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DIFFUSION BEHAVIOUR OF LUBRICANTS IN POLYMERIC INSULATION MATERIALS

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The diffusion of lubricants in insulation materials, which is the core parameter of the electrical and mechanical long-term behaviour of solid insulation interfaces, is studied. In this paper the focus is put on pluggable and non-pluggable slip-on cable accessories. Therefore, four different greases, based either on silicone or PTFE as well as a silicone oil, are under investigation on material samples. Grease generally consists of a stabilizer and an oily phase. The diffusion of grease depends both on the solid insulation material and on the grease itself. The highest diffusion can be measured by the combination of a silicone grease and silicone rubber. However, for silicone rubber there are low and no diffusion lubricants available. The diffusion in EPDM, EP and XLPE is commonly much lower. In EP and XLPE, no type-dependency of the grease can be observed. With the knowledge of the diffusion behaviour, the desired interface properties can be achieved for the whole lifespan of the high voltage equipment.

1. Introduction

Solid Interfaces play an important role in high voltage equipment. On the one hand, they are technically required (e.g. slip-on joints to connect cables); on the other hand, they are the base for innovative accessories with easy installation and handling (e.g. dry pluggable systems, dry terminations). However, they must be deeply understood and demand for a suitable lubrication. In the following subchapters the interfaces itself, their demand on lubricants and the properties of grease are discussed.

1.1. Interfaces

Due to production, installation and handling issues, solid interfaces in high voltage equipment are required and beneficious. Interfaces are the contact area of two different components. From a technical point of view, the surfaces of the contact partners are not perfectly smooth and thus described by roughness parameters.

The roughness leads to a contact which is not extensive, but punctiform. Without any lubricant, the areas in between are gas-filled and thus electrically weak in comparison to the solid insulation material. The goal is to reduce the size or even avoid the appearance of these gas-filled voids. Two strategies are commonly used to increase the electrical strength of the interface:

- Increasing the contact pressure leads to bigger contact areas and thus smaller voids, especially if at least one contact partner is soft
- Exchanging the comparatively weak air in the voids with electrically stronger lubricant.

In Figure 1 the typical interface situation (called tribosystem) between the cable insulation made of cross-linked polyethylene (XLPE) and the slip-on accessory made of silicone rubber (SiR) is shown on the left hand side. In the middle, the reduction of the void size due to enhanced interface pressure is shown and on the right hand side, the void is filled with grease, which is commonly used as lubricant.

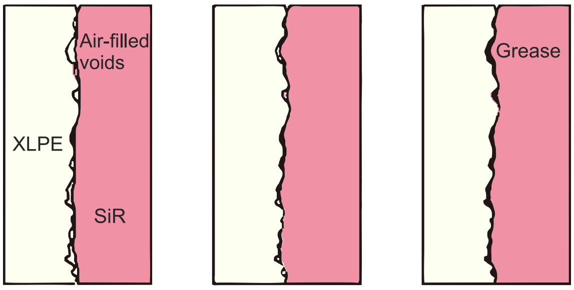

Figure 1: The interface between SiR and XLPE as tribosystem [1]
Left: Low interface pressure and no grease lead to big air-filled cavities in the interface
Centre: High interface pressure and no grease lead to small air-filled cavities in the interface
Right: High interface pressure lead to small cavities, which are additionally filled with grease

The parameters influencing the dielectric strength of the interface are displayed in Figure 2. Grease plays the major role in increasing the dielectric strength of the interface and thus it must last the whole lifespan of the equipment to keep it robust and maintenance-free.

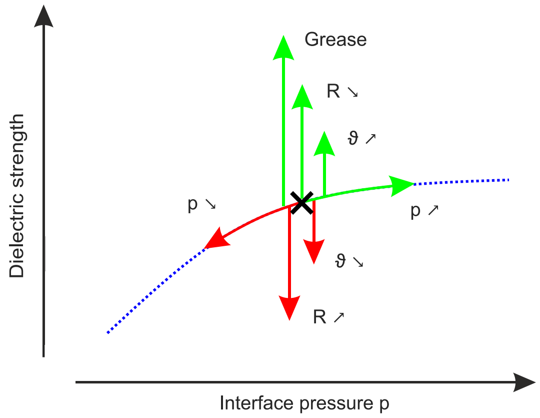

Figure 2: Influence of the surface roughness of the XLPE ("R"), the interface pressure ("p") and the temperature ("ϑ") on the dielectric strength of the interface [1]

