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DESIGNING WITH PTFE

Material, Design Criteria, Processing, System Solutions

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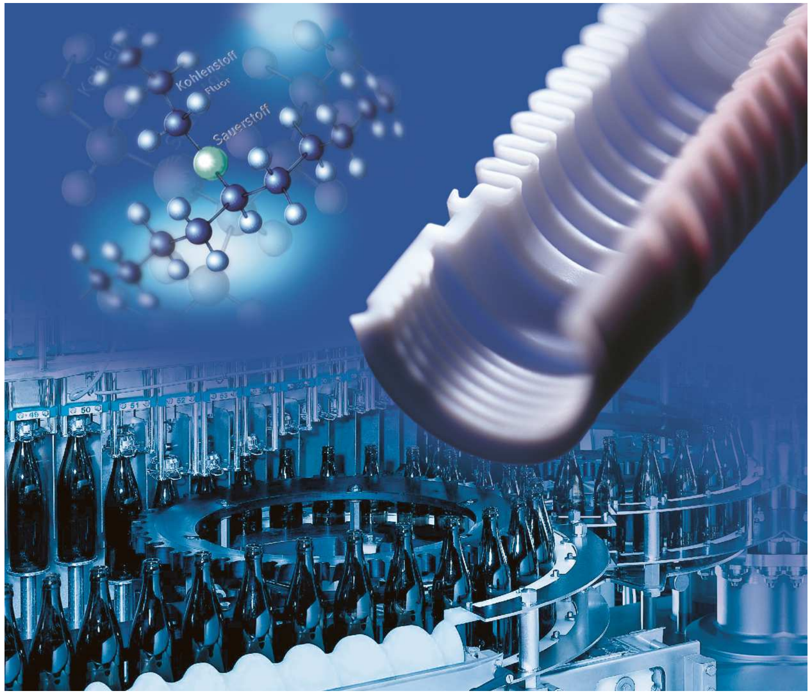

INTRODUCTION

Polytetrafluorethylene (PTFE) was first discovered by the 27-year-old Roy Plunkett (1910 - 1994) on 6 April 1938 while he was experimenting on new cooling agents for DuPont in their Jackson Laboratory in Deepwater, New Jersey (USA). Plunkett was faced with the problem that, despite unaltered weight, no gas escaped from the valve of compressed gas cylinders filled with tetrafluorethylene (TFE). When searching for the cause, he finally discovered a white granulate in the gas cylinder: PTFE into which the TFE gas had obviously spontaneously polymerized itself overnight. When investigating this granulate, Plunkett immediately realized that it had a highly unusual behavior. Since it neither reacted with the offered substances nor dissolved in any other medium - not even in the most aggressive acids -, the new product was unusable for chemical reactions. However, during extensive research in the plastics laboratory, the potential of this new class of plastics was quickly realized.
As so often happens with new products, PTFE was first of all used for military applications: as a sealing material in the preparation process for the production of uranium 235, it resisted the most aggressive acids. Due to its excellent insulation properties in connection with minimal damping values, it was used for high-frequency cable insulation for radar systems. The lack of suitable processing techniques and the fact that PTFE did not adhere to anything went firstly against a broader use of the material. Later, between 1955 and 1960, the material slowly began to be used as a non-stick coating for household goods, e.g. frying pans.

It was only after new techniques in processing plastics were developed that the foundation stone for industrial applications was laid. More recently the unique construction material PTFE (Figure 1) can increasingly be found in objects of daily use such as the mobile phone. Its advantageous properties can be targeted to the corresponding requirements of the different end usage.

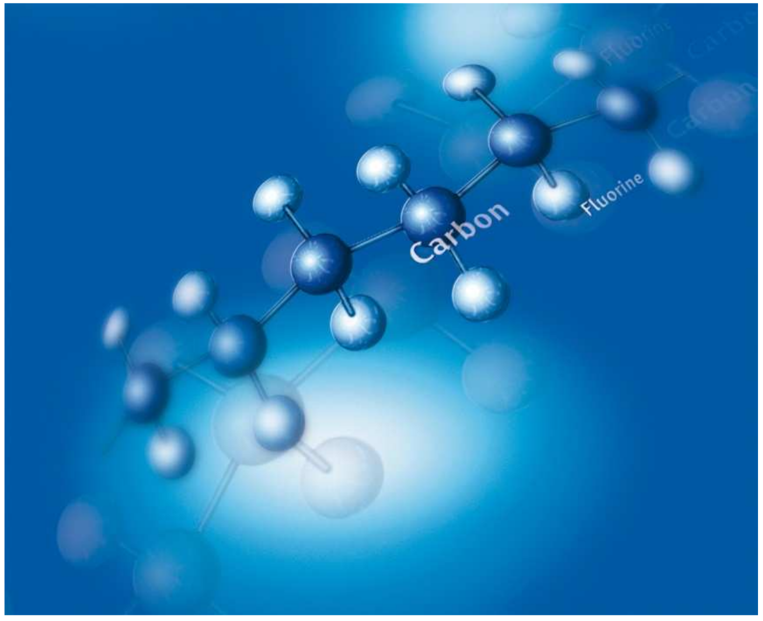

Figure 1: Molecular structure of PTFE

This book aims to show designers and users the unusual versatility of the special class of plastics. First of all, as well as the usual PTFE materials, the new meltprocessable PTFE will be described. Design criteria and processing techniques as well as special PTFE products cover the spectrum to industrial applications. Case studies and engineering solutions from many sectors emphatically show the potential of the design material PTFE. The preconditions for legal approval for the use of PTFE are also explained in detail.

PTFE Materials and Pre-Products

PTFE is characterized by its special properties which set it apart from all other plastics. This chapter will explain the molecular basis of PTFE and its influence on production, processing and applications. PTFE materials can be divided as follows:

- standard PTFE
- modified PTFE
- PTFE compounds
- meltprocessable PTFE

Standard PTFE

Polytetrafluorethylene (PTFE) is still one of the most important representatives of fully fluorinated (perfluorinated) polymers from the class of polyhalogenolefins. The carbon chain is nearly completely shielded by fluorine atoms (Figure 1) and thus protected from external influences. The carbon-fluorine connection is one of the strongest bondings in organic chemistry (dissociation energy 460kJ/mol). This results in the unusually high chemical resistance and thermal durability of PTFE. The melting temperature is 327^{o}C. PTFE is produced industrially by the polymerization of the monomer tetrafluorethylene (TFE) (page 19 ff). Depending on whether the polymerization is carried out in suspension or emulsion, the resulting product is described as either suspension PTFE or emulsion PTFE. Although it is basically a thermoplastic, PTFE cannot be processed by a thermoplastic technique. Due to the very high molecular weight of up to 10^{8}g/mol, the viscosity of the molten material would be too high.

The processing of suspension PTFE - also called pressed powder - calls for special press and sinter techniques which are very similar to the processing of sintered ceramics (page 29 ff). The powder is firstly pressed under a high pressure then sintered to melt the individual particles whereby the material still maintains its actual consistency. Finally the sintered product is transformed into the end product through a machining process. Emulsion PTFE - also called fine powder or paste-PTFE powder - is processed by paste extrusion i.e. quasi thermoplastic processing at room temperature. The basic profile from this process then receives its final properties in a subsequent sintering process. Corresponding to this special processing technique, the fields of application for emulsion PTFE and fluorothermoplastics overlap e.g. in coatings for wires and cables and for hoses and tubing.

Unsintered PTFE has a high degree of crystallization of 90 to 95 % . After one sintering, the degree of crystallization is in the range of 50 to 75 %. PTFE has two relaxation temperatures, one at 19^{0}C and the other at 28^{0}C (Figure 2). The transformation of the structure is manifested by a volatile change in the expansion coefficients. These can specifically influence the properties of the powdered form material suspension PTFE and the dimensional stability of the end product. Therefore special attention should be paid to them.

