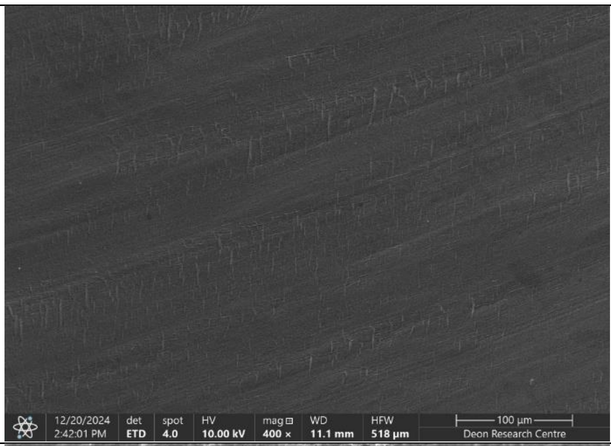

12/20/2024 2:37:38 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 11.0 mm
HFW 130 µm
30 µm
Deon Research Centre

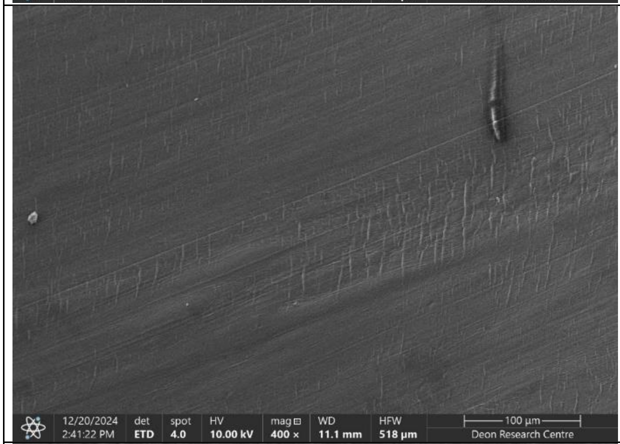
18 cycles

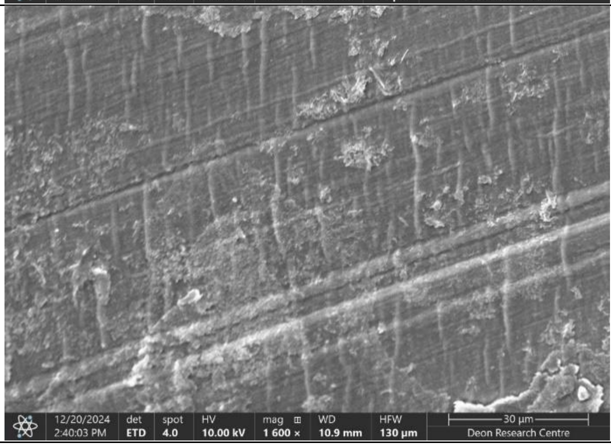

12/20/2024 2:42:18 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 11.1 mm
HFW 4.14 mm
1 mm
Deon Research Centre

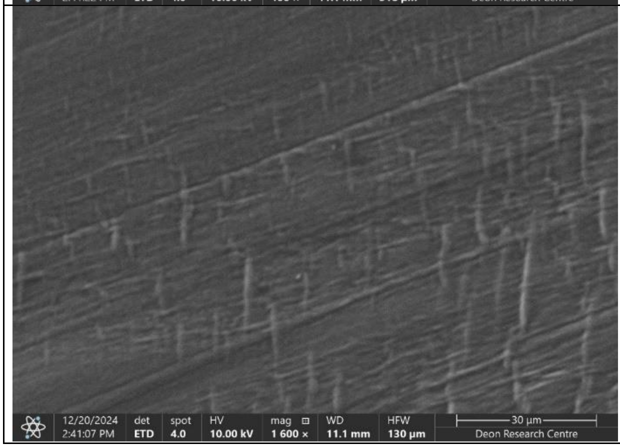

12/20/2024 2:40:33 PM
det ETD
spot 4.0
HV 10.00 kV
mag 50 ×
WD 10.9 mm
HFW 4.14 mm
1 mm
Deon Research Centre