1.2. Lubrication requirements

Additionally to the required dielectric properties presented in the previous chapter, the lubricant must improve the mechanical properties. The coefficient of sliding friction must be reduced during the slip-on mounting procedure. Depending on the type of equipment the lubricant must either allow sticking the contact partner together or –especially in pluggable solutions– keep the coefficient of friction low allowing both thermally driven movement and unplugging. Lubrication supports to homogenizes the interface pressure avoiding both too values leading to necking [2] and too low ones resulting in a lower dielectric strength of the interface

In contrast to the common use-case of grease in e.g. bearings, the situation in the cable accessories technology differs significantly:

- The solid interface partners are polymeric materials having both high coefficients of static friction and in principle allowing the diffusion of the grease or some ingredients of it.
- The movement is extremely slow and thus static friction dominates the movement during the operation.
- There is no remixing of the grease components by e.g. the bearing's balls.
- Longer service life without maintenance in case of HV cable accessories technology compared to e.g. bearing systems.

Normally both the mechanical and dielectrical properties are tested with fresh lubricant. In this paper indeed the aging behaviour of the interface system is the key subject of interest and thus the diffusion of the lubricant in the polymeric insulation material is under investigation.

1.3. Properties of grease systems

Grease is the typical lubricant used in medium and high voltage slip-on cable accessories. It consists of two key materials: The oily phase is responsible for the lubrication and the thickener keeps the oil in position. The typical soap-like structure can be seen in Figure 3.

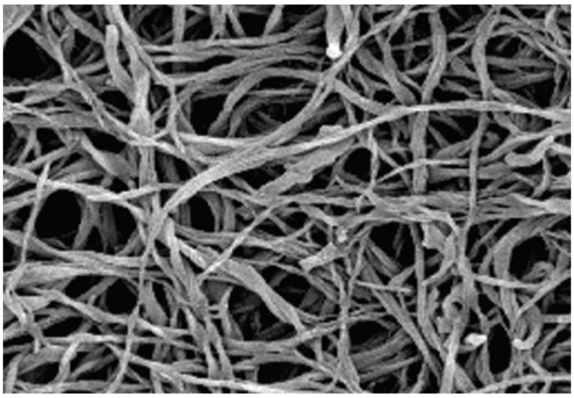

Figure 3: Soap-like thickener structure [3]

Grease separates to achieve better lubrication properties [4]. By this, constantly a small amount of oil being capable to creep and lubricate well is available. In order to maintain a low coefficient of static and sliding friction in the long term, the oil must not diffuse into the insulating material as the thickener alone cannot provide sufficient lubrication.

In this study, two different types of greases are investigated: Silicone-based greases as well as PTFE-based ones. Silicone oil used in the silicone-based greases have a chemical analogy to silicone rubber used as insulation material. PTFE-based grease differs chemically from the insulation materials and it shows residual lubrication properties when separated. Additionally, a pure silicone oil is included in the experiment.

2. Experimental setup

The experiment is split up in two phases: First, there is a preconditioning phase in which the four to six specimen of each type (with a surface area of 160 mm²) are stored at controlled ambient conditions. This lasts for at least two weeks and is done at 60 °C and 35 % relative humidity. The humidity is controlled with a saturated magnesium chloride hexahydrate solution.

If there is no significant weight change anymore, 2 g of lubricant is applied and distributed evenly on one side of the specimen. After one week storage at 60 °C and 35 % relative humidity, the measurement procedure starts: Every specimen is cleaned mechanically with a spatula followed by wiping the surface with alcohol. Weighting is done after the evaporation of the solvent. After this, fresh lubricant is applied and the storage cycle starts again. To achieve information of the course of diffusion, the specimen are weight weekly for nine weeks, thus covering more than 1,500 hours. More information about the experiment are available in [5].

To investigate the influence of the interface pressure on the diffusion process, some soft SiR specimen are mechanically stressed by clamping them between metal plates to emulate the interface pressure.

3. Diffusion results in SiR

From a chemical perspective, SiR is a mixture of both liquid an solid and thus sensitive to diffusion. This can be seen in many properties such as the humidity diffusion in the pre-conditioning phase. Because diffusion is strongest with silicone, most studies are carried out with this material. The results presented in the following subsections are obtained on LSR type SiR specimen.

