MATERIAL SELECTION FOR NON-CONTACTING RADAR PROCESS SEAL ANTENNA

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Mechanical Engineering, Master's thesis

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ABSTRACT

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Material selection for non-contacting radar process seal antenna

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75 pages, 40 figures, 8 tables

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Per- and polyfluoroalkyl substances (PFAS) are a group of over 10 000 chemicals which are widely utilized across different industries and applications due to their unique and extremely good material properties. Polytetrafluoroethylene (PTFE) or better known with its trademark name Teflon falls under the PFAS group. PFAS are referred as "forever chemicals" because it takes extremely long time for them to break down in the environment. PFAS are found everywhere in the environment. They are linked to cause detrimental effects in humans and environmental damage. Due to the rising concerns of the PFAS, European Chemicals Agency (ECHA) have proposed massive restrictions for the use of PFAS.

Emerson utilizes widely different PFAS in their products and possible restrictions can majorly disrupt the business. The objective of this master's thesis is to seek for PFAS-free alternative materials for the Emerson's 5408 non-contacting radar process seal antenna part which is currently made from PTFE. In this master's thesis systematic material selection process is conducted and alternative material options are searched for and evaluated.

As the result of the material selection process, polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) seem to be the most viable PFAS-free alternatives for this specific application. However, based on this thesis PTFE has very unique combination of material properties and it outperforms the alternative materials in many of the key parameters and material properties considered in this master's thesis.

TIIVISTELMÄ

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Materiaalin valinta koskettamattoman tutkan prosessitiivisteantennille

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Per- ja polyfluoroalkyyliyhdisteet (PFAS) ovat yli 10 000 kemikaalin ryhmä, joita käytetään laajasti eri teollisuudenaloilla ja sovelluksissa ainutlaatuisten ja erittäin hyvien materiaaliominaisuuksiensa ansiosta. Polytetrafluorieteeni (PTFE), joka tunnetaan paremmin tavaramerkkinimellään Teflonina, kuuluu PFAS-yhdisteisiin. PFAS-yhdisteitä kutsutaan "ikuisuuskemikaaleiksi", koska niiden hajoaminen ympäristössä kestää erittäin kauan. PFAS-yhdisteet ovat yhdistetty aiheuttavan vahinkoa ihmisille ja ympäristölle. Kasvavien huolien vuoksi Euroopan kemikaalivirasto (ECHA) on ehdottanut valtavia rajoituksia PFAS-yhdisteiden käytölle.

Emerson käyttää tuotteissaan paljon erilaisia PFAS-yhdisteitä, ja mahdolliset rajoitukset näiden käytössä voivat häiritä liiketoimintaa merkittävästi. Tämän diplomityön tavoitteena on etsiä PFAS-vapaita materiaaleja Emersonin 5408 koskettamattoman tutkan prosessitiivisteantennin osaan, joka on tällä hetkellä valmistettu PTFE:stä. Tässä diplomityössä toteutetaan systemaattinen materiaalinvalintaprosessi, jonka tarkoituksena on etsiä ja analysoida vaihtoehtoisia PFAS-vapaita materiaaleja kyseiselle tutkan osalle.

Materiaalinvalintaprosessin tuloksena polyeetterieetteriketoni (PEEK) ja polyfenyleenisulfidi (PPS) näyttävät olevan varteenotettavimmat PFAS-vapaat vaihtoehdot tässä kyseissä käyttötarkoituksessa. Tämän diplomityön perusteella PTFE:llä on kuitenkin hyvin ainutlaatuinen materiaaliominaisuuksien yhdistelmä, ja se ylittää ehdotetut vaihtoehtoiset materiaalit tässä työssä käsitellyissä avainparametreissa ja materiaaliominaisuuksissa.

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I would like to thank Emerson for supporting my studies and making this interesting master's thesis possible. Especially thanks for my supervisors Harri Eskelinen, Pekka Heikura and Lixue Hu. I would also like to give special thanks to my close ones and friends who have been supporting me during my master's thesis and studies in LUT University.

Lauri Paronen

Vantaa, 8.2.2024

SYMBOLS AND ABBREVIATIONS

Roman characters

A	area	m^2
C	cost	
D	distance	m
E	empty distance	m
f	frequency	Hz
L	length	m
p	pressure	bar, Pa
T	temperature	ºC
t	time	s
V	value	

Greek characters

ε	material permittivity	F/m
ε_0	vacuum permittivity	F/m
σ	stress	Pa
σ_{ts}	tensile strength	Pa
σ_y	yield strength	Pa

Constants

c	speed of light	299 792 458 m/s

Dimensionless quantities

n	refractive index
ε_r	dielectric constant

Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry
ECHA	European Chemicals Agency
EU	European Union
FMCW	Frequency Modulated Continuous Wave
ITRC	Interstate Technology & Regulatory Council
KEMI	Swedish Chemicals Agency
PAI	Polyamideimide
PE	Polyethylene
PEEK	Polyetheretherketone
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PI	Polyimide
POM	Polyoxymethylene
PP	Polypropylene
PPS	Polyphenylene sulfide
PTFE	Polytetrafluoroethylene
RADAR	Radio Detection and Ranging
SJR	SCImago Journal Rank

SNIP	Source Normalized Impact per Paper

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1 Introduction

This master's thesis is done in collaboration with Emerson Mölnlycke factory located in Sweden near the city of Gothenburg. The Mölnlycke factory is focused on manufacturing instruments for process level measurement. The purpose of this master's thesis is to conduct a systematic material selection process in order to search for alternative PFAS-free materials for Emerson's non-contacting level measurement radar process seal instead of currently utilized Polytetrafluoroethylene (PTFE) that falls under per- and polyfluoroalkyl substances (PFAS) materials.

1.1 Background and motivation

Per- and polyfluoroalkyl substances (PFAS) are group of over 10 000 known substances widely utilized in different kinds of industries and everyday products. PFAS are synthetic non-naturally occurring and they have been manufactured for decades. Excellent and diverse material properties explain the wide utilization of the PFAS such as stability, chemical and temperature resistance. Extremely strong carbon-fluorine bond is the basis of this stability and endurance. However, also due to its persistence the synthetic PFAS do not completely degrade in the environment, or the degradation process requires extremely long periods of time. Due to these reasons, PFAS are usually referred as "forever chemicals". Persistence causes bioaccumulation of the PFAS in the environment and gradually increases the concentration and enriches even further while moving towards the top of the food chain. In addition, contamination of water sources and soil has also been observed. (ECHA, 2023ab; KEMI, 2023.)

PFAS are known to be toxic and harmful to the environment and animals. According to the KEMI (Swedish Chemical Agency) and ATSDR (Agency for Toxic Substances and Disease Registry) there are several animal studies linking high exposure of the PFAS to adverse effects for example liver damage, changes to reproductive system, high cholesterol and even tumour development. There is currently limited knowledge of the effects of the PFAS in humans and the environment, but several of the PFAS are classified as potential carcinogens and toxins. (KEMI, 2023; ATSDR, 2023.)

Due to the adverse effects caused by persistence and bioaccumulation of the PFAS in the ecosystem there have already been several regulations, restrictions and bans on the use of different PFAS. The European Union has restricted the use of the Perfluorooctane sulfonic acids (PFOS) which is a subgroup of the PFAS for over a decade. (ECHA, 2023ab; KEMI, 2023.) Most recently in 2023 European Chemicals Agency (ECHA) announced its plan to restrict the use of more than 10 000 PFAS in the upcoming years (SGS, 2023; Echa, 2023ab).

1.2 Research objective

Emerson utilizes widely different Per- and polyfluoroalkyl substances (PFAS) in their extensive product portfolio due to the excellent and unique material properties of the PFAS. Research objective of this master's thesis is to seek for alternative and non-restricted materials for the Per- and polyfluoroalkyl substances (PFAS) and conduct a systematic material selection process. The research objective is to search and pursue similar material properties with the new alternative PFAS-free options. Ultimately the constraints based on material properties requirements are driving the material selection process. Dielectric constant, dissipation factor, chemical resistance, broad operating temperature range, low water absorption, pressure resistance and price are the key parameters to be considered in the material selection process.

1.3 Research problem and research questions

Due to the environmental concerns, Emerson's sustainability agenda and upcoming restrictions and ultimately possible bans on the use of PFAS it is extremely important for the Emerson to seek for alternative materials for the PFAS. Restriction of the PFAS materials can disrupt the Emerson's business since it is so extensively utilized and searching for alternative material options with similar material properties could be complicated and time-consuming. The changing of the material might also affect the geometry of the part, operating frequency and thus complicating the material change. The research question that this research should answer are:

- What alternative PFAS-free materials can replace the current material based on PFAS and how the possible replacement is justified?

1.4 Research methods

The research is based on literature review which focuses on searching the available information and scientific publications related to this topic. In the literature review background information about PFAS and its environmental impacts will be reviewed more in depth. The background information is utilized to form the basis for the material selection and it determines the requirements and constraints for the material selection. Systematic material selection process is followed and conducted in this master's thesis. Ranking system is defined based on the material property requirements of the company and the application. Different materials are reviewed, and possible new alternative materials are proposed with adequate and similar material properties meeting the set criteria. The material selection process utilizes the ranking in the evaluation of the possible alternative material options.

Results of material selection process are presented in the next part. In the final part of master's thesis, the results of the material selection process and are discussed and analysed. At this point it is clarified whether the goals of the thesis were achieved.

1.5 Scope

Due to the limitations, this master's thesis is specifically focused on the Emersons 5408 non-contacting process level radar and specifically the process seal part of the radar which is manufactured currently from polytetrafluoroethylene (PTFE) (Emerson, 2023c). PTFE is also commercially known as Teflon that falls under the PFAS material group (KEMI, 2023). In the Figure 1 we can see Emerson's Rosemount model 5408 non-contacting radar level transmitter with the PTFE wetted part process seal antenna option. The PTFE process seal is the white part in the bottom of the figure. (Emerson, 2023b.) Due to the limitations this thesis focuses in depth only on one possible alternative material group which seems to be the best choice based on the literature review done in this master's thesis material selection process.

Figure 1. Rosemount 5408 Non-Contacting Radar Level Transmitter with the PTFE process seal antenna (Emerson, 2023b).

1.6 Contribution

The contribution of this master's thesis is to provide and extensive comparison and collection of information about possible alternative PFAS-free material options for the non-contacting level radar's process seal part and ultimately support the company in the material selection. This information collected in this master's thesis, material selection process and the comparison between alternative materials can be possibly utilized also in different applications where PFAS based materials are utilized since the possible ban and regulations will potentially impact extremely many different applications.

2 Methods

The information in this research is obtained by conducting a literature review and searching for available information and scientific publications such as articles and books related to the topic. The systematic material selection process is conducted based on the information gained in the literature review. We can see a structure of the material selection process in the Figure 2 according to Ashby (2011).

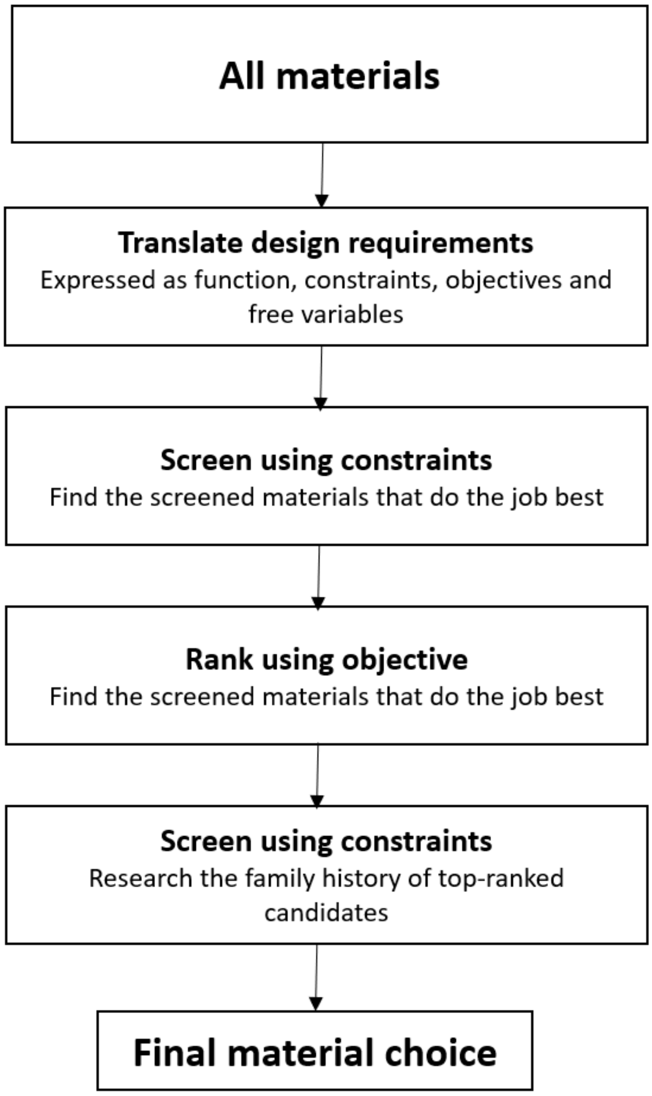


Figure 2. Material selection process (Ashby 2011, p. 103).

According to Ashby (2011) the material selection process starts with setting up the functional requirements. Constraints are also set for the material attributes, shape and process. Based on these set constraints and requirements materials are screened and unsuitable materials are screened out the from material selection process. Materials are ranked and evaluated based on the material attributes and how well they achieve the set objective. Final selection of the material is then done based on the ranking and supporting information that can be for example local expertise, already other commercially available products and other supporting documentation. (Ashby 2011, p. 99-106.) The material selection process should be started with including all of the material families because without doing so it can lead to a missed innovative opportunity (Ashby 2011, p. 98).

According to Ashby (2011), the material selection process is essentially interaction between the requirements of the function, shape, process and material. Setting a up requirement or a restriction for any of the four will also affect the other ones too. For example, functional requirement also sets restrictions for the shape and the material properties. (Ashby 2011, p. 23) In the Figure 3 by Ashby (2011) we can see the relationship between function, shape material and process.

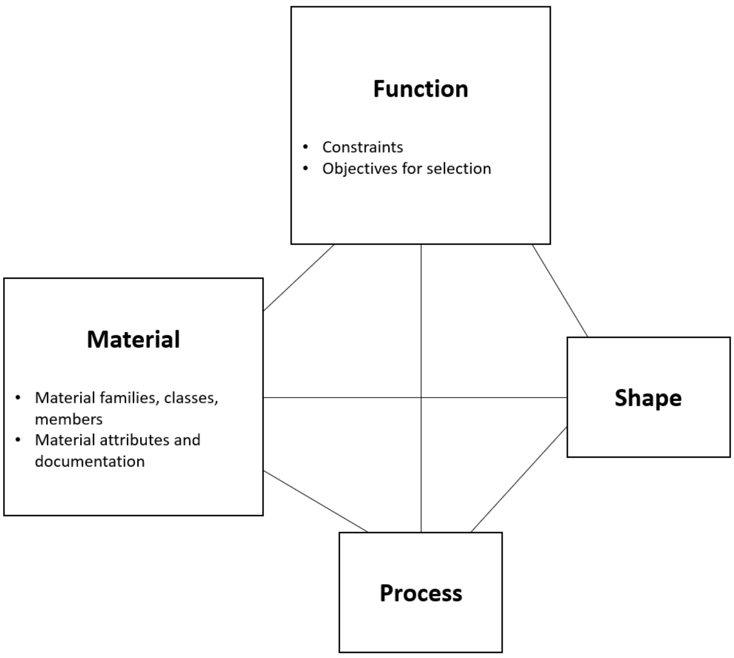


Figure 3. Material selection is mutual relationship between function, shape, material and process (Ashby 2011, p. 99).