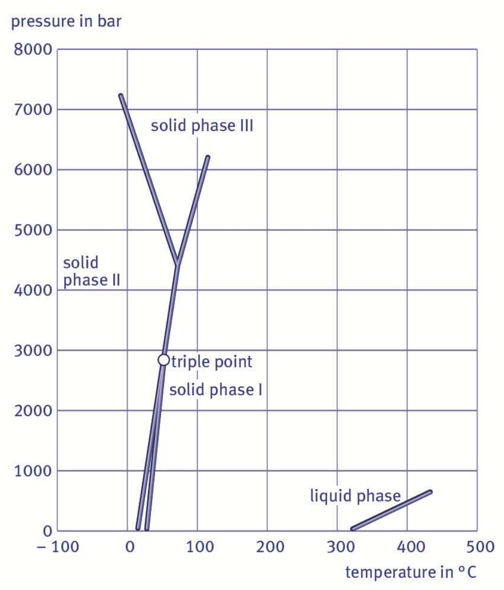

Figure 2: phase Figure of PTFE

A temperature between the two relaxation temperatures is therefore recommended for processing suspension PTFE, e.g. between 21^0 and 25^{0}C. If the granulate is required to have particularly good free-flowing properties, then the powder can also be processed at lower temperatures e.g. between 12^0 and 15^{0}C. When processing PTFE, each production step before the actual extrusion, therefore in particular the mixing of fillers (page 13 ff) or of extrusion aids, should take place at temperatures below 19^{0}C. Only in this way can it be guaranteed that PTFE agglomerate grains are not compacted too much which would make an equal distribution of the lubricants difficult or even impossible. In any case the machining of the sintered product should take place between the two relaxation temperatures in order to avoid greater dimensional deviations.

The following special physical and chemical properties of unfilled PTFE can be singled out:

- almost universal chemical resistance
- exceptionally wide thermal application range from -260^{0}C to +260^{0}C (for a short time also up to +300^{0}C)
- very good sliding properties
- anti-adhesive behavior
- good electrical properties (dielectric, high-frequency damping)
- no water absorption (also resistant to hot water vapor)
- non-combustible; LOI › 95
- light and weather resistant
- physiologically harmless (approved for foods by BgVV, EU and FDA)

The almost universal chemical resistance is the precondition for the use of PTFE in the chemical industry e.g. for seals, corrosion-resistant protective coverings against chemical reactions as well as piping or in the production sectors of fittings and containers. Due to its extraordinarily wide fields of thermal application, PTFE especially lends itself to be used e.g. as sealing elements for valves in refrigeration engineering or in the field of exhaust gas sensors for combustion engines - especially in the automotive sector. But PTFE and related fully fluorinated plastics also play a significant role in environmental protection relating to the desulphurization of flue gases in power stations when it is important to firstly cool waste air flows with aggressive high temperature aerosols and then to neutralize them, thus preventing toxic components escaping into the environment.
The very good sliding properties and low wear are reasons why PTFE or PTFE compounds (page 13 ff) can always be used as sealing materials for dynamic applications when other materials fail.

Therefore these materials are state-of the-art technology for seals in modern high-pressure fuel injection systems or for the low friction sealing of rotating axles in engines and transmissions. Due to the intrinsically good sliding properties, lubricants can often be dispensed with in PTFE applications where there is friction and wear. This advantage is not only used in the medical sector but also in filling plants for drinks, milk and yoghurt as an oily after-taste in foods is highly undesirable. The physiological harmlessness of PTFE is one of the essential preconditions for its application in medical technology or the foods industry.
The excellent electrical properties of PTFE - high relative dielectric constant and low high frequency damping - are used for printed circuit boards (PCB) in mobile phones or in insulation for cables, especially high frequency cables. The strong water-repellent behavior of PTFE means that these properties remain throughout the whole lifespan of the product. The absorption of moisture from the ambient area, a disadvantageous property of nearly all other plastics, is almost completely eliminated. The non-combustibility of PTFE, which is free of additives, is an additional safety factor in electrical applications.
Unfilled PTFE, however, also has some disadvantages which include:

- cold flow
- relatively low wear resistance
- low resistance to high-energy radiation
- pour adhesion
- non-applicability of thermoplastic processing techniques
- can only be welded with the addition of a welding medium e.g. PFA

Modified PTFE

By copolymerizing TFE with a low amount of the also perfluorinated modifier perfluoropropylvinylether (PPVE) and reducing the molecular weight, a copolymere (Figure 3) results, which can be processed by the usual methods for standard PTFE. This new polymer exhibits the typically positive properties of PTFE and in addition has the following advantages:

- cold flow reduced by factor 3
- permeation by chemicals and gases reduced by up to 50%
- porosity reduced by 50%
- minimal tendency to pore forming with stretching
- can be welded according to special methods

Figure 3: molecular structure of modified PTFE

Modified PTFE is especially suitable for applications where either the low permeation rate or the low cold flow is a special advantage. Low permeation rates are required, for example, for protective coverings of chemical installations, for the corrosion protection of metal containers and tubing, for static flange seals or for plastic constructions in the construction of tubing and apparatus. In order to improve these plastic constructions, the outside of the containers and tubing is mostly covered with a GFK or CFK sleeving while the liner of modified PTFE on the inside assumes the function of a permeation barrier resistant to strong chemicals.
The low cold flow of modified PTFE is the reason for the varied applications in the seal sector, especially for static flange seals with a high surface pressure to ensure the purging certainty even at high pressures and temperatures. If additional form stability or dimensional stability are required, as is the case, for example, with pump housings, then modified PTFE is also the solution to the problem here.
Large, complex components, especially in the construction of apparatus, can often not be made in one piece. In these cases the possibility to weld modified PTFE is often used in order to put together by welding a system solution made up of several individual components. Installations for chemical reactions with a total weight of several hundred kilograms have already been manufactured according to this method.

PTFE Compounds

The mixing of fillers in PTFE or modified PTFE in order to build compounds is done for the following reasons:

- reducing the cold flow (increasing the pressure resistance)
- reducing wear
- increasing thermal conductivity (reducing wear rate)

- reducing thermal expansion
- achieving electrical conductivity for use in ATEX sectors
- minimizing the friction in applications which cause wear and friction to protect the mating surface (e.g. abrasion-resistant seals with aluminium as the mating surface).

The reduction of the cold flow can be achieved, on the one hand, by mixing fillers but also by altering the PTFE matrix. As well as the cold flow, however, a number of material properties have also to be optimized in order to take the broad application spectrum of compounds into consideration. These include mechanical properties such as strength, elasticity module, friction coefficient or wear, the thermal expansion co-efficient, chemical resistance and thermal conductivity. How these material properties can be optimized by fillers and/or the polymer matrix can be learned from table 1.

Table 1: Optimizing the properties of PTFE compounds by the parameters polymer matrix and fillers

Influencing parameter	*Mechanical property*	*Cold flow*	*Friction coefficient*	*Wear*	*Chemical resistance*	*Expansion coefficient*	*Thermal conductivity*
Effects when exchanging PTFE for mod. PTFE	→ (blue)	↘↘ (green)	→ (blue)	→ (blue)	→ (blue)	→ (blue)	→ (blue)
Influence of fillers on the product properties of compounds	↘ (red)	↘ (green)	↗ (red)	↘↘ (green)	↘ (red)	↘ (green)	↗ (green)

Trends: → (green) *Positive*; → (blue) *Neutral*; → (red) *Negative*

The wear resistance of standard PTFE is relatively low. This is the consequence of very weak inter-molecular van der Waals forces

between the perfectly shielded carbon chains of the PTFE molecules which is therefore non-polar towards the outside. In the crystalline regions of the material, the molecular chains can be moved due to friction pressure - similar to graphite layers - against each other layer by layer. The polymer compound in the amorphous areas is more stable because of inter-molecular entanglements but this constitutes only approx. 25 to 50 % of the polymer. An essential improvement in the wear resistance is achieved by mineral or metallic fillers such as, for example, carbon, graphite, glass or carbon fibres and bronze. Newly developed special compounds have significantly improved friction behavior and a very low tendency to shrink on the mating surface (Figure 4) even in absolutely oil-free conditions. This is even the case when the mating surface is untempered.