3.1. Influence of the different type of lubricant

Four different greases are applied on six specimen each and a silicone oil is applied on four specimen. The median and the range of the normalized specimen weight for the four different greases is illustrated in Figure 4.

Grease A leads to a very small specimen weight increase in the sub-permille range. Repeated application of grease B has no measurable influence on the specimen weight. The range of the results of these two greases are small, too.

For grease C, there is a remarkable increase of the median of the specimen weight during the nine weeks. The range is still comparatively small and there is a saturation effect visible even if there is fresh grease applied weekly. After nine weeks the median of the specimen weight has increased by about 2.5 %.

Applying grease D leads to both the highest weight increase of nearly 6 % in nine weeks as well as to the highest range. During the measurement period, there is no clear saturation visible and the course of the median of the specimen weight tends towards an even higher weight increase in case of an elongated contact with permanently refreshed grease. Grease A and grease B are PTFE-based greases whereas grease C and D are silicone-based ones.

The silicone oil shows a weight increase of 3.2 %, which is in between the two silicone-based greases. The results show a bigger derivation from the expected saturation-limited curve shape and smaller range. This might come either from material properties or from the fact that only four specimen are used for the oil diffusion measurement.

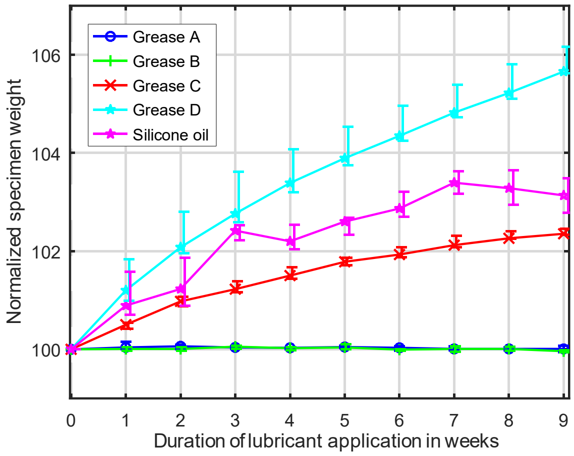

Figure 4: Diffusion result of four different greases and a silicone oil in SiR without pressure

To get a better comparison base in Figure 5 the three greases A to C are displayed in a more detailed manner.

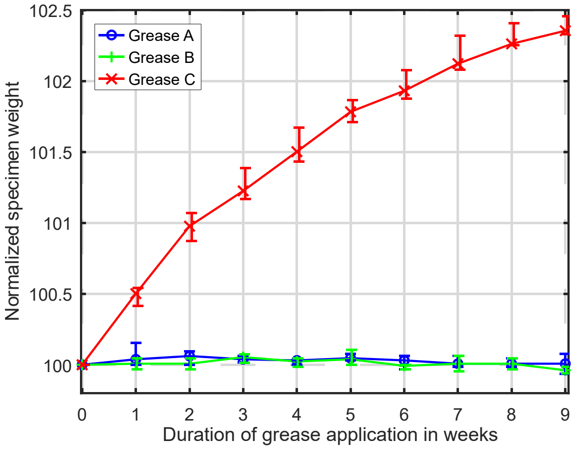

Figure 5: Detailed diffusion result of three different greases in SiR without pressure

Because long-term stable pluggable and flexible connections are the key subject, the focus will be on the greases A to C based on their lower diffusion behaviour.

3.2. Influence of the contact pressure

SiR is elastic and thus can be expanded during the slip-on procedure resulting in an interface pressure. By this, the void size is reduced as shown in Figure 1 and so the dielectric breakdown strength increases as shown in Figure 2. However, this deformation results in an internal mechanical stress of the insulation material and thus the diffusion of the greases A, B and C is examined under an interface pressure of about five bar relative.

The median of the specimen weight of grease A achieves its peak value of about 3 ‰ after four weeks. Finally, the median is about 1 ‰ lower than it was at the beginning. As the range still crosses the 100 %-line, there might be no weight reduction compared with the starting weight.

Grease B shows a similar behaviour with less than half the weight increase in the first half of the experiment and with a nearly constant median of the specimen weight in the second half.