The required functions of the product are essentially driving the material selection process according to Ashby (2011) since without fulfilling the functional requirements the product would be of no use. Ashby (2011) describes a case example of material selection for a helmet protective visor. The protective visor must be transparent in order to be able to see through thus being a functional constraint for the material selection process. The objective in this case is that the new material should be as tough as possible ensuring the protection of the eyes and face. (Ashby, 2011.)

The systematic material selection process according to Eskelinen & Karsikas (2013) shares some similarities with the Ashby (2011). Both material selection processes start with setting up the functional requirements and limitations. Eskelinen & Karsikas (2013) systematic material selection guide also gives many different tools that can be used in the material evaluation in the selection process. It also goes more in depth how materials can be evaluated in the material selection process. The value analysis is utilized in the material screening and ranking of the materials. In the Figure 4 we can see the systematic material selection process according to Eskelinen & Karsikas (2013).

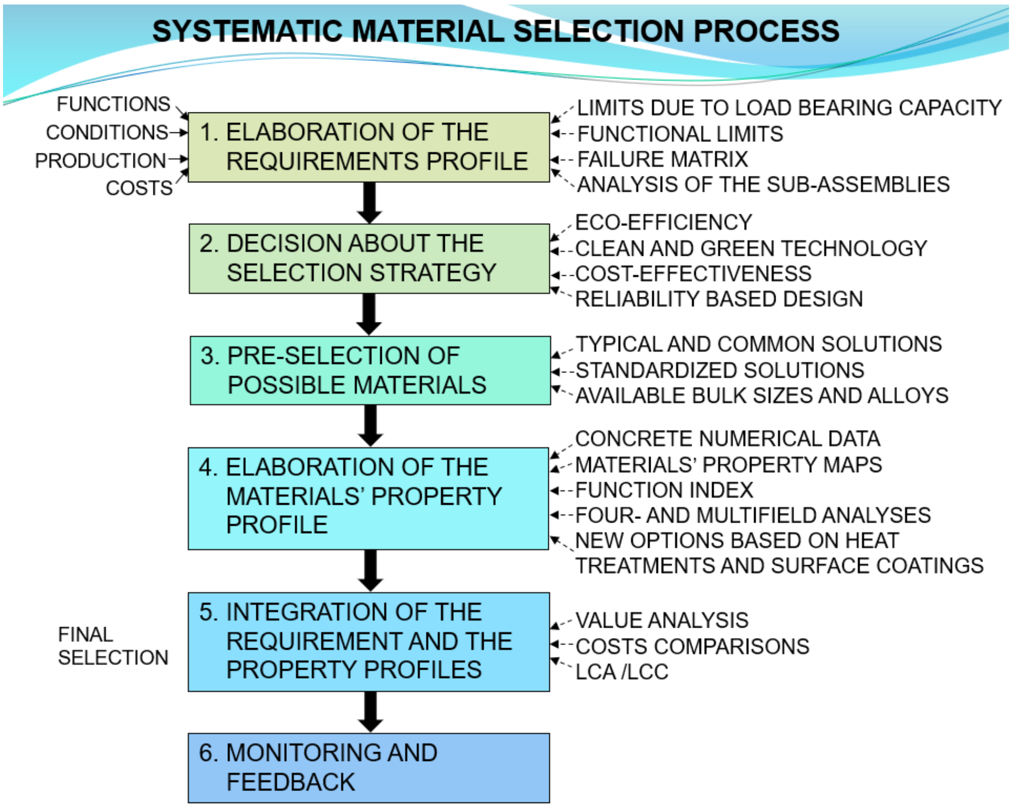


Figure 4. Systematic material selection process (Eskelinen & Karsikas 2013, p. 47).

The purpose of the value analysis is to evaluate the functional performance in relation to the cost. The equation of the value analysis can be seen below (Karlof & Lovingsson 2005, p. 384-385):

$$V = \frac{U(f)}{C(f)} \tag{1}$$

Where V is the value, U is the utility of the functions and C the cost of the functions.

As we can see from the Equation 1 if the cost increases the value decreases and on the other hand if the utility increases so does the value. In this master's thesis value analysis is utilized in order to evaluate the materials based on the relevant material properties determined by the application requirements.

This master's thesis material selection is done based on the guidance of the systematic material selection processes by Ashby (2011) and Eskelinen & Karsikas (2013) with few modifications. In this thesis, the background for the material selection is reviewed first. Based on the background information and requirements for the new material set by Emerson, the constraints and key parameters are also set for the material selection process. These constraints and key parameters are driving the material selection process. Next, the material families are screened based on the literature and common commercial solutions. The most suitable material family is left based on this screening process. Again, based on the literature and commercial solutions the materials inside the selected material family are further screened until handful of materials are remaining and selected for further analysis. Concrete numerical data about the key parameters is utilized in this phase in order to compare the selected materials. Materials are ranked based on the values of these key parameters and value analysis. Graphs, charts, and tables are utilized in the key parameter comparison. Finally, the most suitable materials based on the analysis are presented and the results of this thesis are monitored and discussed further.

3 Background and constraints for the material selection

In this chapter, the background of the master's thesis is discussed and the requirements and constraints for the material selection process are determined based on this background information.

3.1 Level measurement

Process level measurement is essential and very important for manufacturing facilities and plants. There are several different reasons to measure the process level in the industries and for example listed (Emerson, 2021):

- Safety and overfill protection
- Process control and management
- Inventory management
- Custody transfer

The process level can be measured with variety of different methods and technologies. There are for example continuous level, point level and interface measurement technologies. Point level measurements are utilized for example to give indication whether the tank is full or empty. Different kind of technologies are suitable for variety of different applications and processes. In the Figure 5 we can see an extensive table of different level measurement tecnhologies and their capabilities. This master's thesis focuses on the non-contacting radar level measurement technology which is a continous level measurement and is highlighted in the figure. (Gillum, 2009; Emerson, 2021.)

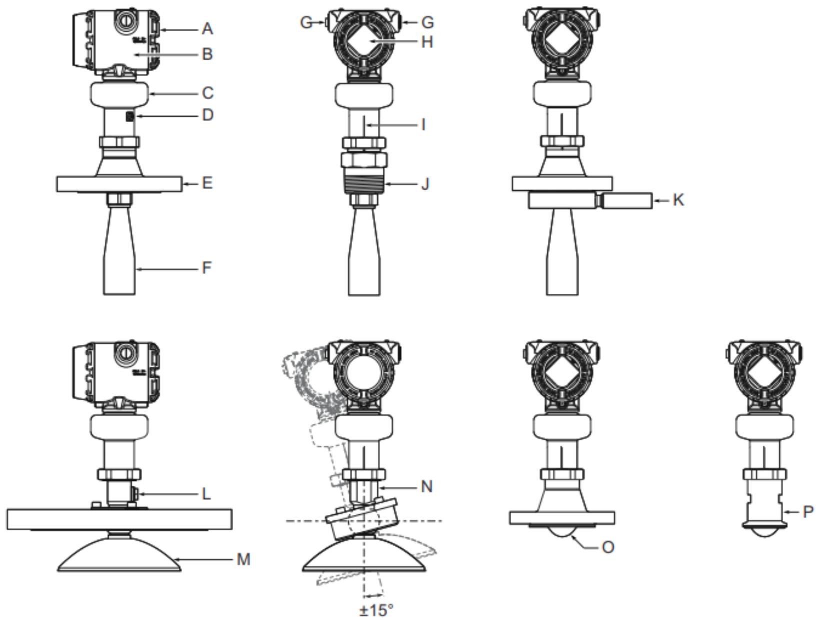
Level measurement category	Continuous level	Point level	Density	Interface	Mass
Manual/mechanical					
Float switches		x		x	
Float systems	x				
Rod gauging / dip probes	x	x			
Sight / gauge glasses	x			x	
Tape levels and tape systems	x		x	x	
Electromechanical					
Displacers	x		x	x	
Magnetostrictive	x			x	
Resistance tape	x				
Rotation suppression		x			
Servo	x			x	
Electronic contacting					
Capacitance	x	x		x	
Conductivity		x			
Optical		x			
Pressure based level technologies	x		x	x	x
Guided wave radar	x			x	
Hybrid (pressure level and radar)	x		x		x
Thermal		x			
Vibrating level (tuning fork)		x			
Ultrasonic gap sensors		x			
Electronic non-contacting					
Laser	x				
Load cells	x				x
Nuclear	x	x	x	x	
Non-contacting radar	x				
Ultrasonic	x				

Figure 5. Different level measurement technologies (Emerson 2021, p. 22).

3.1.1 Non-contacting radar

Radar (radio detection and ranging) level measurement instrumentation tecnhologies have been already available for decades. Non-contacting radars are top-down continous level measurement instrumentation typically used for example in tanks. The advantage of these non-contacting radars is that they are almost maintenance free because there are no moving parts and they are not in direct contact with the process media reducing the wear and corrosion. Non-contacting radars can be used with solids or liquids. There are many different types of antennas available for non-contacting radars and they are suited for different applications. Parabolic or cone style antennas are common types for example. (Gillum 2009, p. 376-398; Emerson, 2021.)

In the Figure 6 we can see Emerson's 5408 non-contacting radar structure with different optional antenna configurations. PTFE process seal antenna is marked with letter O. (Emerson 2023d, p. 14.)



- *A. Terminal compartment*
- *B. Transmitter housing (aluminum or stainless steel)*
- *C. Sensor module with signal processing electronics*
- *D. External ground screw*
- *E. Flanged process connection*
- *F. Cone antenna*
- *G. Two cable/conduit entries (½-14 NPT, M20 x 1.5, or G½); Optional adapters: eurofast™ and minifast™*
- *H. LCD display (optional)*
- *I. Alignment marker (one per side)*
- *J. Threaded process connection (NPT or BSPP (G))*
- *K. Air purge ring (option code PC1 for cone antenna)*
- *L. Integrated air purge connection*
- *M. Parabolic antenna*
- *N. Parabolic antenna with swivel mount*
- *O. Process seal antenna*
- *P. Tri Clamp process connection*

Figure 6. Emerson 5408 non-contacting radar structure (Emerson 2023d, p.14).

Non-contacting level measurement radars typically utilize two of the main technologies which are pulsed radar and Frequency Modulated Continous Wave radar (FMCW). Pulsed radar is based on the time-of-flight technology. Pulse radar sends a signal towards the process that is reflected upon hitting the surface of the process media. The transmitter calculates the elapsed time when the signal returns back to the transmitter. (Gillum 2009, p. 376-398.) In the Figure 7 derived from Endress (2023c) we can see the operating principle of the pulsed radar time-of-flight technology and how the level is calculated.

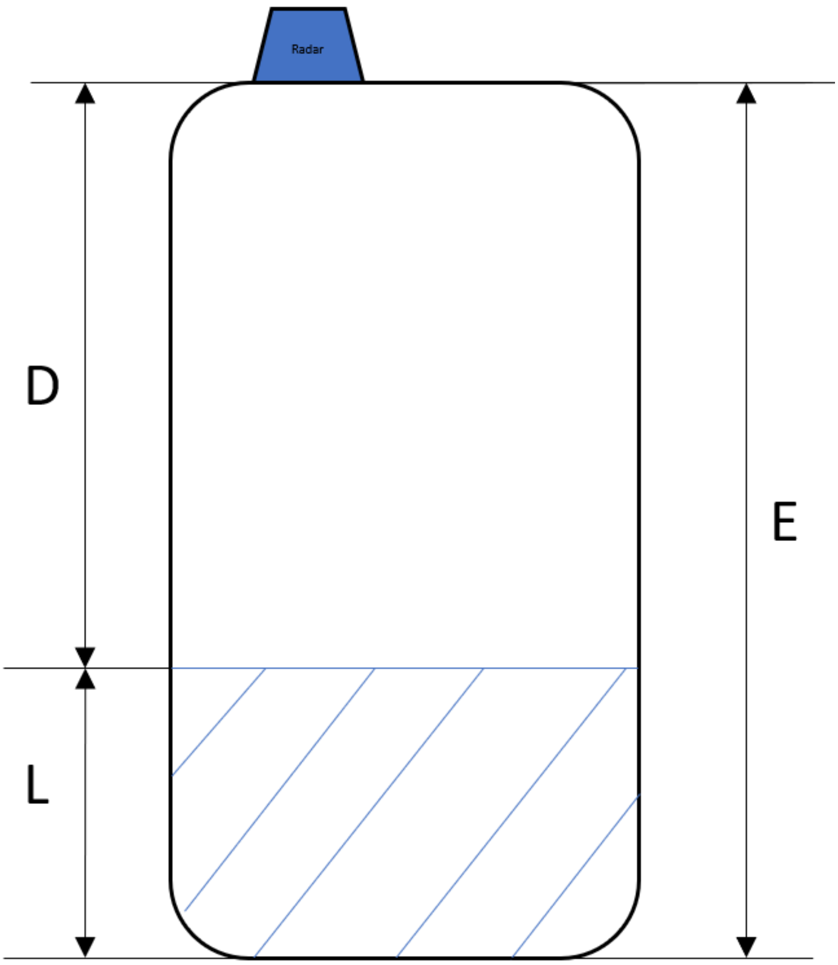


Figure 7. Pulsed radar time-of-flight technology (derived from Endress, 2023c).

The level transmitter calculates the distance according to the following equation below (Endress, 2023c):

$$D = c * \frac{t}{2} \tag{2}$$

In the Equation 2 D is the distance, t is time and c the speed of light.

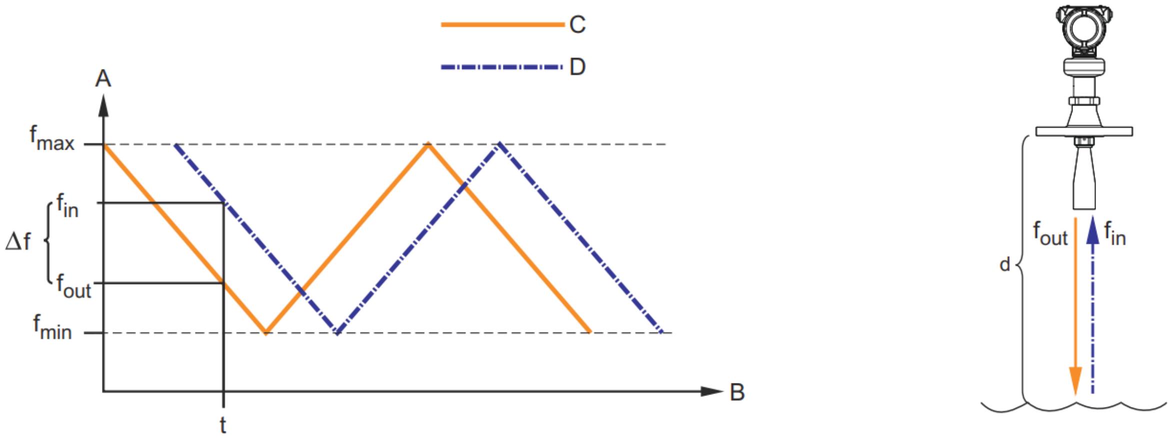
The level is then calculated based on the equation below. (Endress, 2023c):

$$L = E - D \tag{3}$$

In the Equation 3 L is the level, E is empty distance and D is the distance.