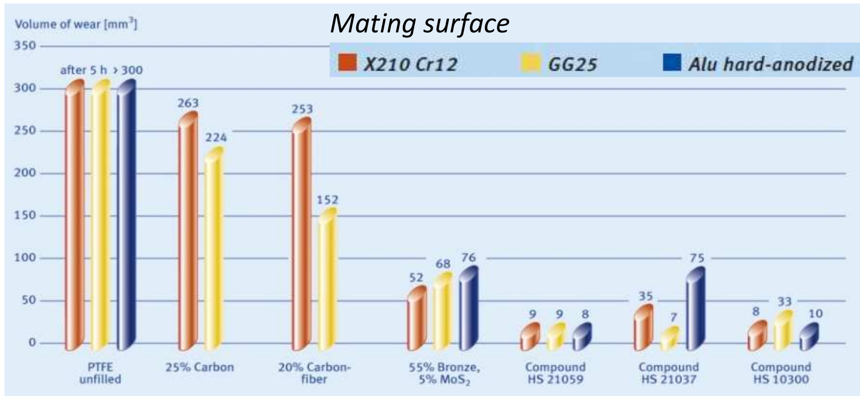

Figure 4: long-term wear (100hrs) of unfilled PTFE at high temperatures in dry applications compared to various compounds: friction conditions; (v = 4m/s, p = 0.42 N/mm2, T = 1000C, Wear volume in mm2 after 5 hrs)

The amount of sliding friction of the respective surfaces does not play a significant role in the abrasion behavior. The wear depends

much more on the application conditions: the kind of contact medium, contact pressure, relative speed, temperature and lubrication. Since no PTFE compound can fulfil all requirements at the same time, the best mixture has to be determined for each individual application.
When determining the wear in experiments, it has to be taken into consideration that each testing method delivers its own set of data (Figure 5). A direct comparison of materials is therefore only possible within each individual testing method or under the same or similar test conditions. The aim should also be to test as close to practice as possible. Applications are very often illustrated in the laboratory on a scale of 1:1. The planning of test runs (DoE) and their evaluation takes place by using statistical methods. With a minimum of number of tests it is attempted that the parameter range is covered in an optimal way and the optimal operating point is determined as quickly as possible.

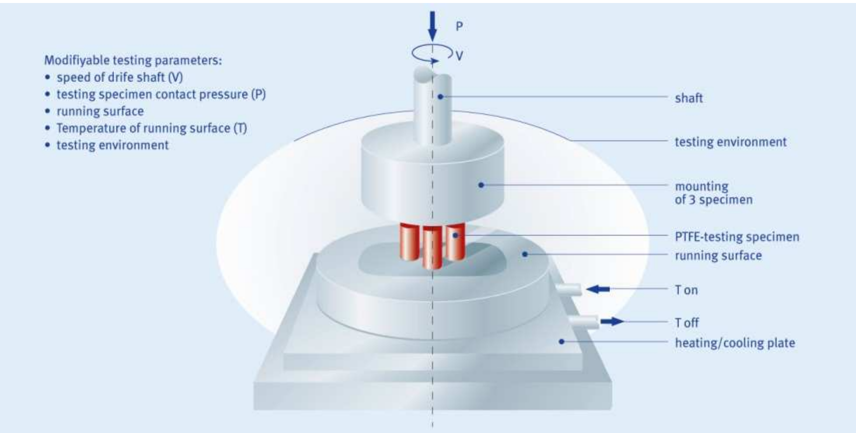

Figure 5: in a long-term wear test with the pin-plate method (the plate can both rotate and oscillate) each test follows as a simultaneous triple test in order to avoid faulty measurements as much as possible. Changeable parameters are: speed of the shaft

(ω), testing piece contact force (P), mating surfaces, mating surfaces temperatures (T), test atmosphere

An example of the optimization of a radial shaft seal can be seen in Figure 6.

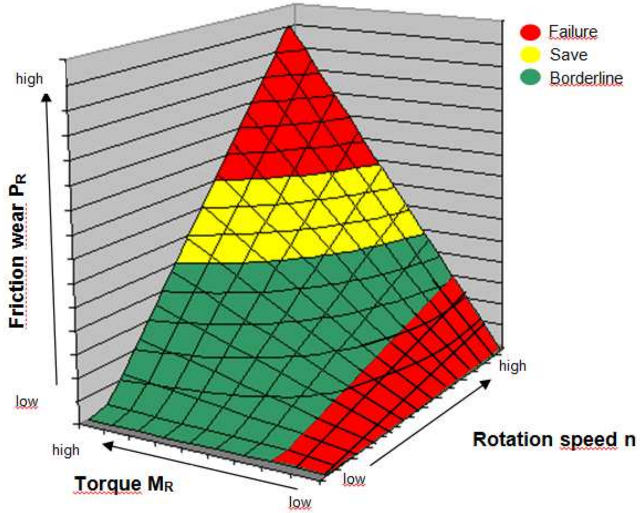

Figure 6: influence of radial strength, rpm and friction wear due to optimizing leak rate of high performance radial shaft seals. Test conditions: radial shaft seal test bench, oil level, radial middle, thick lip material is a PTFE special compound, pressure: 0-10 bar

Meltprocessed PTFE

For years researchers have been working towards combining the excellent properties of PTFE and modified PTFE with the possibility of thermoplastic processing. Approaches have included the further development of production processes for modified PTFE and also the use of continuing polymer chemical measures. By combining these approaches, meltprocessable PTFE was first launched on the market in 2006. In view of the temperature resistance and the permanent service temperature, no more drastic compromises are required as had to be taken into consideration in such processes in the past. The new product is distinguished as follows:

- customized molding/shaping
- suitable for mass production
- short cycle times
- sprue recycling (economical and considerate use of resources)
- low operator requirements
- high process reliability and stability

Meltprocessable PTFE allows a new kind of and economical system solutions and closes a gap in the range of the previously known perfluorinated PTFE materials (PTFE and modified PTFE) and fluorothermoplastic products (PFA, MFA, FEP and FEP-G). The basic data of the new material is shown in table 2. Further advantages shall be explained in detail below.

Table 2: typical properties of meltprocessable PTFE (Moldflon^{TM})

Basic properties	Value
Bulk density Test process according to DIN EN ISO 60	1200g/l
Density Test process according to DIN 53479 Buoyancy procedure	2.160 g/cm^3
Melting point Test process according to DIN EN ISO 3146	318^{0}C
Melting flow index MFR 372/5 Test process according to DIN EN ISO 1133	5 g/(10 min)
Mechanical properties	
Tensile strength Test process according to ASTM D 4894/ DIN 53455 (plate 2mm)	25 MPa
Yield strength Test process according to ASTM D 4894/ DIN 53455 (plate 2mm)	380%
Yield strength Test process according to ASTM D 4894/ DIN 53455 (plate 2mm)	14 MPa
Young's modulus Test process ISO 12086-2, method 511 (plate 2mm) 23^{0}C 50^{0}C 100^{0}C 150^{0}C 200^{0}C	460 MPa 420 MPa 210 MPa 170 MPa 80 MPa
Deformation under load Based on ASTM D 621; 15 MPa, 23^{0}C, 100hrs, permanent deformation	2.4%
Other properties	
Poisson ratio	0.4%

The new type of polymer composition allows even lower cold flow values to be set than with modified PTFE compounds (Figure 7). With meltprocessable PTFE, disadvantages including unlimited chemical resistance, limited approval for use in contact with foods or acids or in other critical applications based on fillers can also be avoided. Additional materials in perfluorinated polymers disturb the compactness of the polymer matrix and cause increased porosity and permeation. These disadvantages can also be avoided by the new meltprocessable PTFE. Regarding chemical resistance, anti-adhesive properties, ageing resistance and electrical insulation, meltprocessable PTFE is in no way inferior to classic PTFE.