For grease C, the only silicone based grease in this experiment, the median of the specimen weight increases by 1.4 % during the nine weeks. Compared to the results achieved with SiR specimen without interface pressure, the range in all three cases is higher.

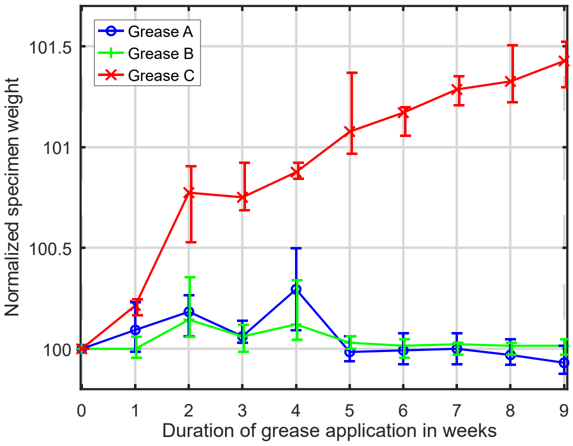

Figure 6: Diffusion result of three different greases in SiR with interface pressure of about 5 bar relative

The pressure leads to higher adhesion of the grease on the surface of the specimen resulting in a more challenging cleaning procedure. This can explain the bigger ranges. Especially in cases where the median differs from the long-term expectation the range is big and mostly covers the long-term expected value. For the PTFE-based greases A and B, there is no significant pressure-dependency measureable. However, in case of grease C a lower diffusion can be observed. Assuming that the diffusion proceeds pressure-independent at the same rate it is reduced by about 40 % due to the interface pressure of about 5 bar.

3.3. Influence of the type of SiR

To demonstrate the influence of the type of SiR on the lubricant diffusion, three different SiRs are treated with the silicone oil. The results are shown in Figure 7.

SiR 1 is the silicone rubber used for the experiments presented in chapter 3.1 and 3.2. As already shown in Figure 4, these specimen show a weight increase of about 3.2 % after nine weeks. During the experiment, there are two weight results differing from the expectation: After three weeks, the weight is higher than expected and higher than it is after four weeks. Additionally, in the last two weeks the weight is decreasing. The second fact is true for all three groups of SiR. There is no other sub-experiment in the study in which such a systematic weight loss occurs at the end of the experimental period. These derivations from the expected values can be explained by undesired humidity changes due to an insufficient humidity control: As silicone rubber is very sensitive on water diffusion the weight change due to water migration can be strongly seen in that part of the experiment. Due to the comparatively small range it seems that there is no problem with cleaning or weighting a single specimen but a general influence on all specimen.

Specimen made of SiR 2 behave nearly identical to the ones made of SiR 1, ending up with a weight increase of 2.9 %.

In contrast, specimen made of SiR 3 show a weight increase of 7.1 %, more than twice the value of the other materials.

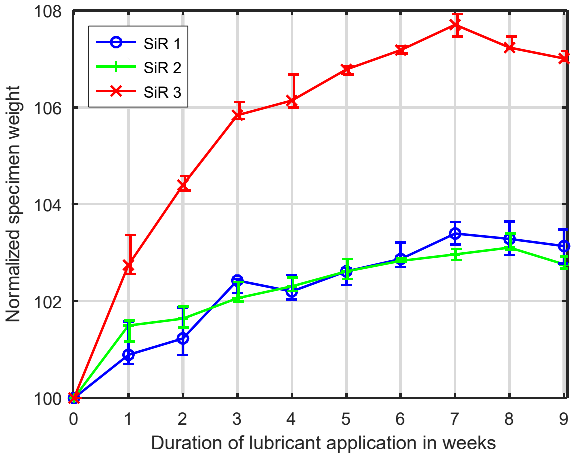

Figure 7: Diffusion result of the silicone oil in three different SiRs without pressure

This behaviour can be explained by the type of material: SiR 1 and SiR 2 are materials from the same family, whereas SiR 3 belongs to a different material type.

4. Diffusion results in other relevant polymeric insulation materials

In this chapter, the diffusion results of other relevant polymeric insulation materials like ethylene propylene diene monomer rubber (EPDM), XLPE and epoxy resin (EP) are shown.