The disadvantage of the pulsed radar technology is that it has lower resolution and accuracy than the Frequency Modulated Continous Wave (FMCW) radar. Extremely short flight-times as low as few picoseconds has to be measured when high level of accuracy is required. The measurement resolution is throttled also by the capabilities and the accuracy of the measuring equipment. (Gillum 2009, p. 376-398.)

FMCW radar technology is different to the pulsed radar technology. The FMCW transmitter sends a continuous signal with altering frequency towards the process media which is then reflected back from the surface. The transmitter picks up the returning signal with different delayed frequency. The distance can be measured by utilizing this information because the delayed frequency is directly proportional to the distance. (Gillum 2009, p. 376-398.) FMCW technology operating principle can be seen in the Figure 8 below (Emerson 2023d, p. 9).



Δf~d=distance

A. Frequency (GHz)
B. Time (s)
C. Transmitted signal
D. Reflected signal

Figure 8. FMCW technology (Emerson 2023d, p. 9).

There are many large different instrument level radar manufactuctures and for example some of them are Emerson, Endress and Vega (Zeroinstrument, 2023). They utilize the similar measurement technologies and have PTFE in their products. In the Figure 9 we can see very similar looking Emerson, Endress and Vega Frequency Modulated Continous Wave (FMCW) radars in the same order from left to right. (Emerson, 2023b; Endress, 2023a; Vega, 2023.)

Figure 9. Emerson, Endress and Vega FMCW radars (Emerson, 2023b; Endress, 2023a; Vega, 2023).

3.1.2 Emerson 5408 non-contacting radar

The Emerson's 5408 non-contacting radar is a premium-tier radar based on the FMCW technology and it is suitable for the most challenging and demanding process applications. It can be also used in general purpose applications. The 5408 can be built with many different variable configurations. For example the performance class, material of construction, process connections and antenna type can be chosen and it affects directly the model code of the 5408 radar. The 5408 radar is built based on the model code. In the Figure 10 we can see an example of full 5408 model code and the decodification. (Emerson, 2023c.)

5408A1SHA2E17R4DASAA4

5408	Radar Level Transmitter
A	Profile: Standard Monitoring and Control Applications
1	Measurement Type: Liquid Level Measurement
S	Performance Class: Standard | +/-2mm | 40m
H	Signal Output: 4–20 mA with HART6
A	Housing Material: Aluminum
2	Conduit / Cable Threads: M20 x 1.5
E1	Hazardous Locations Certifications: ATEX Flameproof
7	Material of Construction: All PTFE Wetted Parts
R	Process Connection Type: Raised Face Flange
4	Process Connection Size: 4-in./DN100/100A
DA	Process Connection Rating: EN1092-1 PN16 Flange
SAA	Antenna Type Operating Temperature & Pressure: Process Seal Antenna | -15 … 363 psig (-1 ... 25 bar) | -76 … 392 °F (-60 … 200 °C)
4	Antenna Size: 4-in. (DN100) | Cone | Process Seal

Figure 10. Example of the 5408-model code (Emerson, 2023c).

The Emerson's 5408 non-contacting radar with process seal antenna (option code SAA in the Figure 10) has the following technical specifications (Emerson, 2023c):

- Operating pressure: -1 to 25 Bar
- Operating temperature: -60 to 200 °C

- Operating frequency: 24.05 to 27 GHz
- Measurement accuracy: +/- 2 mm standard (+/- 1 mm ultra-accuracy option)
- Measuring range: 40 m (standard range and accuracy options)
- Process seal material: PTFE

The PTFE process seal antenna is designed for challenging applications with highly corrosive process medias, applications with severe build-up and condensation and for the hygienic applications (Emerson, 2023c). We can see fully the PTFE process seal antenna part in the Figure 11 (Emerson, 2023e).

Figure 11. PTFE process seal antenna (Emerson, 2023e).

As we can see in the Figure 11 the seal part extends quite a lot inside towards the electronics of the radar device where the electromagnetic signal is generated. Emerson does not manufacture this PTFE process seal antenna part by themselves, it is directly procured in this shape from the Emerson's material supplier.

3.2 Per- and polyfuoroalkyl substances

Per- and polyfuoroalkyl substances (PFAS) are a large family of persistent synthetic compounds that contain at least one perfluoroalkyl moiety (Cheremisinoff 2017, p. 9). Difference between the perfluoroalkyl and polyfluoroalkyl is that perfluoroalkyls have fully fluorinated carbon chain and polyfluoroalkyls have partially fluorinated carbon chain. In the Figure 12 we can see se the basic chemical structures of per- and polyfluorinated substances. (KEMI, 2023.)

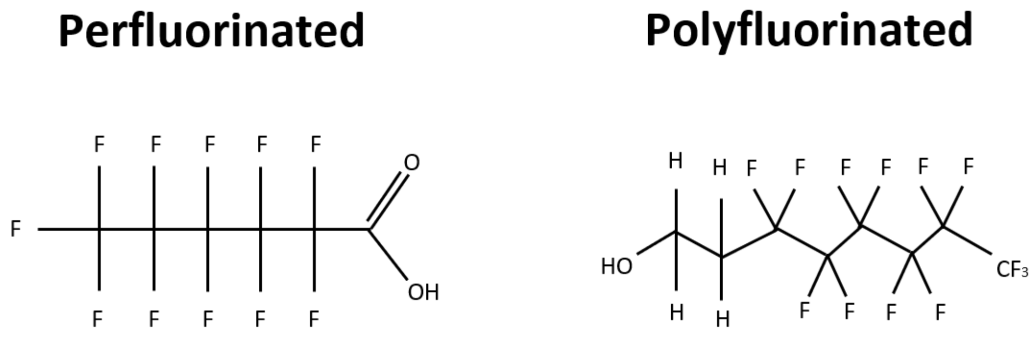


Figure 12. Per- and polyfluorinated chemical structures (KEMI, 2023).

Inside the PFAS family, there are many subgroups and compounds that have different and varying material properties (Cheremisinoff, 2017). In the Figure 13 we can see part of the PFAS family, and not all groups are visible in this figure (ITRC, 2023).

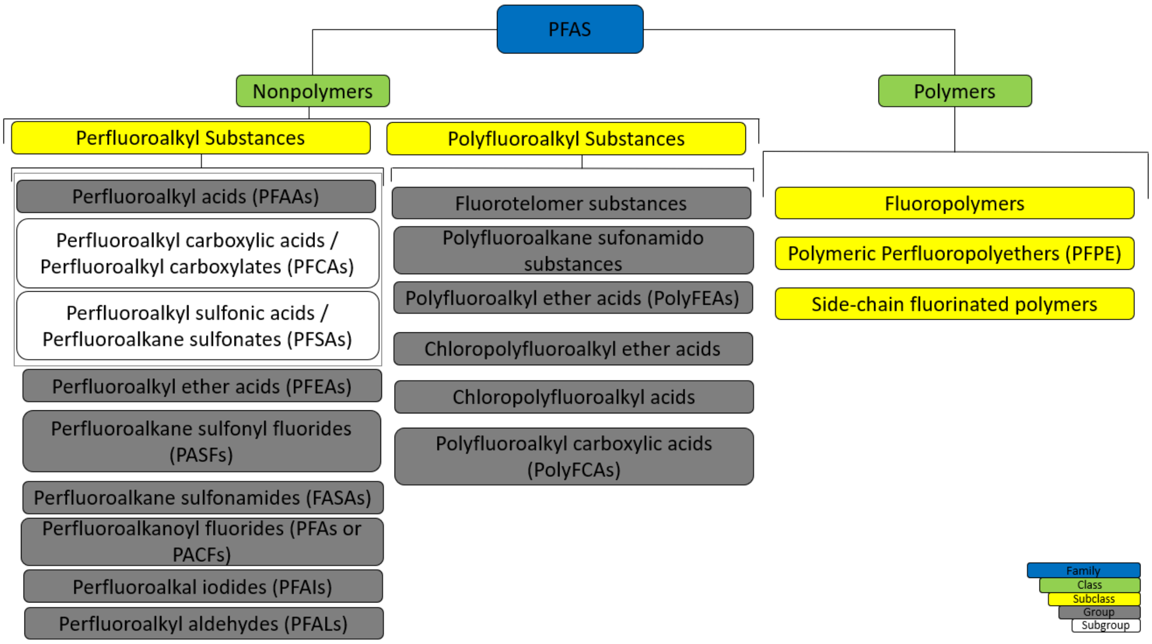


Figure 13. The family tree of PFAS (ITRC, 2023).

We can see from the Figure 13 that the PFAS family is large and separated into polymers and non-polymers which are then further branched into different subgroups.

The PFAS compounds have been utilized widely across different industries and everyday applications since their introduction in the 1940-50's and for example in coatings, textiles, electronics, manufacturing, automotive and aerospace industries. Many of the PFAS have excellent material properties that justify their widespread utilization. (Cheremisinoff 2017, p. 9-10.):

- Hydrophobic properties
- Lipophobic properties
- Thermal stability
- Chemical stability

The excellent material properties of the PFAS are associated with the extremely strong carbon-fluorine covalent bond that requires enormous amount of energy to break. The carbon-fluorine bond is one of the strongest covalent bonds in the organic chemistry. (ITRC, 2023.)

However, the persistence of the PFAS substances is also a major disadvantage and environmental concern. PFAS are often referred as “forever chemicals” due to extremely long time that is required to break down in the environment or not completely breaking down at all. (Meegoda, Kewalramani, Li & Marsh, 2020; KEMI, 2023). The persistence causes PFAS substances to bioaccumulate over time in the environment. Biomagnification also occurs with some PFAS substances on the way to the top of the food chain. (KEMI, 2023; Meegoda et al. 2020; Torres & De-la-Torre 2023, p. 1-3.)

Due to the wide utilization of the PFAS substances, they are found all over the environment and almost in all humans (KEMI, 2023). Food, drinking water, air and different kinds of customer goods are direct ways how humans are exposed to the various different PFAS substances (Blake & Fenton 2020, p. 1-11; Torres & De-la-Torre 2023, p. 1-3). In the Figure 14 we can see a good visualization of how the PFAS substances are spread and circulated through the environment contaminating it and eventually leading to human exposure (Torres & De-la-Torre, 2023).

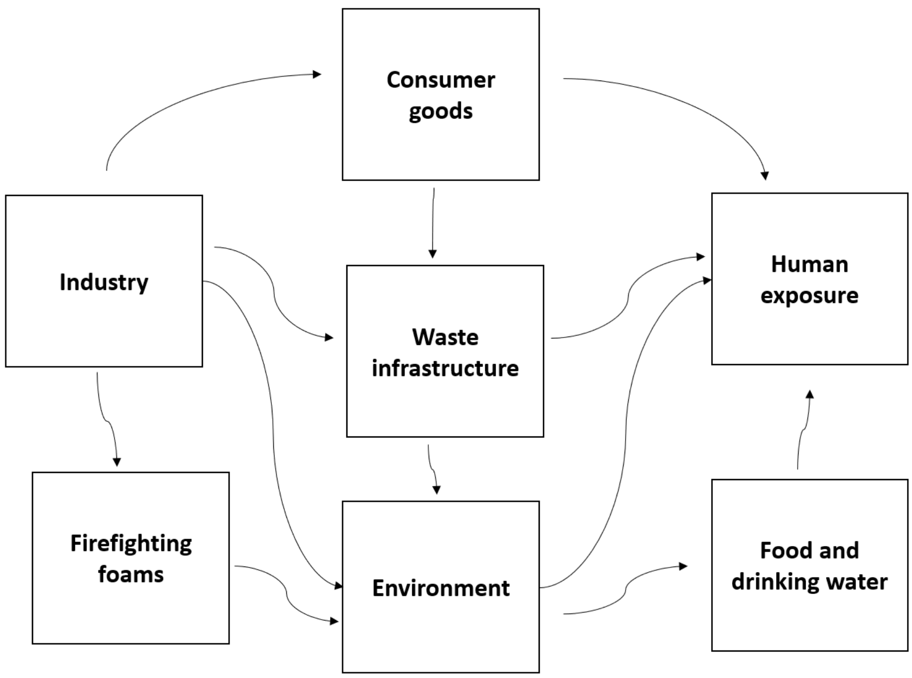


Figure 14. PFAS exposure (Torres & De-la-Torre 2023, p. 2).

Exposure to PFAS substances have been linked to several adverse effects in humans. PFAS subgroups PFOA and PFOS are considered as potentially carcinogenic and reproductive toxins. (KEMI, 2023; Blake & Fenton 2020, p. 1-11) According to ATSDR (2022) studies suggest that high levels of PFAS might cause the following adverse effects in humans (ATSDR, 2022):

- Increased risk of cancer
- High blood pressure
- Increased cholesterol
- Changes to liver enzymes
- Smaller infant birth weights
- Decrease of vaccine response in children

However, there is still limited amount of knowledge of the adverse effects caused by different PFAS and their mixtures (ATSDR, 2022; KEMI, 2023; Blake, & Fenton, 2020). Even though there is not yet sufficient information about the toxicity and adverse effects of all of the PFAS chemicals, according to KEMI there is still good reason to consider them as potentially harmful to the health (KEMI, 2023). The persistence of the PFAS could eventually lead to PFAS levels rising above the safe limits that are yet unknown (Lim, 2023).

The concerns about the detrimental effects of the use of PFAS have led to regulations, restrictions and bans in the recent years (ITRC, 2023; ECHA, 2023ab). In the Figure 15 by ITRC (2023) we can see an extensive list about some of the milestones and responses into the concerns risen from the use of PFAS starting from the year 2000 onwards in the United States.

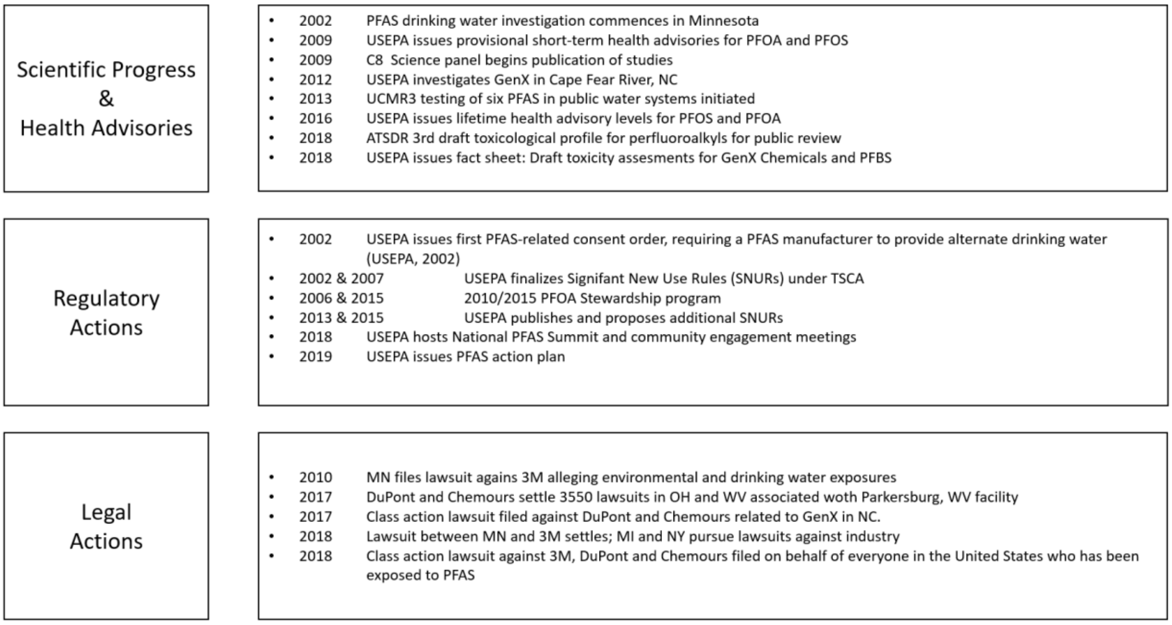


Figure 15. PFAS awareness in the USA in recent years (ITRC, 2023).