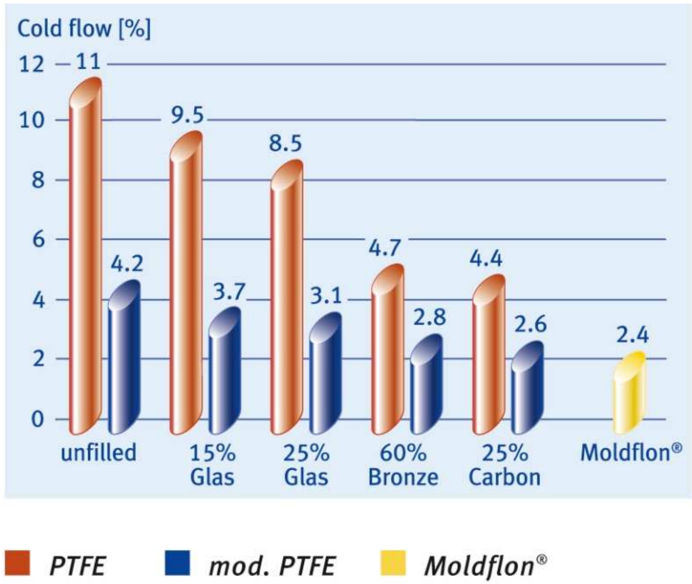

Figure 7: cold flow on unfilled meltprocessable PTFE (Moldflon^{TM}) compared to PTFE, modified PTFE and chosen compounds of these materials

The high temperature resistance of meltprocessable PTFE has not been reached by any other fluorothermoplastic material which can be processed by thermoplastic methods. With a melting temperature of 315^0C up to far above 320^0C it significantly sets itself apart from other fully fluorinated fluorothermoplastic materials such as, for example, PFA, MFA or FEP. This is also a result of the new kind of polymer composition. The gap between modified PTFE on the one hand and PFA, MFA or FEP on the other hand is bridged to the greatest possible extent (Figure 8).

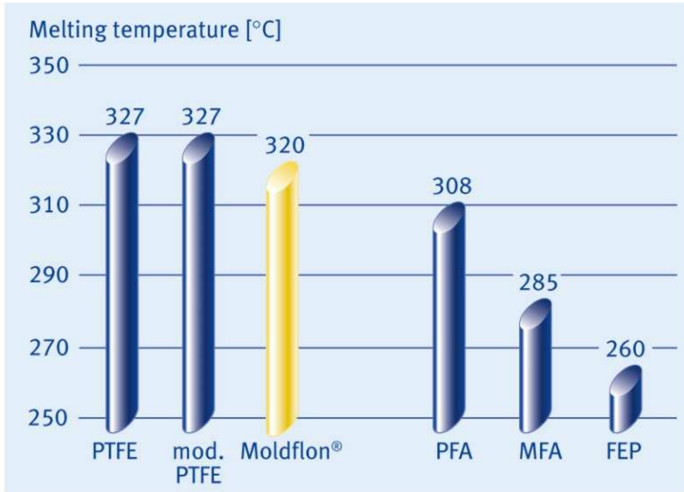

Figure 8: high temperature resistance of meltprocessable PTFE (Moldflon^{TM})

Due to the profile of its properties meltprocessable PTFE is also suitable for special applications with high thermal, chemical, electrical or mechanical requirements. In mechanical requirements the new material can especially prove its superiority under pressure.

Production and Preparation of Suspension and Emulsion PTFE

The following explains how the process of suspension polymerization and emulsion polymerization is technically implemented and what preparation processes can be used in order to produce suspension PTFE and emulsion PTFE to further produce the required pre-products.
In the case of suspension polymerization the monomer TFE is transformed into a high-polymer pre-product in a polymerization reactor with water as the reactant. In the radical polymerization which takes place in the absence of an emulsifier , a polymerization level of up to 10^6 and thus a molecular weight of 10^8g/mol can be reached. The raw polymerizate is then ground by a grinder under water flow. Then the reactant water is separated in a process consisting of several steps. The production is then finished by finely grinding to a medium-sized grain of between 15 to 50 µm. This typically takes place in an air-jet grinder. The material obtained after this process either comes onto the market as pourable suspension PTFE - also called pressed powder - or it is first processed in further steps with the following processes (Figure 9):

- by means of agglomeration the non-pourable PTFE is transformed into pourable suspension PTFE with a grain size of between 200 and 900 µm
- by means of additional thermal treatment of the pourable suspension PTFE you get pre-sintered suspension PTFE

- after adding fillers the non-pourable suspension PTFE is transformed into non-pourable suspension PTFE compounds
- if the non-pourable suspension PTFE is additionally subject to an agglomeration process, you get pourable suspension PTFE.

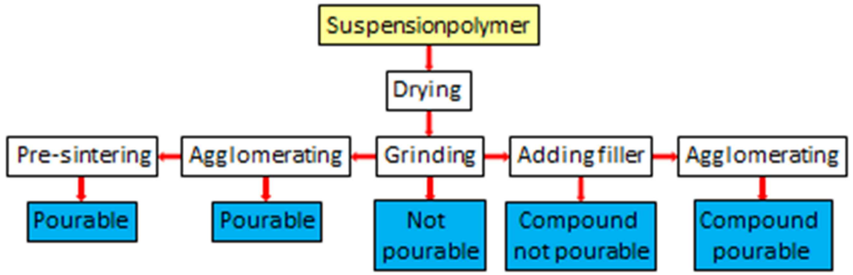

Figure 9: processing schematic and product range of suspension

In the case of emulsion polymerization, the monomer TFE is also transformed into a high molecule pre-product through radical polymerization in a polymerization reactor with water as the reactant, but with an emulsifier present. The polymer comes in the form of a watery emulsion whose PTFE particles have a diameter of between 200 and 280 nm. This emulsion can be prepared according to several processes (Figure 10):

- If the emulsion is first precipitated, coagulated and then separated in a multilevel process from the reactant water and the emulsifier and finally dried, you get a powdery emulsion PTFE which is also called fine powder or paste PTFE powder. This material is characterized by its excellent pouring qualities and be further processed in a paste extrusion process (page 32 ff).
- If the emulsion is concentrated and the emulsifier required for the polymerization is then replaced by another non-fluorite surface-active agent, you get PTFE dispersion. Such

dispersions are, for example, for coating frying pans or temperature-resistant textile weaves.

– By precipitating and drying the dispersion from an emulsion PTFE specially structured with a low number of molecules, you get PTFE micro-powder. Such powders are especially used as additives for plastics or paint as well as to increase the viscosity of lubricants.