4.1. Diffusion results in EPDM

Two different EPDM mixtures are examined both with grease A and C. The different EPDM mixtures 1 and 2 are represented with solid and dotted lines in Figure 8. Generally, there is a slightly decreasing median of the specimen weight in case of the application of grease A and an increasing one in case of grease C. EPDM 1 shows a higher weight decrease respectively increase compared to EPDM 2 . The median of the specimen weight increase after nine weeks is below 2 ‰ and thus about 10 % of the behaviour with SiR. The range seems comparatively high, especially in cases when the median differs from the long-term expected values.

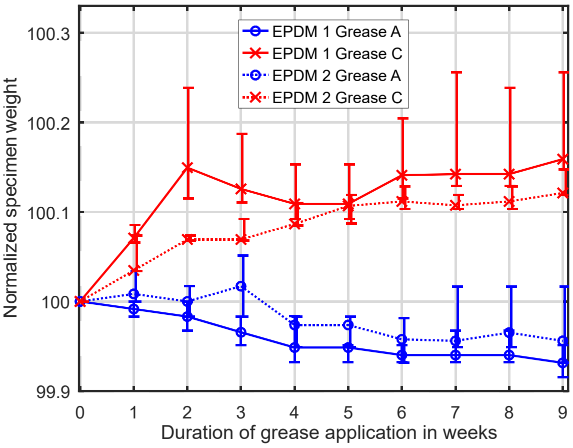

Figure 8: Diffusion result of two different greases in two different EPDM rubbers without pressure

The weight decrease due to the application of grease A might come from a dissolving process of some EPDM components. In contrast to this, the usage of grease C results in significant weight increase due to diffusion of grease or some of its ingredients.

The comparatively big range in Figure 8 is a result of both the scaling of the abscissa due to the low weight change and the more challenging cleaning procedure of the EPDM surface compared to SiR. Especially in the case of grease C, which is more viscose and thus stickier and harder to clean, the range is increased.

4.2. Diffusion results in XLPE

XLPE has a chemical structure differing from all greases with both crystalline and amorphous regions [6]. The latter contain water and some polar cross-linking byproducts. In these regions with polar molecules, the charges can be attracted leading to a space charge accumulation. This accumulation of charge carriers can be caused by the wiping process during cleaning and can influence the result determined by measuring the weight.

In Figure 9 the graphs of the normalized specimen weight including the range for the greases A, B and C are displayed. For all three lubricants the median of the specimen weight is both increasing and decreasing during the experiment. At the end, there is no significant weight increase in case of grease B and C. In case of grease A, there is a weight increase of about 1.5 ‰ and the range does not cross the 100 %-line. Due to the charge accumulation, the range of the specimen weight is the highest of all insulation materials under test. Only for EPDM the range is bigger in case the median differs from a long-term expected value.

There are fluctuations in the median between 1 ‰ in case of grease C to 5 ‰ in case of grease A. It is assumed that charge applied by handling and cleaning is a key reason for this weight fluctuation. Due to the viscosity, cleaning should be the most intensive in case of grease C and the less intensive in case of grease A. This is in contrast to the fluctuation of the median of the specimen weight, increasing from the specimen with grease C to the ones with grease A. This means that the intensity of the cleaning procedure is no clear indication for the charge phenomena. Nevertheless, for all the tested greases surface charge accumulation can be observed.

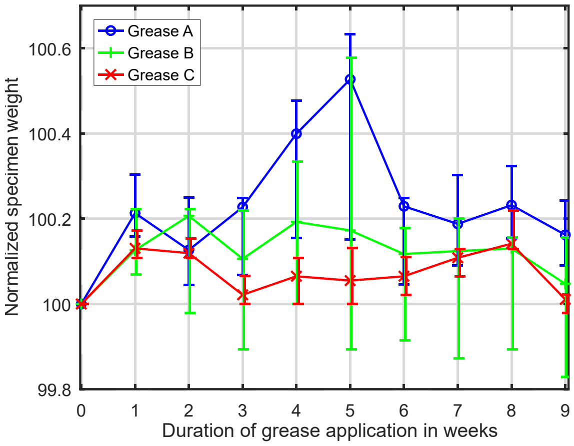

Figure 9: Diffusion result of three different greases in XLPE without pressure

Since there is no noticeable difference between the measured values at the end of the test and those at the beginning, it can be assumed that there is practically no diffusion of grease into the polymer. This can be explained by the different chemical structures of XLPE and both grease types.