The restrictions on the use of Perfluorooctane Sulfonic Acids (PFOS) in the European Union have been effective for over a decade. Ban on the use of Perfluorooctanoic acids (PFOA) has been imposed in 2020. In early 2023 ECHA proposed a large restriction of use affecting around 10 000 PFAS. (ECHA, 2023a). Due to the regulations and possible upcoming bans a major PFAS manufacturer 3M has announced that they will end production of the PFAS by 2025 (Tullo, 2023). According to the Guardian (2023) article from July the EU has received heavy pressure from the industries to be severely less strict on the proposed ban on the PFAS (Guardian, 2023).

3.3 Polytetrafluoroethylene

Polytetrafluoroethylene (PTFE) is a fluoropolymer that is a subgroup of the PFAS family (ITRC, 2023). PTFE is more commonly known by its trademark name Teflon, and it was discovered in 1938 by DuPont employee Roy Plunkett. The PTFE chemical structure can be seen in the Figure 16. (Drobny & Ebnesajjad 2023, p. 3-5.)

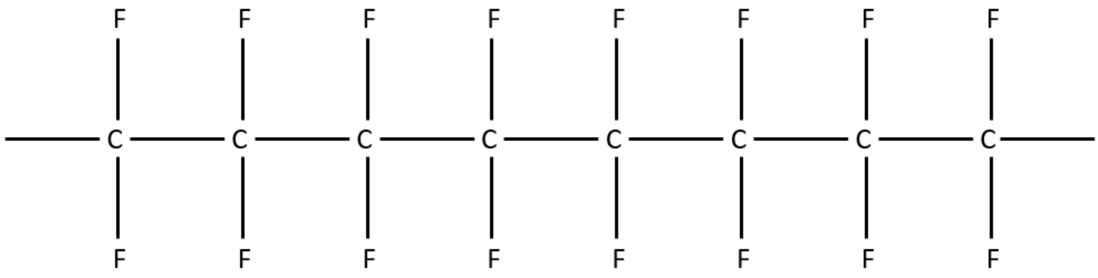


Figure 16. PTFE chemical structure (Drobny & Ebnesajjad 2023, p. 4).

The larger scale commercial production of the PTFE started in the late 1950s. PTFE is easily the most widely utilized fluoropolymer with over 50 % share of the consumption globally in 2023 as we can see in the Figure 17. (Drobny & Ebnesajjad 2023, p. 4-7.)

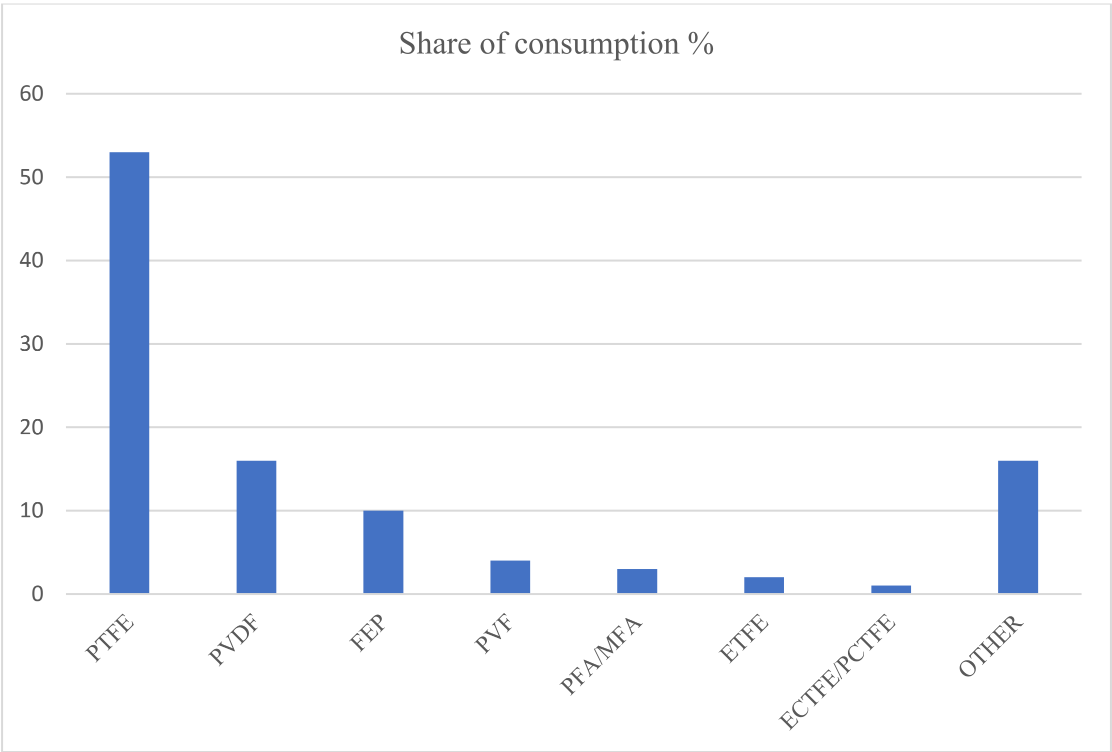


Figure 17. Different fluoropolymer shares of consumption in 2023 (Drobny & Ebnesajjad 2023, p. 7).

Similarly with other fluoropolymers the extremely strong carbon-fluorine bond protects the carbon backbone and is linked to the extremely good material properties of the PTFE.

Thermal stability and excellent chemical resistance of the PTFE is directly linked to these extremely strong bonds. The outer layer of fluorine also causes the PTFE to have non-stick properties with lower coefficient of friction. (Drobny & Ebnesajjad 2023, p. 51-55.)

PTFE has excellent chemical resistance for various of different chemicals but can be attacked by fluorine, fluorine compounds in elevated temperatures and molten or dissolved alkali metals such as potassium and sodium (Standard Fluoropolymers, 2023).

Limitations of PTFE are the low mechanicals properties such as softness, creep resistance and abrasion resistance. These limitations can be tackled by utilizing fillers. Glass filled-PTFE or harder polymers for example PEEK or PPS are used as filler materials. (Kemmish 2011, p. 110-111.)

Dielectric and electrical properties of the PTFE are also exceedingly good and justify its wide utilization in microwave applications (Eskelinen & Eskelinen 2003, p. 64). According to Drobny & Ebnesajjad (2023) the dielectric constant of the PTFE remains the same in the frequency range from 5 Hz to 10 GHz and temperature range from -40 to 250 °C (Drobny & Ebnesajjad 2023, p. 58).

According to Lim (2023) article there is no other material like PTFE or it is near impossible to find a replacement with all the similar material properties of PTFE. However, the replacement material could only have the few necessary material properties depending on the application. (Lim, 2023.) According to ITRC (2023) PTFE and fluoropolymers in general have been considered as polymers of low concern in the PFAS regulation. PTFE itself can possibly have small environmental risk but in the manufacturing phase releases of other known harmful PFAS have occurred. (ITRC, 2023.) According to the article by Lohmann, Cousins, DeWitt, Glüge, Goldenman, Herzke, Lindstrom, Miller, Ng, Patton, Scheringer, Trier & Wang (2020) there are actually serious environmental concerns about the polymers of “low concern” since other dangerous PFAS are emitted to the environment during the manufacturing, use and disposal phases of the fluoropolymers. It is said in the article that limited amount of industrial fluoropolymer waste are recycled and even less from consumer waste. Recycling is said to be difficult because the waste is also contaminated with other unwanted substances. The article mentions the example case of fluoropolymer coated non-stick pan that will likely encounter uncontrolled breakdown of the fluoropolymer in metal smelter and cause PFAS emissions. Disposal of the fluoropolymer by landfilling is also an environmental concern because of the PFAS leachate. There is also major concern about the incineration of fluoropolymers since there is limited data available of whether fluoropolymers are totally destroyed in the incineration process and especially in the case of standard municipal waste incinerator without forming other toxic PFAS in the process. (Lohmann et al. 2020.) Globally 9 % only of the total plastic waste recycled was recycled in 2019. In the Figure 18 we can see the share of plastic disposal methods (OECD, 2023).

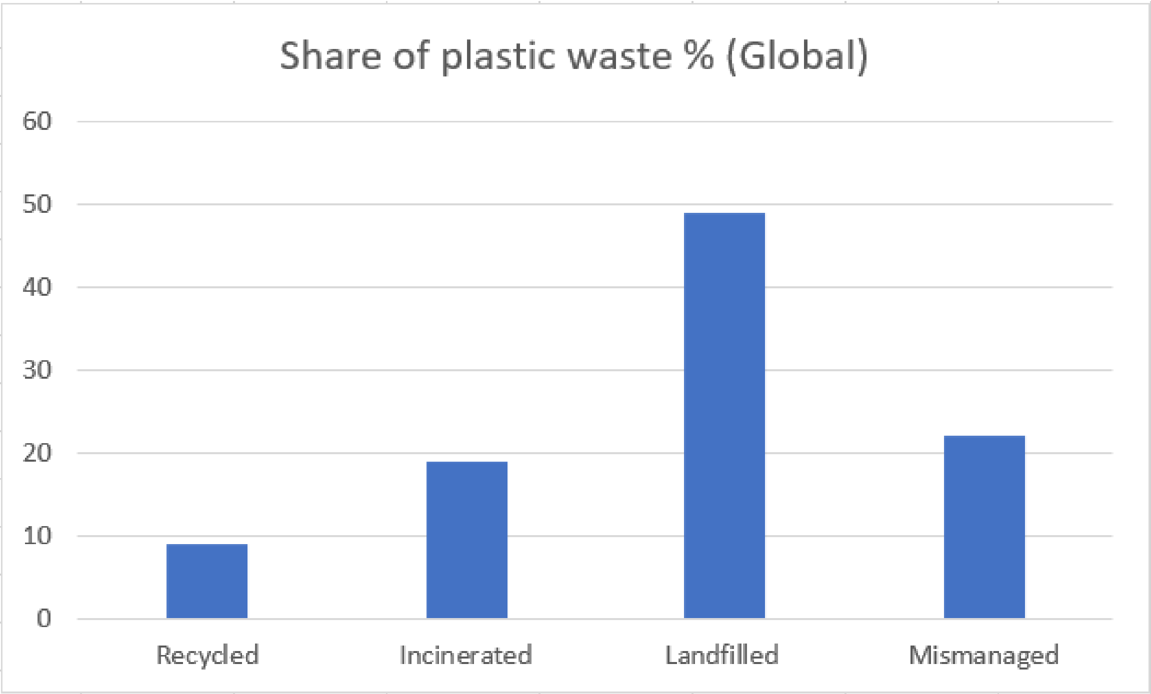


Figure 18. Disposal method of all plastic waste in 2019 (OECD, 2023).

As we can see from the Figure 18 alarming numbers of plastic waste are mismanaged and landfilled. Most of the plastic waste is landfilled as we can see from the figure but there are no safe landfills and even modern barrier protected landfills eventually leak to the environment (Pecci, 2018). According to Greenpeace (2023) plastic recycling is also not that straightforward and good solution. Plastics are made of 13 000 different chemicals with 3200 of those being chemicals of concern. Recycling plastics will also transfer the hazardous chemicals in the process. Recycling can combine chemicals from different plastics and create new hazardous chemicals in the process. (Greenpeace, 2023.)

According to the R5-principle of the waste reduction hierarchy the most important thing is to refuse, refuse to generate unnecessary waste. Second is to reduce the use of wasteful products. Third comes reuse, reuse the product if possible. Fourth is repurpose, find alternative use for the product. Recycling should be the last option based on the R5-waste hierarchy that can be seen in the Figure 19. (Roadrunner, 2023.)

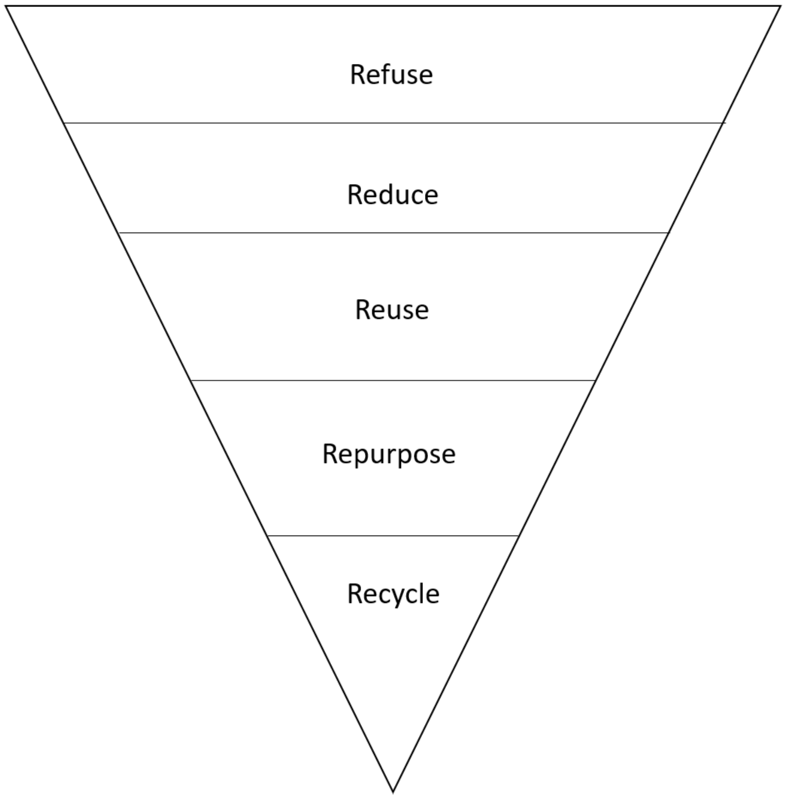


Figure 19. R5-waste hierarchy (Roadrunner, 2023).

Next, the material properties of the PTFE are analysed. In the Table 1 we can see relevant material properties of the PTFE for this specific non-contacting radar application and based on the material property requirements determined by Emerson.

Table 1. Relevant PTFE material properties (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	Value
Dielectric constant at 1 MHz	2,1
Dissipation factor at 1 MHz	0,0003
Maximum continuous service temperature (°C)	260
Minimum service temperature (°C)	-200
Compressive strength (MPa)	47,7
Tensile strength (MPa)	27,5
Tensile Modulus (MPa)	425
Water absorption, equilibrium in water at 23 °C (%)	0
Chemical Resistance	Excellent
Relative price to PE	16,7

As we can see from the Table 1 backed by numerical data, PTFE has excellent dielectric properties with low dielectric constant and dissipation factor. PTFE has extremely wide continuous service temperature range. Chemical resistance is excellent and there is virtually no water absorption.