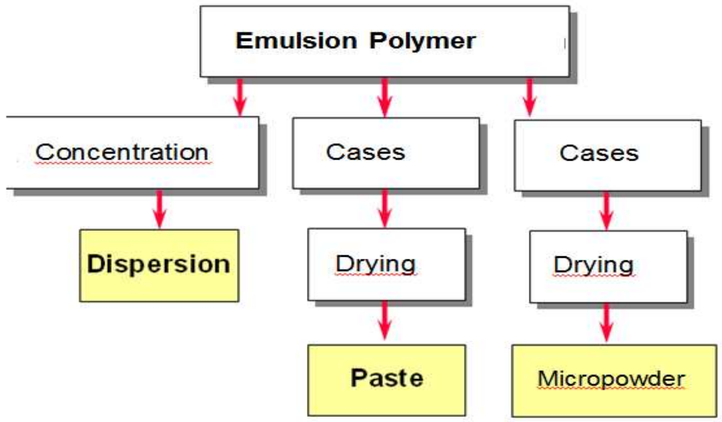

Figure 10: processing schematic and product range of emulsion polymerization process

FROM PRE-PRODUCT TO PRODUCT

Design Criteria

If you categorize fluoropolymers, especially standard PTFE, modified PTFE, meltprocessable PTFE and the group of fluorothermoplastics in the total environments of plastics, you immediately recognize the special position of this product group. Figure 11 presents the PTFE materials and the fluorothermoplastics regarding their permanent service temperature and the heat resistance under load in comparison with other plastics. While fluoropolymers assume a special position regarding the permanent service temperature due to their excellent properties, they have disadvantages with regard to the heat resistance under load. As a result of weaknesses in the profile of their properties, they can only be used as self-supporting construction material under certain circumstances. PVDF, which sets itself apart from the other fluoropolymers due to its mechanical parameters, is the most likely to be characterized as a construction material. It is therefore often used in the construction of valves in the production of full plastic engineering solutions. PVDF is also used in order to manufacture complete tubing systems for applications in the semi-conductor industry and to produce, store and transport pure chemicals.

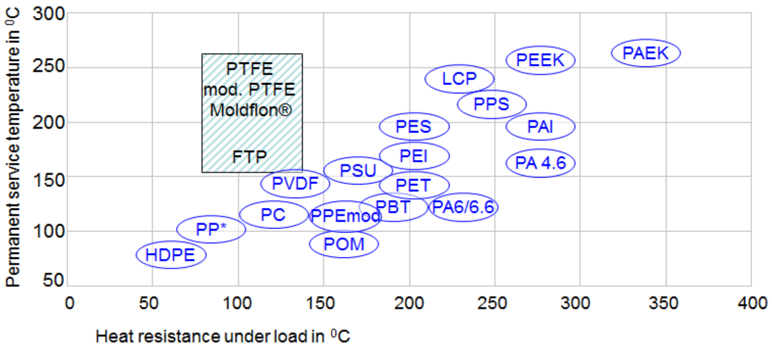

Figure 11: comparison of PTFE and modified PTFE. Meltprocessable PTFE (Moldflon™) and fluoroplastics (FTP) with other plastics regarding permanent service temperature and heat resistance under load

Yield Point

In order to characterize mechanical material properties, preferably values for the tensile strength or the tensile elongation are given. This kind of product characterization can be suitable for the production of raw materials but proving the quality consistency of the product is of no consequence for the design engineer. In order to explain this fact, Figure 12 shows the stress-strain graph of modified PTFE. According to this Figure modified PTFE has a tensile strength of approx. 38 N/mm^2 and a strain at break of approx. 600 %. For the design of plastic components it is not the value of the failure of the plastic which is decisive but, taking into account the softness of the fluoropolymers, those values where the plastic

begins to change its properties. In the given example these values are defined by the yield point, which means the point in the stress-strain graph when the material begins to flow. The characteristic parameters for the yield strength for modified PTFE only amount to approx. 14 N/mm^2 and the strain at yield of approx.. 25 %. The designer has to base the design of the components on these values.

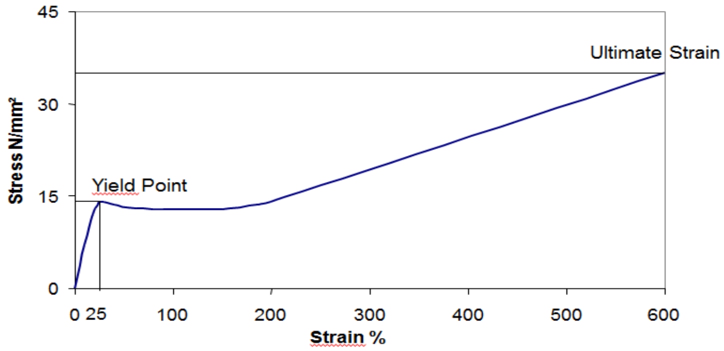

Figure 12: stress-strain graph of modified PTFE

Chemical Resistance

Apart from high constant service temperatures, full fluorinated representatives of the fluoropolymer group are characterized by excellent chemical resistance. While for plastics in general, reliability lists comparing a number of aggressive media or solvents are used to describe chemical properties, the opposite way is followed for full fluorinated fluoropolymers. As an almost universal chemical resistance is presumed, only exceptions are noted and these are then used to characterize resistance (table 3).

Table 3: fluoropolymers are characterized by a nearly universal chemical resistance with only few exceptions.

Cause	Effect
Fluorinated hydrocarbons	Swelling, reversible after short-term exposure, irreversible after longer contact
Alkaline metals, dissolved or melted	Elimination of fluoride and polymer destruction
Halogene, elementary fluoride and chlorine trifluoride	At high temperatures sometimes strong chemical reaction and material degradation
Nitrosulphuric acid (mixture of concentrated sulphuric and nitric acids)	Above 100^{0}C slow material decomposition, carbonation
Monomers: incl. styrene, butadiene and acrylonitrile	Penetrating possible. In the case of spontaneous polymerization, swelling or polymer degradation: popcorn effect
Ionizing rays (gamma and beta rays)	A ray dose of 10 kGy can reduce strength by more than 50%

Permeation

In practical experience it can sometimes happen that a engineering solution using a full fluorinated fluoropolymer does not work to complete satisfaction although the construction material used is consistent from the chemical point of view. The cause of this problem in those cases is often permeation. In this process a chemical or solvent penetrates the fluoropolymer or even saturates it without attacking the material. From a scientific point of view

permeation is understood as the product of diffusion and solubility (Figure 13).

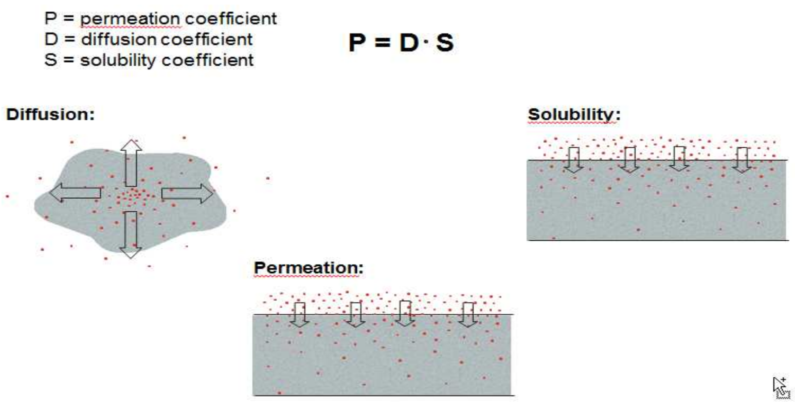

Figure 13: permeation: effect of diffusion and solubility

Due to the Brownian molecular movement chemicals spread in all directions after they have permeated a material and according to certain principles. This process is described as diffusion. The lower the boiling point of a chemical or the relevant solvent is, the more the diffusion is noticeable.
The solubility of a substance in a plastic is basically determined by its chemical similarity to the matrix material. The more similar the substance and the chemical are, the more critical is the solubility. The chemical similarity is, for example, the reason why chlorofluorocarbon (FCKW) is a suitable solvent in order to swell fluoropolymers. This swelling effect can be reversible if there is short-term exposure, but it can lead to a system failure in the case of a longer reaction time.
What possibilities does the user then have to prevent problems related to permeation if it is not possible to at least minimize them? Factors which influence the reduction of permeation are:

– The use of modified PTFE instead of standard PTFE; in an ideal case this can result in an approx. 50% reduction in permeation.
– Increasing the layer thickness: permeation and layer thickness behave inversely proportional.
– Reducing the operation temperature: by lowering the temperature by 12 to 15^{0}C, the permeation rate can be halved.