12/20/2024
2:40:19 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 10.9 mm
HFW 518 µm
100 µm
Deon Research Centre


12/20/2024
2:42:01 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 11.1 mm
HFW 518 µm
100 µm
Deon Research Centre


12/20/2024
2:41:22 PM
det ETD
spot 4.0
HV 10.00 kV
mag 400 ×
WD 11.1 mm
HFW 518 µm
100 µm
Deon Research Centre


12/20/2024
2:40:03 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 10.9 mm
HFW 130 µm
30 µm
Deon Research Centre


12/20/2024
2:41:07 PM
det ETD
spot 4.0
HV 10.00 kV
mag 1 600 ×
WD 11.1 mm
HFW 130 µm
30 µm
Deon Research Centre

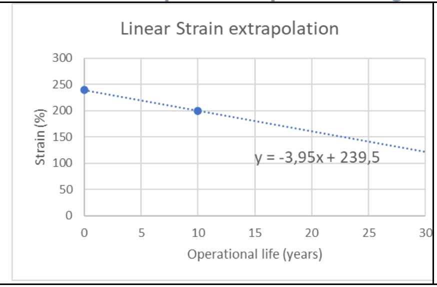
Appendix G

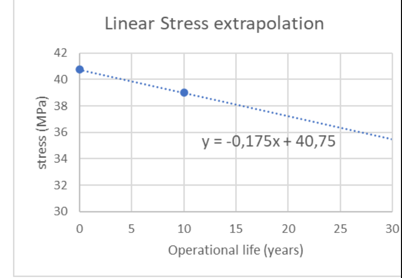
Mechanical properties degradation model:

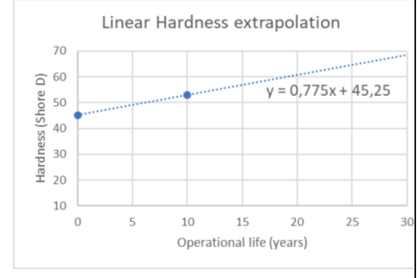
Since no trends could be observed from the tensile test results and the hardness test results, it is not possible to use Arrhenius models with the combination of failure criteria regarding x% decrease in material properties, as Kun has utilized [17].

Therefore, another model to predict lifetime is to use the results of the mechanical analyses. Inter- or extrapolation methods could be used to predict the material properties after a certain amount of years. Utilizing the Reference DH hose that was 10 years in operation and compare its material properties to the unaged hose. Even if it only shows two data points, they can be extrapolated with caution to compute the expected mechanical properties after 30 years lifetime. Table 5 shows the figure plots of linear and exponential model extrapolation plots while only using two data points from the mechanical analysis part.

Table 5: Extrapolation plots using 2 data points; unaged and REF DH







The predicted material properties reduction and increases are listed in Table 6 below. Values are compared to the unaged hose and predicted to 30 years.

Table 6: Change in material properties for the different life prediction models after 30 years operation

	Max. strain (%)	**Max. stress (MPa)**	**Hardness (Shore D)**
Linear	-49,48%	-12,88%	51,38%
Exponential	-41,73%	-11,31%	60,64%

It is carefully assumed that the PTFE hoses continue a linear degradation path, from the unaged hose to the reference year-10 hose regarding the material properties. Therefore it can be concluded that strain, stress and hardness decrease with roughly 49,5%, 12,9% and increase with 51,4% respectively. This approximation is highly sensitive to the measurement error used to compute values for max strain, max stress and hardness, as they are all averaged vales. Another limitation is the fact that is unknown how the reference hoses were treated during its 10-years operational life and the subsequent mission profile (temperature cycles etc.). All these factors play a huge roll in determining the extrapolated value for the material properties. The estimated properties are therefore not used nor recommended as they need more data points to validate the linear trend and fitted model. It would be very helpful if 3 or more reference hoses are obtained with different operational life's.