4.3. Diffusion results in EP

The last material group investigated is an epoxy resin moulding material, which is a mixture of epoxy resin and a filler. Thus, there are interfaces and irregularities in the insulation material allowing especially the oily components of the grease to penetrate it. In Figure 10, the course of the median and the range of the specimen weight is displayed.

All specimen show the same final weight increase of 0.8 ‰ and an exponential saturation course of the median of the specimen weights. The range of the specimen weight slightly increases within the grease contact time.

There are two possible explanations for the grease-independent weight increase: Either there is a grease-type independent diffusion or the preconditioning time of more than two weeks is not sufficient to achieve a steady state concerning the humidity. The first point is supported by the fact that from chemical point of view both greases differ strongly from EP and Al_2O_3 serving as filler and thus the oils can be trapped at the interface of the filler independently of its chemical structure.

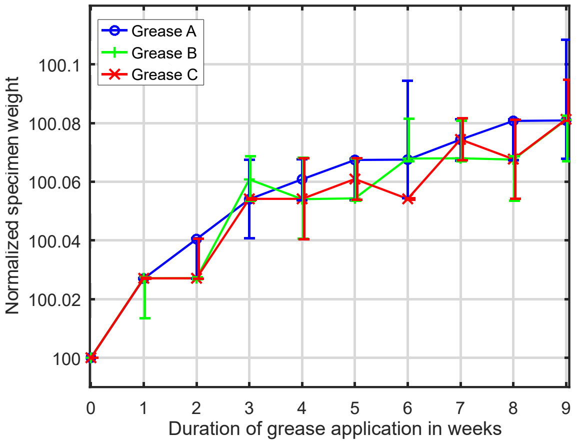

Figure 10: Diffusion result of three different greases in EP without pressure

In a second experiment, the preconditioning phase is elongated. The water content in the specimen is saturated after two weeks and thus no significant weight increase is measured in the further weeks.

5. Summary and conclusion

Diffusion of grease respectively the oily phase of it in the insulation materials is the core parameter influencing both the electrical and especially the mechanical long-term properties of solid interfaces in MV and HV slip-on cable joints and terminations. Thus, proper understanding and long-term testing of the suitable lubrication is vital.

The long-term behaviour depends on both the lubricant and the polymeric insulation material as well as on the interface pressure in case of a SiR-based grease on SiR insulation material.

For silicone rubber the highest diffusion can be seen by usage of silicone-based lubricants. Additionally, the diffusion of silicone-based grease is pressure-dependent. In contrast to this, there are PTFE-based greases available, which are showing no diffusion in SiR. The type of SiR also influences the diffusion strongly.

In EPDM, EP and XLPE the diffusion is at least one order of magnitude lower than it is in SiR. In EPDM, there might be a dissolving process of ingredients as there is a weight decrease by applying grease A. In EP, the slight diffusion is independent of the type of grease applied. In XLPE, there is practically no diffusion measurable and the weight fluctuation is mainly driven by the accumulated surface charge.

6. Literature

[1] J. Kaumanns, G. Schröder, „Bedeutung von Grenzflächen bei Design, Entwicklung, Prüfung und Inbetriebnahme von Hochspannungs-Kabelgarnituren“, *ETG-Fachbericht 99*, S. 201-206, 2005

[2] L. Höfer, M. Heckel, „Mechanisches Verhalten von XLPE unter dem Einfluss von Temperatur und Druck – Messung der Einschnürung mittels Modellanordnung“, *Fachtagung polymere Isolierstoffe*, Zittau, Germany 2021

[3] “Lubricating Greases Basics“, *PDF*, Exxon Mobil, 2012, downloaded March 1st 2021 https://www.mobil.ca/lubricants/media/files/global/us/industrial/tech-topics/lubricating-oil-grease-basics-technical-topic.pdf

[4] P. Lugt, “Grease Lubrication in Rolling Bearings”, *Wiley*, West Sussex, UK, 2013

[5] L. Höfer, M. Heckel, „Diffusion behavior of greases in interfaces in organic insulation materials“, *NordIS*, Trondheim, Norway 2022

[6] J. Thomas, S. Thomas, Z. Ahmad (editors), “Crosslinkable Polyethylene” Springer, 2021