A typical application where permeation cannot be completely prevented even by implementing the above-mentioned measures is the corrosion protection of chemical processes against aggressive hydrogen chloride gas at high temperatures by means of fluoropolymer coatings. In this case corrosion can present. Figure 14 shows the cross-section of a distillation column which is coated with a fluoropolymer film. There is no fixed connection between the fluoropolymer film and the wall of the column, which is why the construction is also called the “loose shirt housing”. The fixing of the coating film inside the distillation column is made by crimping and clamping in the flange area.

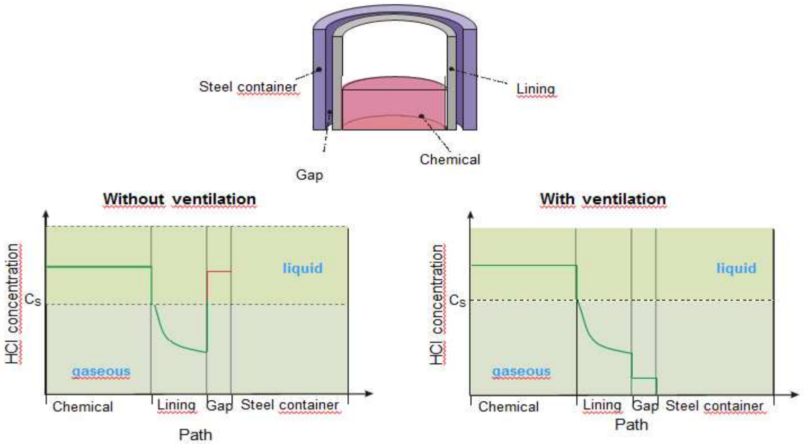

Figure 14: corrosion protection due to “loose-shirt housing” of a distillation column with a fluoropolymer film.

Left: due to lack of ventilation, HCl gas enriches itself between the film and the steel container to such an extent that corrosion occurs

Right: due to ventilation the diffused HCl gas is specifically removed and corrosion permanently avoided

On the left-hand side the installation is shown without ventilation. The hydrogen chloride slowly diffuses through the coating film in a gaseous state and enriches itself in the gap between the coating film and the steel container. After exceeding the saturation concentration, condensation (liquidation) occurs and thus provides all preconditions for corrosion.
On the right-hand side installation is shown with built-in ventilation. The gaseous hydrogen chloride which slowly diffuses through the coating film into the gap between is specifically removed so that the saturation concentration cannot be reached. As an electrolyte as well as an electro-chemical potential has also to be present for the corrosion process, corrosion can be avoided by the introduction of ventilation.
By means of the effective thermal insulation of the whole design, the corrosion danger can be reduced even further: the higher the temperature between the coating film and the steel container, the more unlikely it is that it falls below the dew point of the hydrogen chloride diffused into the given concentration. In this case, too, condensation will occur.

Standard Processing Techniques

Four different standard techniques are available for processing suspension PTFE:

- hydraulic pressing
- automatic pressing
- isostatic pressing
- ram extrusion

In the case of hydraulic pressing, the PTFE powder or the compound produced from it are firstly compressed under a pressing power of between 120 and 700 bar and, after being removed from the press mould, sintered in a hot-air oven. This is what gives the end product its actual rigidity.
In the case of automatic pressing, the dosage of powder in the mould, the pressing and the ejection of the compressed powder take place in an automatic process. This process is especially suitable for parts with a simple geometry but which have to be produced in high numbers. After the parts are pressed, they are transformed into the required end product in a subsequent sintering process (Figure 15).

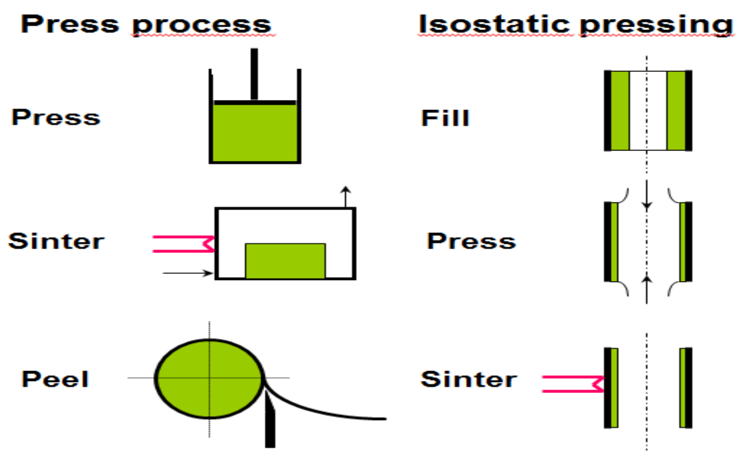

Figure 15: the various press processes for suspension PTFE

Isostatic pressing is special in that various versions have been further developed especially for processing PTFE. The principle underlying all versions is that an elastic diaphragm which is pressure coated with water or a hydraulic liquid compresses the PTFE powder. The acting pressing power compromises the PTFE powder from various directions but always with the same pressure. After being removed from the mold, the isostatic pressed PTFE parts are transformed into the end product in a subsequent sintering process.
These processing techniques for suspension PTFE described up to now have one thing in common: the pressing and sintering take place in two separate, subsequent steps. If these two steps are concentrated into one step, then we speak about ram extrusion.
In the case of ram extrusion, the PTFE powder is pressed in batches through a heated tube by means of periodic stamping whereby the pressing power required for the compressing is generated either by wall friction or by an additional brake. Various heating zones which create a temperature profile are installed along the extrusion tube so that a complete through sintering is guaranteed during the

extrusion process. Especially simple geometric parts, for example, tubes or rods, are produced with the economical ram extrusion process (Figure 16). A disadvantage could be the comparatively high internal stress with which is put on the product. This is especially the case when a subsequent machining process is required in order to manufacture parts with a high dimensional stability. Table 4 shows what kind of products are suitable for each process.

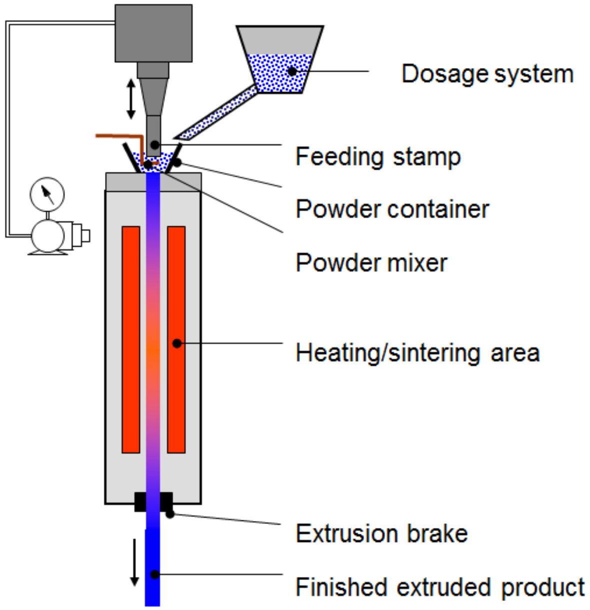

Figure 16: ram extrusion: economical production of PTFE semi-finished products with simple geometry

Table 4: powder settings in the case of processing suspension PTFE

Powder setting	Hydraulic pressing	Automatic pressing	Isostatic pressing	Ram extrusion
Pourable	yes	no	yes	no
Not pourable	yes	yes	yes	yes
Pre-sintered	no	no	no	yes

The processing of emulsion PTFE takes place exclusively with a paste extrusion process. In this process, the paste PTFE powder is first mixed with a lubricating agent - in most cases benzine with different boil fractions are used - and subsequently processed by means of piston extrusion to semi-finished products such as, for example, hoses, tubes or strands (Figure 17). The added benzine is first of all removed from these semi-finished products in a drying step and then transformed into the end product by sintering - e.g. hoses or tubes. In order to manufacture stretched paste bands, the extruded strands are firstly transformed into a film by calendaring and then dried in a manufacturing process similar to that for hoses or tubes. The film is then not sintered but transformed into the end product by stretching at temperatures below the melting point.