3.4 Constraints and requirements for the material selection

Next, the requirements for the new 5408 non-contacting radar process seal antenna material are determined. The main criteria is that the new material must be free of per- and polyfluoroalkyl substances (PFAS). The new material should obviously be able to pass through the radar's electromagnetic waves in order to function as intended. The non-contacting radar is not in direct contact with the process media, but it is exposed to the operating and atmospheric conditions (e.g., closed tank or open atmosphere). The new material should be able to handle these conditions such as operating temperature and operating pressure. The process seal lens antenna is exposed to different kinds of chemical vapours, condensate and build-up and therefore the new material should have high chemical resistance, be resistant to water absorption and preferably have also non-stick properties. Since the 5408 non-contacting radar is designed for wide variety of different and challenging applications the new material should have also wide operating temperature range and have high chemical resistance for various of different chemicals. (Emerson, 2023c.)

Emerson has determined several key parameters and material properties that should be specifically considered in the material selection process. These key parameters are the basis of the material selection, and the goal is to pursue similar or better material properties as PTFE with the new alternative PFAS-free material:

- Low dielectric constant
- Low dissipation factor
- Wide operating temperature range
- High chemical resistance
- Strength
- Low water absorption
- Price

These key parameters are further analysed in the following subparagraphs.

3.4.1 Dielectric constant and dissipation factor

Dielectric constant or relative permittivity is electrical property of a medium. It is a dimensionless quantity that expresses insulators tendency to polarize. Dielectric constant is the ratio of the dielectric constant of the medium and vacuum. (Ashby 2011, p. 51-54.) According to Sebastian (2008, p.11) the relative permittivity is defined as following: “The relative permittivity of the material shows its energy storing capacity when a potential is applied across it.” According to Singh & Ulrich (1999) material with less than 3.9 dielecric constant is classified as low dieclectric constant material and higher than 7 is classified as high dielectric constant material (Singh & Ulrich, 1999). For comparison vacuum has a dielectric constant of 1, Air 1.006, Polypropylene 2.2, Aluminun Oxide 8.5 (Zulkifli, Johar, Marwah, & Ibrahim, 2017) and water around 80 (Hu, Liu, Ren, Saeed, Wang, Cui, Huai, Huang, Xia, Fu, Zhang & Chen 2022, p. 678). The dielectric constant or relative permittivity can be shown with the following equation below. (Ashby 2011, p. 51-54):

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{4}$$

Where ε_r is the dielectric constant, ε permittivity of the material (F/m) and ε_0 permittivity of free space or vacuum (F/m).

Electromagnetic losses occur in materials that are not perfect dielectrics (conductive materials). Electromagnetic waves (for example microwaves or radio waves) which travel through these non-perfect dielectrics attenuate in the process and lose some of the energy carried by the electromagnetic wave and it gets converted into heat. On the other hand, perfect dielectric material does not absorb any energy of the electromagnetic wave and attenuate it. (Ulaby & Long 2014, p. 35-38.) According to Omnexus (2023) the dissipation factor and loss tangent tan (δ) refers to the same dimensionless material property that measures how much of the electrical energy gets absorbed in the material and most of it is converted into heat. Low dissipation factor value is associated with polymers. Temperature, humidity and frequency affects the dissipation factor. (Omnexus, 2023a.)

Dielectric constant of the material can be also affected by many different variables such as (Sebastian 2008, p. 11-43):

- Frequency
- Temperature
- Humidity
- Pressure
- Porosity

If water is absorbed into the polymer material the dielectric constant increases because the dielectric constant of water is around 80 (Hu et al. 2022, p. 678).

Propagating microwaves are slowed when entering dielectric material. Lower permittivity is linked to higher microwave propagation speed. Material refractive index is related to the dielectric constant with the following equation below (Sebastian 2008, p.11.):

$$\varepsilon_r = n^2 \tag{5}$$

Where ε_r is the dielectric constant and n is the dimensionless refractive index (Sebastian, 2008, p.11).

Higher refractive index is linked with higher dielectric constant and higher material density (Ashby 2011 p. 54).

Dielectric lens antennas utilize this phenomenon where electromagnetic waves propagate slower through material with higher dielectric constant. The lenses shape causes the electromagnetic waves propagating from to source to straighten and form a planar wave. The dielectric lens also causes the returning planar wave to converge. We can see the operating principle of the dielectric lens antenna in the Figure 20. (Das 2014, p. 877-878.)

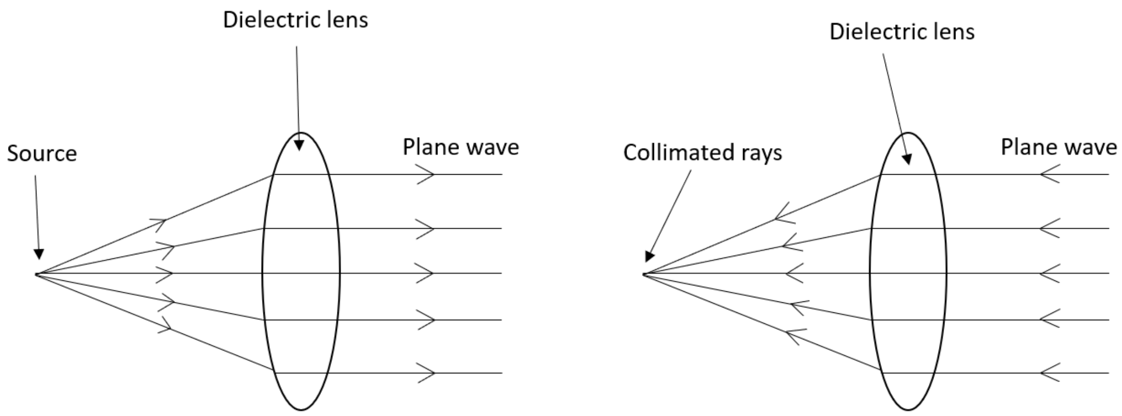


Figure 20. Dielectric lens operating principle (Das 2014, p. 877).

According to Cruickshank the purpose of aiming for low dielectric constant in radar and radome applications is to minimize the electromagnetic losses when propagating through material, increase the transparency for electromagnetic waves and reduce the reflections (Cruickshank 2011, p. 165).

According to Choudhury (2019) low dielectric constant can be achieved with lower density and by decreasing the polarizability by using low-polar chemical bonds such as carbon-carbon and carbon-hydrogen. In low dielectric applications polymers and silica-based materials are commonly used. However, the main problem with polymers is thermal property limitations. (Choudhury 2019, p. 6-8.)

The request by Emerson is that the new material should pursue the similarly low dielectric constant as of PTFE 2.1.

3.4.2 Temperature

Wide operating temperature range is required from the new material, since process level radars are operated in various of different temperatures (Emerson, 2023c). Maximum service temperature tells the maximum service temperature of the material without significantly degrading its properties for example causing high creep or chemical change. On the other hand, minimum service temperature tells when the material becomes unsafe to use for example because of the brittleness. (Ashby 2011, p. 46-47.)

3.4.3 Chemical resistance

The non-contacting radar is exposed to the process conditions and different kinds of corrosive fumes. The Emerson's 5408 radar is a premium tier radar for most demanding applications and therefore high chemical resistance to different substances, similar to PTFE is required from the new alternative PFAS-free material. (Emerson, 2023c.)

3.4.4 Strength properties

Strength properties of the new materials are evaluated based on tensile strength, compressive strength, and tensile modulus. According to Ashby (2011), tensile strength displays the ultimate tensile strength before failure and compressive strength displays how much the material can resist compression which is the opposite of tensile stress (pull). For example, polymers tend to have 20 % higher compression strength than tensile strength. Tensile modulus or Youngs modulus is the slope of stress-strain curve displaying the response to compressive or tensile load. In the Figure 21 by Ashby (2011) we can see a stress-strain curve. (Ashby 2011, p. 38-40.)

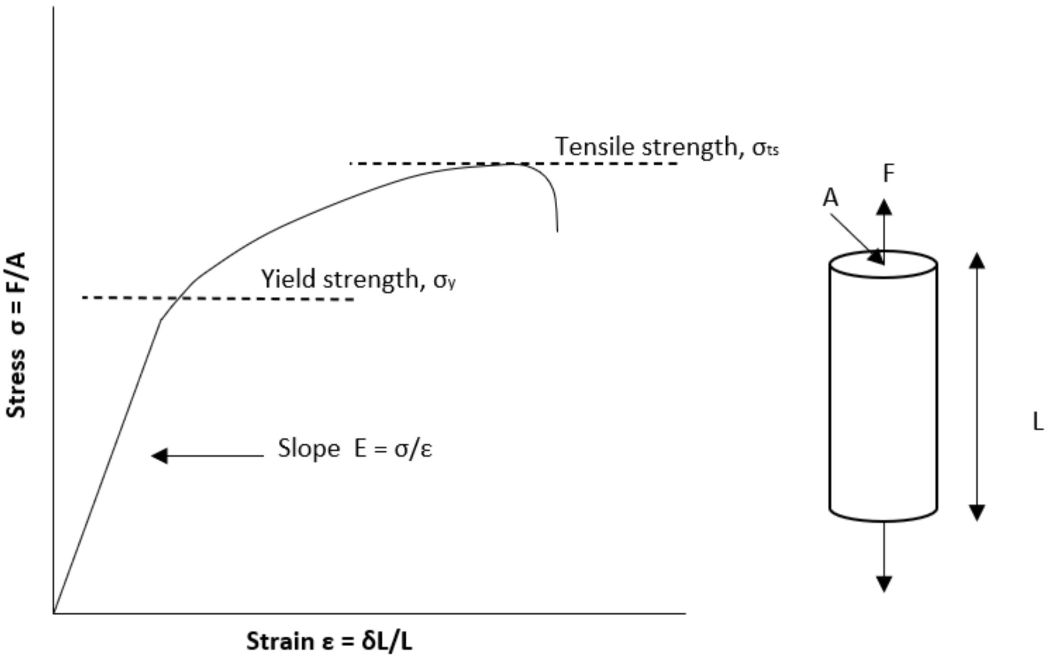


Figure 21. Stress-strain curve (Ashby 2011, p. 38)

3.4.5 Water absorption

Low water absorption is required from the new material since it also affects the dielectric properties of the material (Hu et al. 2022, p. 678; Omnexus, 2023a). Water absorption also decreases the polymer aging resistance, strength and electrical properties and it also causes dimensional changes (Omnexus, 2023a). Water absorption of the materials is evaluated based on the equilibrium in water at 23 °C (%).

3.4.6 Price

Prices are dependant from multiple different factors such as agreements, discounts, availability, demand, and size of the batch. The price of the alternative materials is evaluated based on the available pricing information. Relative prices compared to the polyethylene are utilized in the evaluation. In the value analysis of the materials the functional points are divided with the relative prices according to the Equation 1.

3.4.7 Background and material selection constraints summary

PFAS-free alternative materials are searched for because of the upcoming regulations on the use of PFAS due to the rising environmental and health concerns. The application where the new material is searched for is non-contacting radar process seal antenna and it has to able to pass through the radar waves in order to operate as intended. The currently utilized PTFE material that falls under the PFAS material group is extremely versatile material with unique combination of material properties. The new PFAS-free material should pursue similar materials properties as PTFE and the key parameters that are driving the material selections are dielectric constant, dissipation factor, temperature range, chemical resistance, strength, water absorption and price.

4 Material selection

This chapter focuses on the material selection for the non-contacting radar process seal antenna. First, the material families presented. Next, the material families are screened based on the set constraints and requirements and then screened based on the common commercial applications. Based on these screenings only one material family is left and the materials inside the family are screened further with the same conditions. Next, the handful of materials are analysed and evaluated based on the concrete numerical data regarding the key parameters.

4.1 Material families

According to Ashby (2011), materials are usually categorized into 6 different families of materials: metals, polymers, ceramics, glasses, elastomers, and hybrids. We can see the 6 families of materials and some of the common materials inside the families illustrated in the Figure 22. (Ashby 2011, p. 33.)

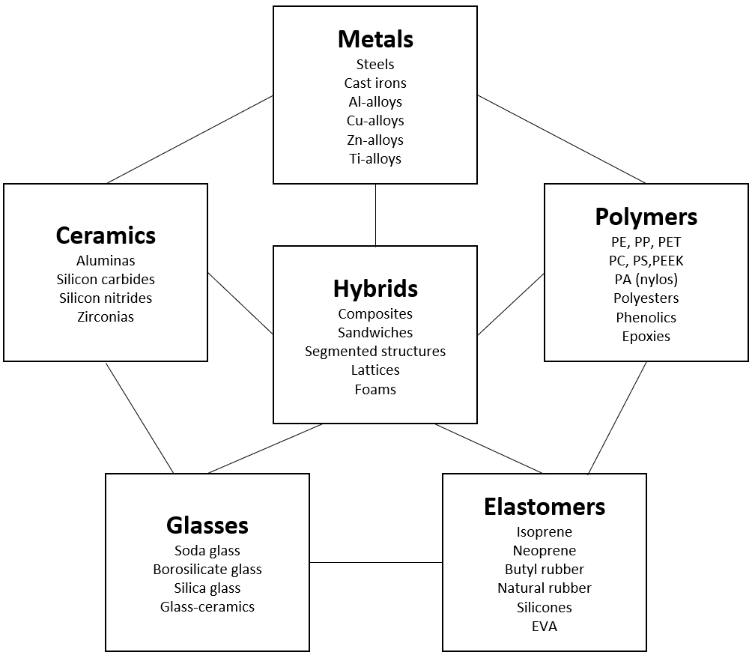


Figure 22. Families of materials (Ashby 2011, p. 33).

Next, the main characteristics of these presented six different materials families are discussed and outlined. In this research, the material selection process focuses on the most suitable material family based on the literature reviewed further.

Polymers have many great material properties, they are easy to shape, generally inexpensive and exhibit great corrosion resistance. They have low modulus of elasticity but high strength-to-weight ratio and have dielectric properties. (Brinson & Brinson, 2008, p. 69.)

Elastomers have exceedingly low modulus of elasticity that increases when temperature increases. Isoprene and neoprene are examples of common elastomers. (Ashby 2011, p. 33-34.)

Ceramics are brittle but very hard and abrasion resistant. They can handle also very high temperatures and have good corrosion resistance. (Ashby 2011, p. 33-34.)

Glasses have similar material properties to ceramics they are very hard but brittle. Silica glass and soda glass are examples of common glass materials. (Ashby 2011, p. 33-34.)

Metals have high elastic moduli and are stiff. Pure metals are typically easily deformable and soft but alloying and different treatments can make them very high strength. Metals are vulnerable to corrosion. (Ashby 2011, p. 33.)

Hybrid materials combine two or more materials and their attractive material properties. These can be very expensive and not easy to manufacture. (Ashby 2011, p. 35.)