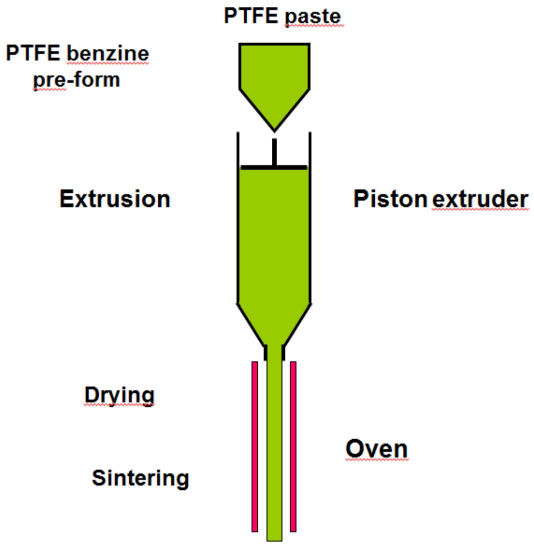

Figure 17: schematic representation of manufacturing process of emulsion PTFE

PTFE special Products

Special processing techniques allow the production of porous PTFE, laminates and new types of compounds. As a result, the original PTFE properties are extended in different directions and new applications for PTFE products are opened up.

Porous PTFE

By using a special pressing and sintering technique, suspension PTFE can be processed into porous PTFE. The powder properties are so attuned to the press power that a statistic pore size distribution is achieved during the pressing. The choice of process parameters thus assures that there is also a porous structure after the sintering. The special product differs basically from non-sintered or partly sintered porous PTFE which is produced from emulsion PTFE and used for breathable linings for jackets or gloves to protect against wetness. The average pore size of fully sintered porous PTFE can be adjusted within a very broad range of between approx. 1 and 50 µm. Figure18 shows the structure of fully sintered porous PTFE as visible through a scanning electron microscope.

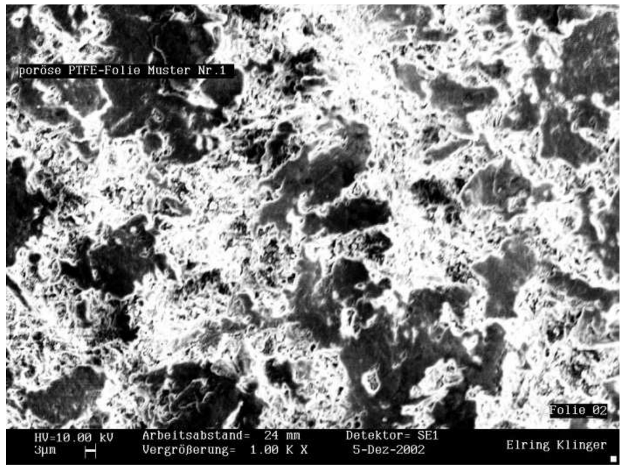

Figure 18: structure of porous PTFE

One of the essential properties of this material is a very high mechanical rigidity which enables self-supporting designs. It distinguishes itself positively from alternative products which are not sintered and therefore mechanically very fragile and often have to be supported in applications.

Usual parameters to characterize porous PTFE for applications in the separation of media are air permeability and water column resistance. Figure 19 shows the representative values for the parameters for film/sheet thicknesses ranging from 0.1 to 3.0 mm.

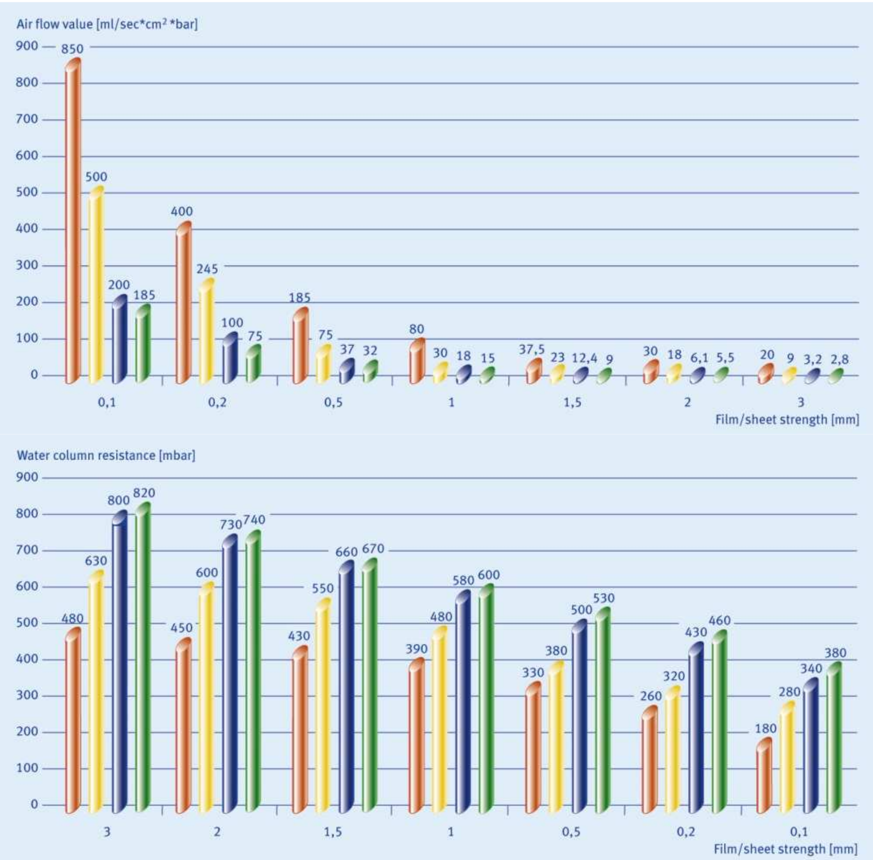

Figure 19: air permeability (above) and water column resistance

Porous PTFE is eminently suitable for optical applications as it has a high reflecting power for light rays in ultra-violet, visible and nearly infra-red wavelength areas (Figure 20).

Figure 20: the reflection spectrum of porous PTFE

Between 300 and 1800 nm, the reflective capability is nearly constant and thus independent of the wavelength. Typical applications are Ulbricht integrating spheres to measure diffuse reflections and scattered transmissions and to characterize light sources such as, for example, bulbs or light diodes (LED) or to measure the performance of lasers, laser diodes or light diodes. As well as that, porous PTFE is used for Lambertian reflectors and diffusers. These are used, for example, as normal reflectors, projection screens or detection sensors and light reducers (Figure 21).

Figure 21: Ulbricht integrating sphere in porous PTFE

LAMINATES BASED ON PTFE AND MODIFIED PTFE

By laminates we understand reinforced PTFE which is designed, on the one hand, from one or several PTFE films or sheets and, on the other hand, from a substrate. The material layers are connected firmly with each other. Fabrics, fibres or knitted fabrics can be used as substrates as well as films. The substrate consists of, for example, glass, metal, ceramics, an elastomer or high-performance polymer. The construction of the laminate can consist of two or more layers. Designs which consist of up to seven layers are not uncommon.