4.2 Material screening based on the set constraints and requirements

Since high corrosion resistance, good dielectric properties, low price and easy formability are required from the new PFAS-free alternative material, the polymers material family seem a good and reasonable choice. Ceramics could also be potential material, but these set constraints are still leaning more towards the polymer's material family. Since low dielectric constant is one of the key parameters it should be specifically considered in the material selection process. The metals material family are screened out because these are the opposite of dielectrics being conductive, and metals are also vulnerable for corrosion (Ashby 2011, p. 33). As previously stated according to the Choudhury (2019) low dielectric constant is a characteristic associated with polymers and silica-based materials. Low dielectric constants are also associated with low-polar chemical bonds and low densities that polymers have. (Choudhury 2019, p. 6-8.) Ceramics seems to have higher dielectric constants compared to polymers based on the Eskelinen & Eskelinen (2003) book. The current material used in the process seal antenna which is PTFE fluoropolymer also supports and suggests the material selection from the polymer family (Emerson, 2023c). The material properties can also be tailored for the application by utilizing reinforcing filler materials. PTFE can be glass-filled or reinforced example with PEEK or PPS to tackle its own limitation. (Kemmish 2011, p. 110-111.)

4.2.1 Material screening based on commonly used materials in microwave applications

In this part of the material selection process materials that are common and typical in similar applications are searched. According to Eskelinen & Eskelinen (2003) polymers are commonly used in microwave applications. There are wide variety of different kinds of polymers but some of most notable and useful in microwave applications according to Eskelinen & Eskelinen (2003) are PTFE (polytetrafluoroethylene), PEEK (polyetheretherketone) and PE (polyethylene). (Eskelinen & Eskelinen 2003, p. 64-65.)

The radome case study example by Ashby (2011) suggests polymer material for radome applications because the material must be transparent to microwaves and minimize absorption and reflections. Polymers PP (polypropylene), PE (polyethylene), PPS (Polyphenylene sulfide), PAI (polyamideimide) and PTFE (polytetrafluoroethylene) are mentioned in the Ashby (2011) radome case study example. Ceramics are also proposed for applications with exceptionally high temperature such as Silica (SiO2) and alumina (Al2O3). (Ashby 2011, p. 189-194.) However, based on the Eskelinen & Eskelinen (2003) book, ceramics tend to have much higher dielectric constants when compared to polymers and thus supporting the choice of the new material also from the polymer family.

Based on the market research and publicly available information, polymer materials are widely used in the similar non-contacting radar applications as Emerson's 5408. For example Endress+Hauser offers PEEK and PTFE antenna with Micropilot FMR62 (Endress, 2023ab). Vega has PP, PEEK and PTFE available with Vegapuls 6X non-contacting radar (Vega, 2023). Siemens Sitrans LR250 radar has PP and PTFE lens antenna options available (Siemens, 2023).

4.2.2 Further material screening

The screening based on the set material requirements and screening based on the commonly used materials on microwave applications both suggest material selection from the polymer family as the choice for the new alternative PFAS-free material. Supported by the material screenings and due to the limitations only the polymer material family is discussed further in this thesis. Since there are so many different polymers only the most widely known and commercial polymers are discussed also due to the limitations. Based on the screenings done and commercially available solutions PEEK, PPS, PP, PE and PAI are taken into further consideration at this point. In the Figure 23 by de Leon, da Silva, Pangilinan, Chen, Caldona, & Advincula (2021) we can see hierarchy of common polymers based on the chemical resistance, temperature resistance and mechanical strength.

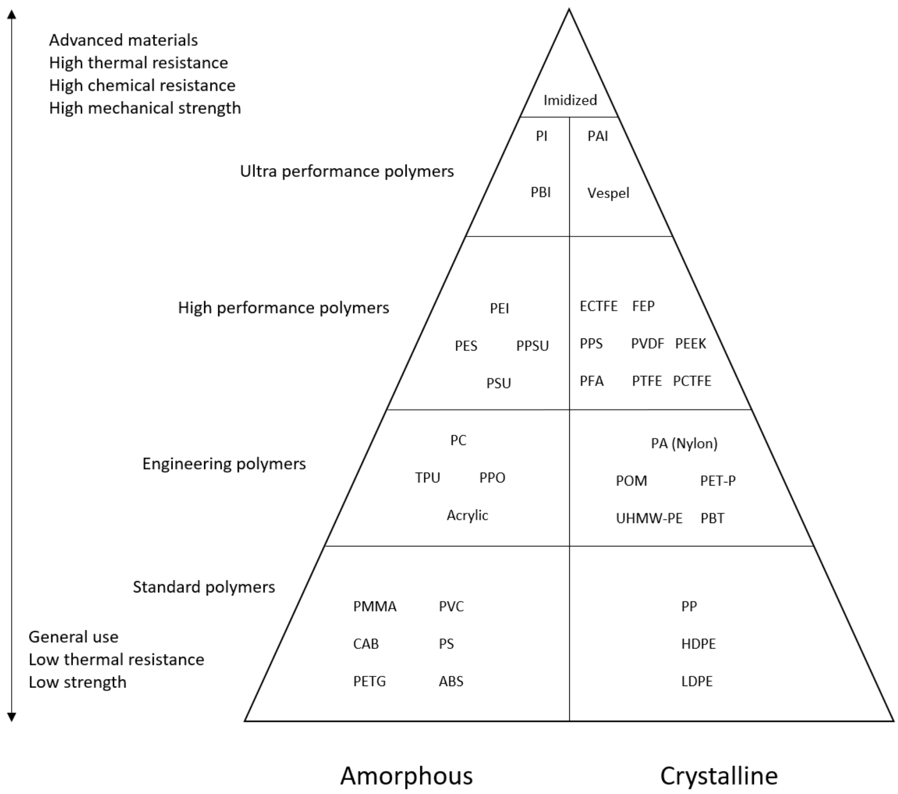


Figure 23. Polymer material hierarchy (de Leon et al. 2021, p. 162).

Already selected polymers based on the screening and commercial solutions can be seen also in this Figure 23 and how they rank in the hierarchy.

Low water absorption is required from the material and according to Ensinger (2023) PEEK, PE, PPS, PE, and PE are examples of polymers with very low water absorption and POM has low water absorption rate. On the other hand, PTFE has virtually zero water absorption rate. (Ensinger, 2023a.)

Dimensionally stable polymers are for example PPS, PEEK and PI, that have the ability to retain their dimensions despite of the underlying environmental conditions. Dimensionally stable polymers have low thermal expansion rate. (Ensinger, 2023a.)

POM and PI that can be seen also in the Figure 23 are the final polymers taken into further consideration because of the relevant good material properties such as low water absorption and high dimensional stability. In the final screening phase, the following materials are discussed and analysed further:

- PEEK
- PPS
- PAI
- POM
- PP
- PI
- PE

4.2.3 Polyetheretherketone

Polyetheretherketone (PEEK) is a high-performance thermoplastic polymer. PEEK has excellent mechanical strength, chemical resistance, and thermal resistance alongside with excellent creep resistance and dimensional stability. PEEK has low coefficient of thermal expansion ensuring dimensional stability and it has also low water absorption. Machining, injection moulding and extrusion can be utilized in PEEK processing. (Ensinger, 2023b.) Despite of the exceptional performance PEEK has also limitations. PEEK has low resistance to UV light, and it is very expensive. PEEK is vulnerable to acids (such as nitric acid and sulfuric acid) and halogens. (Omnexus, 2023b.) According to Wastetrade (2023) Mechanical and chemical recycling methods can be used to recycle PEEK but it is expensive (Wastetrade, 2023). In the Figure 24 by Omnexus (2023) we can see the chemical structure of the PEEK.

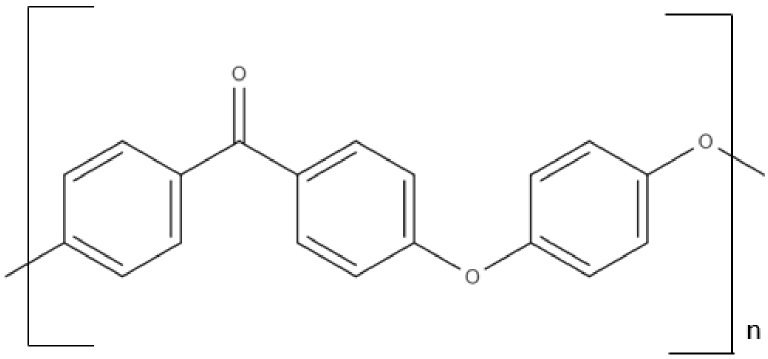


Figure 24. Chemical structure of PEEK (Omnexus, 2023b).

In the Table 2 below we can see the relevant material properties of PEEK.

Table 2. Relevant material properties of PEEK (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Dielectric constant at 1 MHz	3,2
Dissipation factor at 1 MHz	0,003
Maximum continuous service temperature (°C)	260
Minimum service temperature (°C)	-70
Compressive strength (MPa)	143,5
Tensile strength (MPa)	87,5

Table 2 continues. Relevant material properties of PEEK (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	Value
Tensile Modulus (MPa)	3950
Water absorption, equilibrium in water at 23 °C (%)	0,3
Chemical Resistance	Excellent
Relative price to PE	70

As we can see from the Table 2 PEEK has very good dielectric properties and mechanical properties, but it has very high relative price compared to polyethylene with the value of 1.

4.2.4 Polyphenylene sulfide

Polyphenylene sulfide (PPS) has excellent material properties, and it is thermoplastic high-performance polymer. It has excellent chemical resistance and below 200 °C there is no known solvent for the PPS. PPS has great thermal and strength properties, and it is resistant abrasion, aging, and UV-light. (Park & Seo 2011, p. 477.) PPS has low water absorption and good dielectric properties. It can be extruded, injection moulded, and machined. Chemical and mechanical recycling methods can be utilized for PPS, and it considered as non-toxic. In the Figure 25 we can see chemical structure of PPS. (Omnexus, 2023d.)

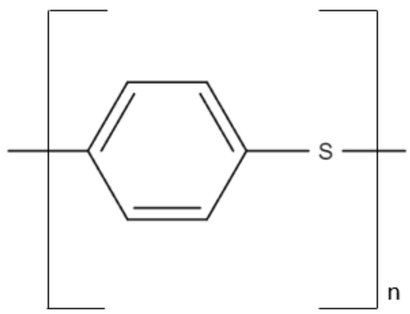


Figure 25. PPS chemical structure (Omnexus, 2023d).

In the Table 3 we can see relevant material properties of PPS.

Table 3. Relevant material properties of PPS (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Dielectric constant at 1 MHz	3,85
Dissipation factor at 1 MHz	0,0011
Maximum continuous service temperature (°C)	240
Minimum service temperature (°C)	-50
Compressive strength (MPa)	112
Tensile strength (MPa)	90
Tensile Modulus (MPa)	3800
Water absorption, equilibrium in water at 23 °C (%)	0,02
Chemical Resistance	Excellent
Relative price to PE	16,7

As we can see from the Table 3 PPS has excellent mechanical and dielectric properties. The operating temperature range is wide, strength is better than with PTFE, and it has also excellent chemical resistance. Water absorption is low with the PPS.

4.2.5 Polyamideimide

Polyamideimides (PAI) are high-performance polymers and one of the most utilized PAI is Torlon trademark by Solvay. Torlon PAI has exceedingly good thermal and mechanical properties and it can be extruded, and injection moulded. It has very good chemical resistance, but it is vulnerable for water absorption and that is a major disadvantage.

(Kemmish 2011, p. 75-78.) In the Figure 26 we can see the chemical structure of Torlon PAI.

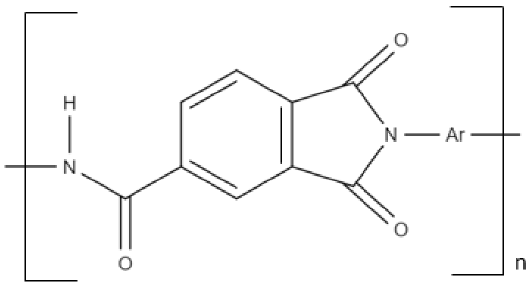


Figure 26. Chemical structure of Torlon PAI (Wypych, 2022).

In the Table 4 we can see the relevant material properties of PAI.

Table 4. Relevant material properties of PAI (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Dielectric constant at 1 MHz	3,9
Dissipation factor at 1 MHz	0,031
Maximum continuous service temperature (°C)	260
Minimum service temperature (°C)	-150
Compressive strength (MPa)	169
Tensile strength (MPa)	169,5
Tensile Modulus (MPa)	4690
Water absorption, equilibrium in water at 23 °C (%)	0,33
Chemical Resistance	Very good
Relative price to PE	90

As we can see in the Table 4 PAI has very high strength and wide operating temperature range, but on the contrary, it is extremely expensive. Also, the dielectric constant and dissipation factor are higher than with previously discussed polymers.

4.2.6 Polyoxymethylene

Polyoxymethylene (POM) also known as acetal is versatile engineering polymer with excellent machinability and wear resistance (Ensinger, 2023f). In the Figure 27 we can see the chemical structure of POM (Omnexus, 2023g).

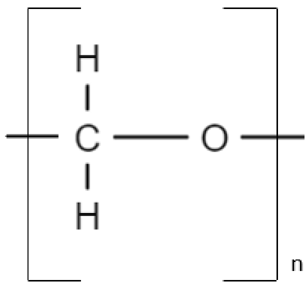


Figure 27. POM chemical structure (Omnexus, 2023g).

We can see the relevant material properties of POM in the Table 5 below.

Table 5. Relevant material properties of POM (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	Value
Dielectric constant at 1 MHz	3,35
Dissipation factor at 1 MHz	0,0055
Maximum continuous service temperature (°C)	90
Minimum service temperature (°C)	-30
Compressive strength (MPa)	85

Table 5 continues. Relevant material properties of POM (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Tensile strength (MPa)	56
Tensile Modulus (MPa)	2800
Water absorption, equilibrium in water at 23 °C (%)	1,225
Chemical Resistance	Good
Relative price to PE	3,3

As we can see in the Table 5 POM is relatively cheap and cheaper than PTFE. However, the operating temperature range of POM is not that wide, it has higher water absorption compared to polymers that are discussed earlier and the chemical resistance is good but not excellent.

4.2.7 Polypropylene

Polypropylene (PP) is similar cheap general use polymer such as polyethylene. It has however some advantages over polyethylene such as better strength and stiffness, but in comparison with other high-perfomance polymers it is lacking in these same areas. (Park & Seo 2011, p. 476.) Polypropylene cannot handle temperatures below -20 °C and it has poor UV resistance (Omnexus, 2023e). In the Figure 28 we can see the chemical structure of PP.

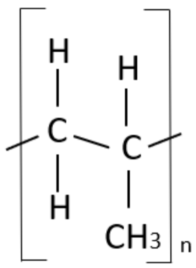


Figure 28. Chemical structure of PP. (Omnexus, 2023e).

We can see the relevant material properties of PP in the Table 6 below.

Table 6. Relevant material properties of PP (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Dielectric constant at 1 MHz	2,4
Dissipation factor at 1 MHz	0,0005
Maximum continuous service temperature (°C)	100
Minimum service temperature (°C)	-20
Compressive strength (MPa)	40
Tensile strength (MPa)	29
Tensile Modulus (MPa)	1700
Water absorption, equilibrium in water at 23 °C (%)	0,03
Chemical Resistance	Good
Relative price to PE	1

As we can see in the Table 6 polypropylene has excellent dielectric properties, but it is hindered in this application because of the relatively narrow operating temperature range. Strength of the polypropylene is not that high but is very cheap and has low water absorption.

4.2.8 Polyimide

Polyimides (PI) are wide group of high-performance polymers. Ensinger trademark Tecasint and DuPont trademark Vespel are one of the best-known polyimides. PIs have excellent thermal and wear properties. Polyimides are vulnerable to water absorption. (Kemmish 2011, p. 81-86.) In the Figure 29 we can see the chemical structure of PI.

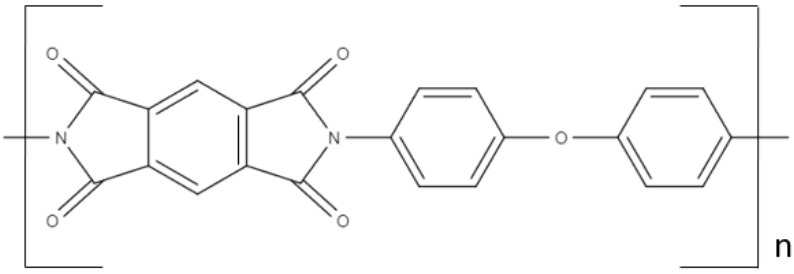


Figure 29. Chemical structure of PI. (Wypych, 2022).

In the Table 7 we can see the relevant material properties of PI.

Table 7. Relevant material properties of PI (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	Value
Dielectric constant at 1 MHz	3,55
Dissipation factor at 1 MHz	0,0034
Maximum continuous service temperature (°C)	300
Minimum service temperature (°C)	-269
Compressive strength (MPa)	192
Tensile strength (MPa)	161
Tensile Modulus (MPa)	2500
Water absorption, equilibrium in water at 23 °C (%)	1,645
Chemical Resistance	Very good
Relative price to PE	100

As we can see in the Table 7 PI has exceptional strength and mechanical properties but is the most expensive polymer so far. Also, the water absorption rate is the highest when compared to the other polymers that are discussed.

4.2.9 Polyethylene

Polyethylene (PE) is general use plastic and most widely utilized plastic. It easily processable and low-cost option. It has good chemical resistance, but it is attacked by hydrocarbons. PE has very good dielectric properties and very low water absorption. However, PE is limited by its thermal and strength properties and has lower continuous use temperature compared to the high-perfomance polymers. PE has also poor UV resistance. (Omnexus, 2023c.) In the Figure 30 we can see the chemical structure of PE.

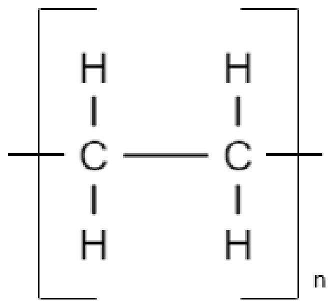


Figure 30. Chemical structure of PE (Omnexus, 2023c).

In the Table 8 we can see the relevant material properties of PE.

Table 8. Relevant material properties of PE (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	**Value**
Dielectric constant at 1 MHz	2,4
Dissipation factor at 1 MHz	0,001
Maximum continuous service temperature (°C)	100
Minimum service temperature (°C)	-70
Compressive strength (MPa)	20
Tensile strength (MPa)	39,3

Table 8 continues. Relevant material properties of PE (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

Material property	Value
Tensile Modulus (MPa)	215
Water absorption, equilibrium in water at 23 °C (%)	0,0075
Chemical Resistance	Good
Relative price to PE	1

As we can see in the Table 8 Polyethylene has very good dielectric properties, has low water absorption and is very cheap. However, polyethylene does not handle high operating temperatures, has not that high strength or chemical resistance.

4.3 Material screening based on numerical data

In this part of the material selection most of the pre-selected materials are screened out based on the concrete numerical data acquired in the material selection process. In the Figure 31 we can see combined data table of all of the pre-selected polymer materials. (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023.)

	PTFE	PEEK	PPS	PAI	POM	PP	PI	PE
Dielectric constant at 1 MHz	2,1	3,2	3,85	3,9	3,35	2,4	3,55	2,4
Dissipation factor at 1 MHz	0,0003	0,003	0,0011	0,031	0,0055	0,0005	0,0034	0,001
Maximum continous service temperature (°C)	260	260	240	260	90	100	300	100
Minimun service temperature (°C)	-200	-70	-50	-150	-30	-20	-269	-70
Compressive strength (MPa)	47,7	143,5	112	169	85	40	192	20
Tensile strength (MPa)	27,5	87,5	90	169,5	56	29	161	39,3
Tensile modulus (MPa)	425	3950	3800	4690	2800	1700	2500	215
Water absorption, equilibrium in water at 23 °C (%)	0	0,3	0,02	0,33	1,225	0,03	1,645	0,0075
Chemical resistance	Excellent	Excellent	Excellent	Very good	Good	Good	Very good	Good
Relative price to PE	16,7	70,0	16,7	90,0	3,3	1,0	100,0	1,0

Figure 31. Combined data table for material comparison (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

In the Figure 32 we can see a visualization of dielectric constants and dissipation factors of the materials under consideration.

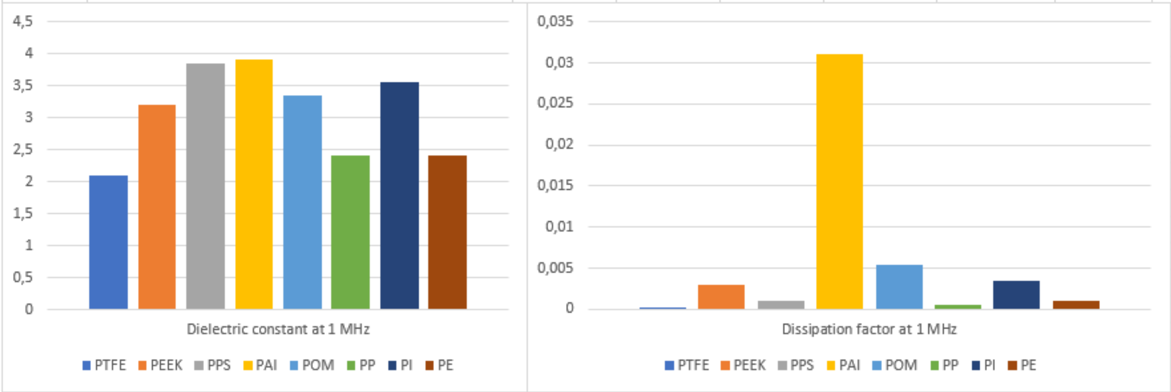


Figure 32. Dielectric constants and dissipation factors based on (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

As we can see from the Figure 32 PTFE has clearly the best properties in these two categories. In the Figure 33 we can see the visual comparison of the relative price and temperature ranges.

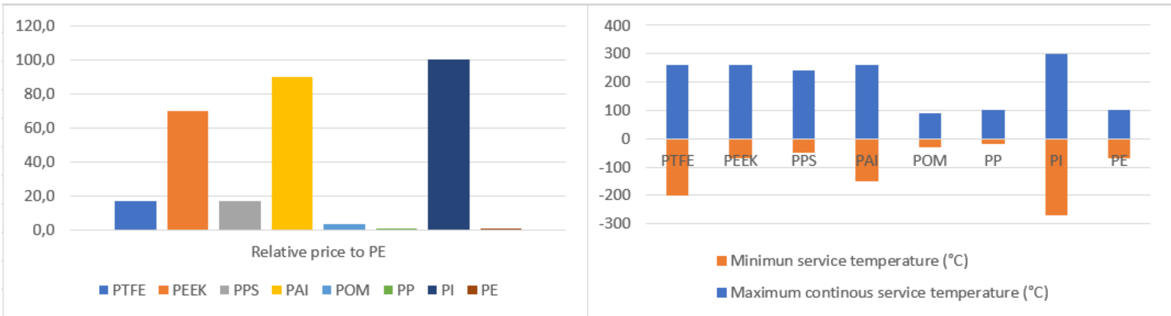


Figure 33. Relative price and temperature range comparison (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

We can see from the Figure 33 that PI, PAI are extremely expensive, but they have very wide operating temperature ranges. PEEK is quite expensive, but it has good operating range. PE, PP and POM are relatively very cheap, but they have narrow operating ranges compared to the other polymers.

In the Figure 34 we can see visual comparison of water absorption and compressive strength.

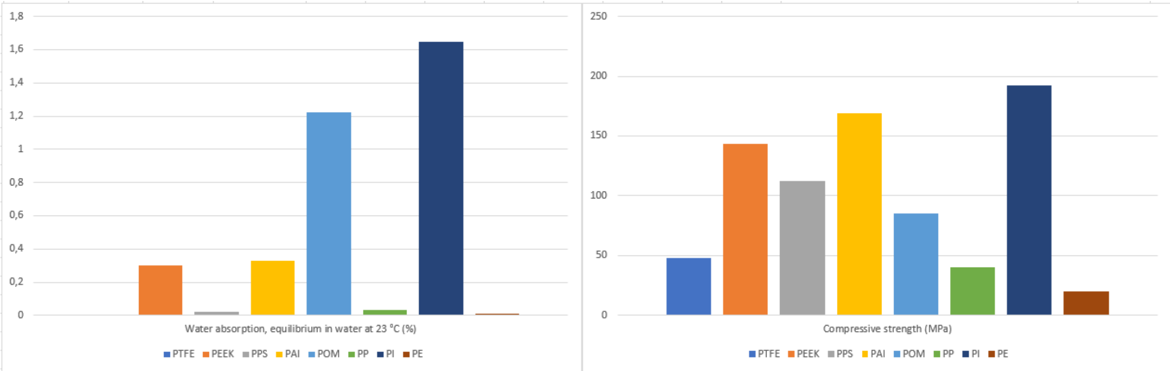


Figure 34. Water absorption and compressive strength comparison (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

We can see from the Figure 34 that PTFE has relatively low compressive strength and only PP and PE has lower value. However, PP and PE has very low water absorption rates along with PPS. In the Figure 35 we can see comparison of tensile modulus and tensile strength.

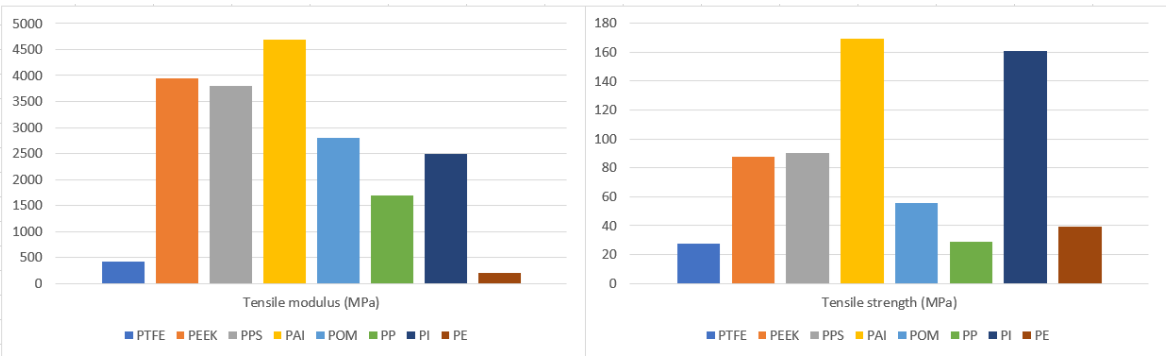


Figure 35. Comparison of tensile modulus and tensile strength (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

We can see from the Figure 35 that PTFE has the lowest strength of the compared materials, and PI and PAI have extremely high tensile strength compared to the other materials analysed.

Value analysis is perfomed for the materials and the material properties are given points from 1 to 5 evaluating the functionality in comparison with the PTFE. The strength properties are weighted less since the current material PTFE can handle the operating conditions and other polymers in discussion have better strength values, so it is not that important especially when compared to the other relevant material properties where PTFE is outstanding. We can see the results of the value analysis in the Figure 36.

	PTFE	PEEK	PPS	PAI	POM	PP	PI	PE
Dielectric constant at 1 MHz	5,00	3,95	3,33	3,29	3,81	4,71	3,62	4,71
Dissipation factor at 1 MHz	5,00	4,81	4,93	3,00	4,65	4,97	4,78	4,94
Maximum continous service temperature (°C)	4,33	4,33	4,00	4,33	1,50	1,67	5,00	1,67
Minimun service temperature (°C)	4,54	3,34	3,15	4,08	2,96	2,87	5,00	3,34
Compressive strength (MPa)	1,00	1,75	1,58	1,88	1,44	1,21	2,00	0,42
Tensile strength (MPa)	1,00	1,52	1,53	2,00	1,33	1,17	1,95	1,23
Tensile modulus (MPa)	1,00	1,84	1,81	2,00	1,60	1,36	1,53	0,51
Water absorption, equilibrium in water at 23 °C (%)	5,00	4,09	4,94	4,00	1,28	4,91	1,00	4,98
Chemical resistance	5,00	4,50	4,50	3,50	3,00	3,00	3,50	3,00
Total points	**31,88**	**30,12**	**29,78**	**28,08**	**21,33**	**25,87**	**28,38**	**24,79**
Relative price to PE	16,6667	70,0000	16,6667	90,0000	3,3333	1,0000	100,0000	1,0000
Value analysis (points/price)	**1,91**	**0,43**	**1,79**	**0,31**	**6,40**	**25,87**	**0,28**	**24,79**

Figure 36. Value analysis of the materials.

As we can see from the Figure 36 PEEK and PPS have the highest total points when compared to the other new material candidates. However, PTFE still has the highest points of all of the materials in discussion. The result of the value analysis is totally different compared to the material with highest points, PP and PE clearly having highest rating. However, this is mostly due to extremely low cost of these polymers compared to the high-performance polymers.

Based on the set requirements and constraints PE, PP and POM are screened out because of the narrower operating temperature range and lower chemical resistance. POM also has relatively high water absorption rate compared to the other materials. PI and PAI are screened out because of the exceptionally high relative prices. PI also has high water absorption. PAI has higher dielectric constant and dissipation factor compared to the other materials discussed here. If this application would not be so strict with temperature and chemical resistance requirements PP and PE could be very inexpensive tempting material choices also based on the value analysis results. However, PP and PP are more suitable for general purpose application radars. In the Figure 37 we can see these values highlighted that affected the screening decision.

	PTFE	PEEK	PPS	PAI	POM	PP	PI	PE
Dielectric constant at 1 MHz	2,1	3,2	3,85	3,9	3,35	2,4	3,55	2,4
Dissipation factor at 1 MHz	0,0003	0,003	0,0011	0,031	0,0055	0,0005	0,0034	0,001
Maximum continous service temperature (°C)	260	260	240	260	90	100	300	100
Minimun service temperature (°C)	-200	-70	-50	-150	-30	-20	-269	-70
Compressive strength (MPa)	47,7	143,5	112	169	85	40	192	20
Tensile strength (MPa)	27,5	87,5	90	169,5	56	29	161	39,3
Tensile modulus (MPa)	425	3950	3800	4690	2800	1700	2500	215
Water absorption, equilibrium in water at 23 °C (%)	0	0,3	0,02	0,33	1,225	0,03	1,645	0,0075
Chemical resistance	Excellent	Excellent	Excellent	Very good	Good	Good	Very good	Good
Relative price to PE	16,7	70,0	16,7	90,0	3,3	1,0	100,0	1,0

Figure 37. Data table with values highlighted that affected the screening decision based on (Wypych, 2022; Ensinger, 2023d; Matweb, 2023; Omnexus, 2023f; Precisionpunch, 2023).

This screening based on the value analysis and the material application requirements leaves PEEK and PPS left for further analysis as the PFAS-free PTFE replacement material for the non-contacting radar process seal antenna.

According to Crompton (2014) PPS and PEEK are polymers with excellent material properties for applications requiring good thermal and dielectric properties alongside with PTFE (Crompton 2014, p. 104). According to Reading plastics (2023) PPS is significantly cheaper than PEEK and is generally offed as lower cost option.

4.4 Final selection

The final material selection is between PEEK and PPS based on the screening process. Further comparison of the results of the value analysis can be seen in the Figure 38 below.

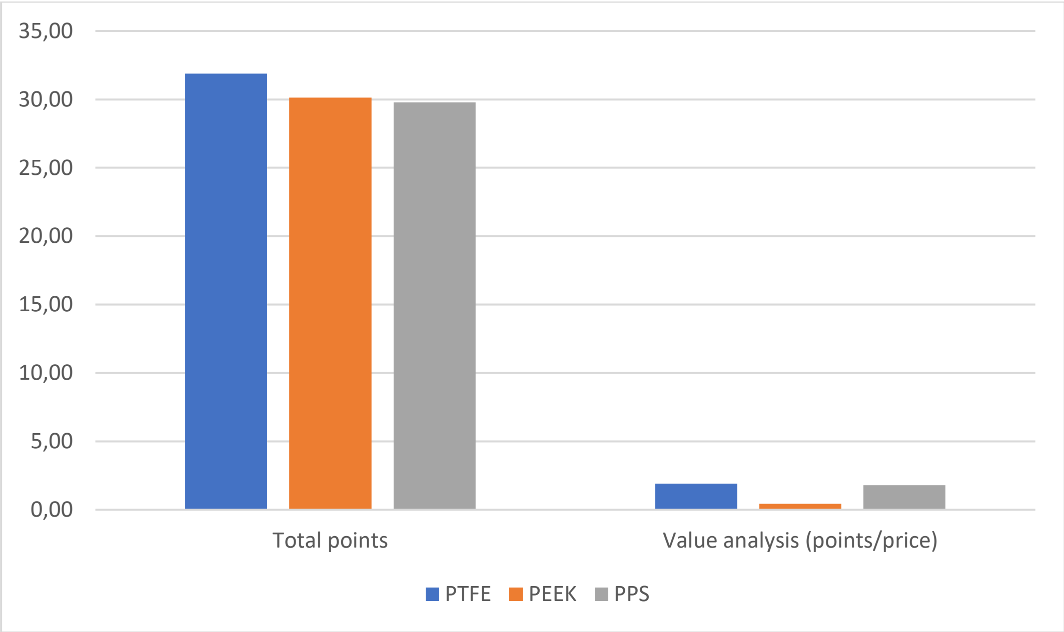


Figure 38. PTFE, PEEK and PPS total points and value analysis comparison.

As we can see from the figure 38 PTFE has the highest total points and highest value based on the value analysis. PEEK has the highest total points of new material candidates and PPS the highest value of the remaining new candidates.

In the Figure 39 we can see a spider chart comparison of the material properties.

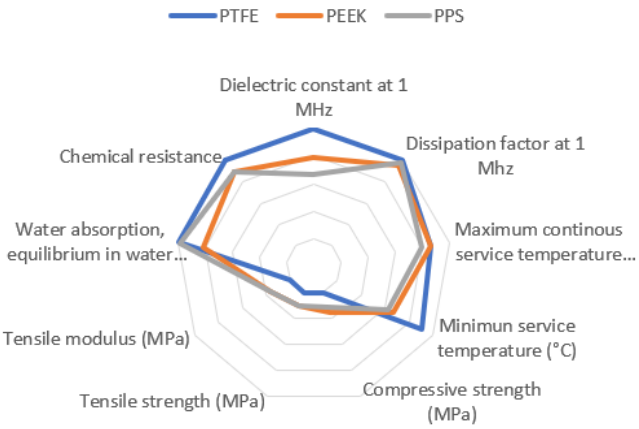


Figure 39. Spider web chart based on the material property evaluation.

We can see in the Figure 39 that PTFE is only lacking in the strength properties when compared to PEEK and PPS. In the Figure 40 we can see the spider chart excluding the strength properties since PTFE can handle the operating conditions anyway.

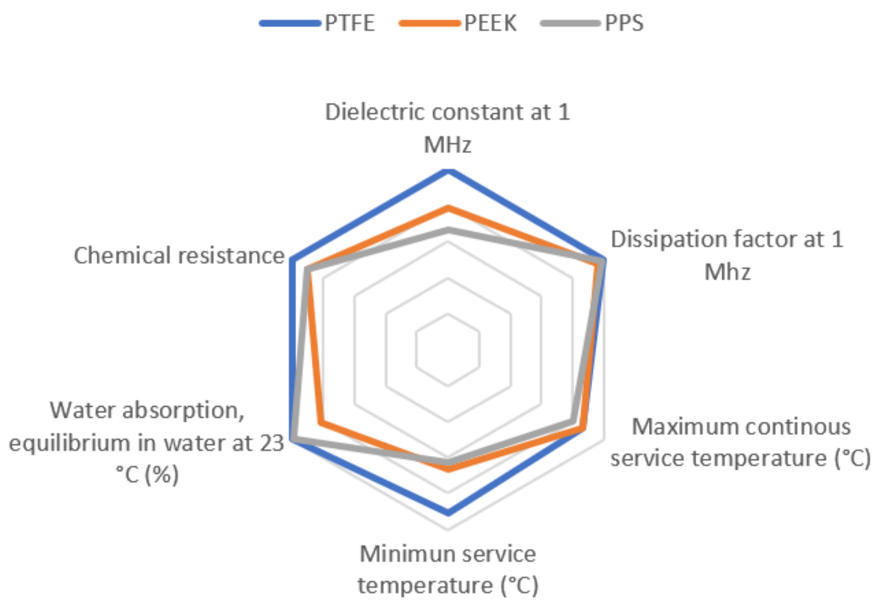


Figure 40. Spider web chart material evaluation without strength properties

As we can see in the Figure 40 PTFE has the largest area in the spider chart compared to PEEK and PPS. PTFE outperforms the other candidates in all of these relevant material properties that were in the comparison. PEEK is especially hindered because of its very high costs. Based on this material property ranking and value analysis PPS seem to be the most suitable alternative for PTFE only narrowly over PEEK, mostly due to the costs. Based on this research PEEK is also widely already utilized in commercial non-contacting radars and other radar applications supporting the material choice. PEEK and PPS are both recyclable PFAS-free alternatives for PTFE, and ultimately the choice is the company’s. Functional testing of the materials is suggested as the next step in the future research.

5 Discussion

In this chapter the results of this master's thesis are further discussed and analysed. The comparison with former research is analysed. Reliability and objective of the results are discussed.

5.1 Comparison and connections with former research

This master's thesis focused on finding PFAS-free alternatives to PTFE for specific application the non-contacting radar process seal. During the literature review and searching for information I did not came across with similar material selection researches for PFAS-free alternatives and especially for such specific application. The search for PFAS-free alternatives is extremely current topic since the possible bans and regulations of the PFAS.

However, there are studies and sources with similar results about the detrimental effects of the PFAS and about the rising concerns and upcoming proposed regulations related to it referred in this thesis: ATSDR (2022), Blake & Fenton (2020), ECHA (2023ab), ITRC (2023), KEMI (2023), Lohmann et al. (2020), Meegoda et al. (2020) and Torres & De-la-torre (2023) and Tullo (2023). The material selection process can be done with many different ways and different evaluation criteria. Examples of different material selection processes that are referred in thesis are Ashby (2011) and Eskelinen & Karsikas (2013). Polymers are suggested for low dielectric applications or radar applications based on following sources: Choudhury (2019), Eskelinen & Eskelinen (2003) and Ashby (2011). PEEK utilization in radar applications are based on these following sources by Ashby (2011), Eskelinen & Eskelinen (2003) and commercial sources Endress (2023ab) and Vega (2023) PPS utilization in microwave applications are based on the Ashby (2011) source. Ceramics are mentioned for low dielectric microwave applications in these sources: Ashby (2011), Choudhury (2019), Eskelinen & Eskelinen (2003). The material property values are based on the following sources: Wypych (2022), Ensinger (2023d), Matweb (2023) and Omnexus (2023f). Overall, the utilized sources and referred parts in this thesis supported each other and there were no contradicting references, at least in my opinion.

5.2 Objectivity and reliability of the results

This master's thesis utilized multiple different sources in the research. By utilizing many different sources, the reliability of the results improves because the information presented in this thesis is supported by different source materials. The sources utilized in this thesis are mostly relevant scientific publications and books. However, commercial company sources (e.g. Emerson and Ensinger), databases (e.g. Matweb and Omnexus) and sources from different agencies were also utilized (e.g. ECHA, ITRC and KEMI).

According to Elsevier (2023) journals impact can be measured for example with SCImago Journal Rank (SJR) and Source normalized Impact per Paper (SNIP) ratings. SJR ranks journals based on the citations and citations from other journals with higher SJR rating are weighted more. SNIP ranks journals based on the impact of the publication compared to the citation potential in its own field of work. (Elsevier, 2023.)

Some of the sources utilized in this thesis are from publishers that are ranked high on The Education University of Hong Kong academic publisher ranking list for example Elsevier, Oxford University Press and Springer. (The Education University of Hong Kong, 2023.)

The material selection is mostly based on the material property value evaluation that are acquired from multiple different sources. Different sources can display material property information about different polymer trademarks and the values can also vary based on different source. The material properties can also be measured by different methods and standards. However, based on the different sources that were looked up in this thesis, the values of the material properties used in the thesis seem to be in line and realistic. The material selection process can be done with different ways and based on different evaluation criteria possibly with different outcome.

The pricing information was quite difficult to acquire and prices about the different polymers is based on one source and that must be considered. The pricing information is generally also affected by the volume, material availability, discounts and agreements so there is no absolute fixed price at any point in time. In this thesis prices are portrayed as "relative prices" and should be treated as such, not as exact values. However, as relative prices they seem realistic and in line with other sources.

The outcome of the material selection process is also supported by commercially available similar applications and other studies of similar microwave applications mentioned and referred in this thesis.

The material selection process done in this thesis is based on a literature review and should also be confirmed with functional tests in the future, even though there are similar commercial solutions available with the same materials it should be also tested with the Emerson non-contacting radar, its dimensions and operating frequency. For example, dielectric constant is dependent on the frequency, temperature, and humidity so the materials should be tested in possible process conditions.

5.3 Key findings and conclusions

PTFE has unique combination of extremely desirable material properties. Based on this thesis PTFE outperforms the PFAS-free alternatives in the terms of material properties that are relevant for this application. According to Lim (2023) there is no other material with similar set of material properties, or it is near impossible to find exactly similar alternative. In this thesis there are also similar findings, and it is ultimately tradeoff between some of the material properties.

PEEK and PPS are higher strength materials compared to PTFE but in this application other material properties are valued more, for example the dielectric properties. PEEK and PPS could replace PTFE in this application but with small decreases in the performance based on the results of the thesis. PEEK and PPS as high-performance material for microwave applications are supported by studies referred in the thesis and for example PEEK is utilized similar commercial applications. Based on this thesis PEEK has the highest total points and PPS higher value analysis points. Utilization of PEEK is hindered because of its relatively high costs when comparing to PTFE and especially other cheaper polymers such as PP and PE. However, it must be taken into account that the cost of the process seal antenna is only the cost of one single part of the whole non-contacting radar and the cost can be relatively insignificant when comparing to the total cost of the device.

Based on this thesis PP and PE could be utilized in more general-purpose applications. These are very cheap materials and have good dielectric properties. The utilization of PP and PE in similar applications are also supported by some studies referred in this thesis and PP for example is already used in some other commercial non-contacting radars.

In the recent years there have rising awareness and environmental concerns about the utilization of different PFAS chemicals and in the early 2023 ECHA announced possible restriction of over 10 000 PFASs (ECHA, 2023a). There are so many industries and applications utilizing different PFAS and PTFE that it will have very serious impact if they are totally banned. PFAS have unique properties making them hard to replace. According to Guardian (2023) article ECHA received significant pressure and feedback from the industries and that caused ECHA to reconsider the magnitude of the possible regulations and bans. It currently seems that there won't be total bans on the use of PFAS because they are so widely utilized because of the unique material properties.

The objective of this master's thesis was to find possible materials that could replace PTFE with PFAS-free material for non-contacting radar process seal antenna and justify their selection. This objective was achieved, and possible PFAS-free alternative materials are provided in this thesis with justifications. The results of this research can help Emerson to decide on how to replace PFAS material in the process seal antenna application.

5.4 Novelty value of the results

This master's thesis provides material selection and evaluation of the materials for a very specific non-contacting radar application with specific material property requirements. This thesis also provides information about potential PFAS-free replacement materials. This information about the possible alternative materials can also be potentially utilized in other applications as well. Due to the possible PFAS bans and regulations it is very important to seek for alternative materials since PFAS are so widely utilized across the industries.

5.5 Generalization and utilization of the results

This thesis provides Emerson guidance in the material selection for PFAS-free alternatives in non-contacting radars and the information can be utilized in other applications too. The results of this thesis can be potentially utilized also by other companies in similar or other different applications where PFAS-free alternatives are required. Material property combination of the PTFE is so unique that based on this thesis there is no material with same combination of properties. Ultimately changing to PFAS-free alternative might cause a reduction in some of the material properties but in the other hand increase in some other properties. PEEK and PPS have somewhat similar relevant material properties to PTFE based on this specific application, but they have better strength properties. PP and PE could be potentially used in more general-purpose applications with less severe requirements especially on the operating temperature range, supported by the value analysis results of this thesis and also other commercial applications. PI and PAI have extremely high strength properties and wide operating ranges and those could be possibly utilized in other applications where these kind of material properties are valued more.

5.6 Topics for future research

The future research should include functional testing of PEEK and PPS in process conditions and testing with different and operating frequencies, since these kinds of tests were not included in the scope of this thesis. Future research could also include further investigation of different materials groups such as ceramics as radar process seal antenna material as it was one of the other relevant material groups based on this thesis. Investigation and future research of other polymers that are not so widely utilized and known could be one topic.

6 Summary

There have been increasing environmental concerns regarding the use of PFAS and ECHA proposed a ban of over 10000 chemicals in the early 2023. Since Emerson widely utilizes PFAS in their products the potential ban could severely disrupt the market. The purpose of this master’s thesis was to search for PFAS-free alternative materials for the specific application, the Emerson’s 5408 premium tier non-contacting radar process seal antenna part. Systematic material selection process was conducted in this thesis in order to find the PFAS-free alternative materials. The current material PTFE has extremely good and unique set of material properties that are extremely hard to replace. The material selection process done in this research suggests PEEK and PPS as possible PFAS-free alternatives for PTFE in this application. However, PTFE still outperforms the proposed alternative materials based on the analysis done in this thesis in this specific application. This thesis provides possibly useful information also for other companies and applications seeking for PFAS-free alternatives.

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