Figure 22 shows a film/sheet made of conductible PTFE laminated with glass fibres. A lamination with carbon fibre fabric would also be possible to improve the chemical resistance - especially for applications which come into contact with liquid acids.

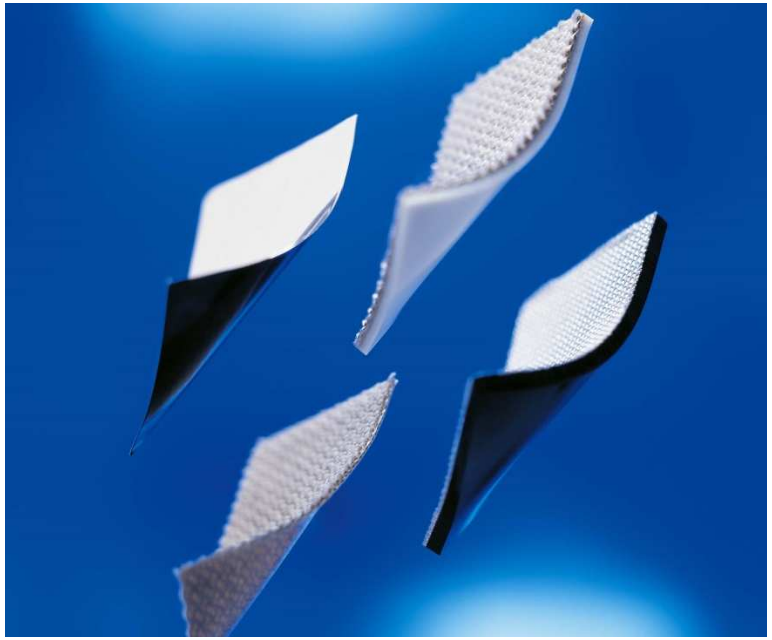

Figure 22: laminate with conductible PTFE film

Typical applications are liners in equipment engineering, components for electric and electronic applications, as well as diaphragms in pump and sensor engineering or optically permeable composites for textile architectural projects (Figure 23).

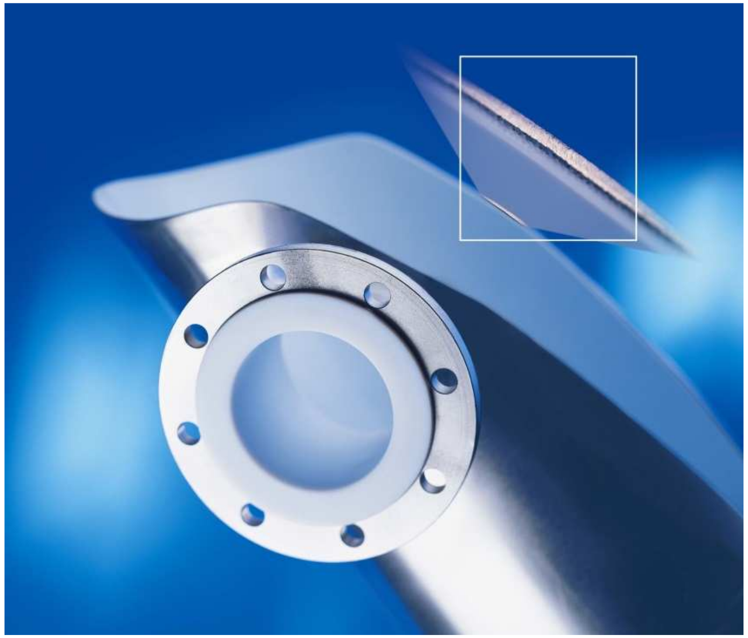

Figure 23: structure and application of laminates based on PTFE and modified PTFE using the example of tank lining

LAMINATES BASED ON STANDARD PTFE ARE CHARACTERIZED BY THE FOLLOWING PROPERTIES:

- excellent and universal chemical resistance
- very broad temperature applications usually limited in the upper ranges by the reliability of the adhesive used
- very good anti-adhesive properties
- resistant to deformation and stress cracking
- no embrittlement or ageing

When using modified PTFE as a film/sheet, these properties are further improved by the following:

- thick polymer structures with few pores
- low permeability
- better weldability

ANISOTROPIC PTFE COMPOUNDS

By means of a special process it is possible to produce a PTFE compound reinforced with carbon fibres (C fibres) with an anisotropic profile; the carbon fibres are mainly arranged in the X-Y levels (Figure 24). This new kind of material is produced as plate, disc or ring as is required. It is characterized by:

- nearly universal chemical resistance
- extremely high tensile strenght
- high pressure resistance
- superior cold flow resistance
- high abrasion resistance

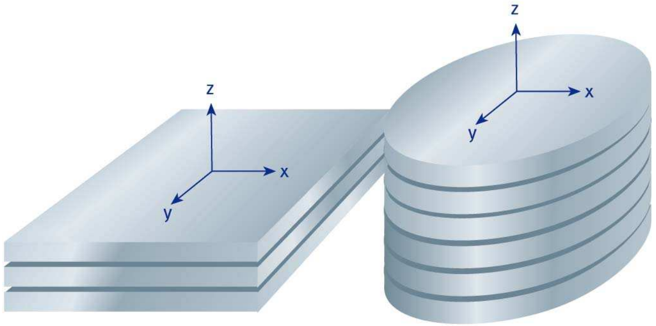

Figure 24: structure of anisotropic PTFE compounds (XYMON)

In comparison to unfilled PTFE or typical compounds with carbon or glass fibre fillers, the performance increase- measured parallel to fibre direction - is huge (table 5). The very good chemical resistance of long carbon fibres and the fact that these are closely surrounded by fluoropolymers lead to the unique resistance which comes very close to that of pure PTFE. The material can, for example, be used with liquid acids, hydrochloric acids, phosphoric acids, mineral oils, tetrahydrofuran and many other media. Typical examples of applications are valve seals, bearings, valve seats, flat gaskets, pump impellers, valve components, piston rings and seals in the automotive industry.

Table 5: properties of anisotropic PTFE compounds compared to standard PTFE materials (parallel to fibre direction)*

Property	XYMON type 1	XYMON type 2	PTFE 25% carbon	PTFE 25% glass fibre	PTFE unfilled
Young's modulus	10 000 MPa*	5000 MPa*		800 MPa	750 MPa
tensile strength	60 MPa*	45 MPa*	15 MPa	17 MPa	33 MPa
deformation under load	< 1%	< 2%	4.5%	8.5%	11%

CASE STUDIES BASED ON PRACTICAL EXPERIENCE

What system solutions can be realized with products based on PTFE? Based on the special requirements of each particular application, this question will be answered with the help of concrete examples from various sectors. We describe how the problem can be solved by choosing a suitable material in connection with the correct product design.

Seals for the automotive Industry

PTFE sliding rings in CVT transmissions

Variable transmissions such as manual transmissions, automatic transmissions, automated manual transmissions and double clutch transmissions always present a compromise between driving dynamics, consumption and driving comfort. The constant variable transmission ratio of a CVT transmission enables, on the other hand, the optimal power transfer. The advantages of the system lie in the high driving comfort, the smooth power transfer, the low fuel consumption and the very compact design. At the time of writing this book, CVT transmissions are suitable for engine torque up to approx. 420 Nm and can thus cover the whole range of engines of upper middle class vehicles. The following demands are made on the sealing elements:

– service temperature range -40⁰C to +120⁰C
– pressure load to maximal 60 bar
– axial stroke up to 20.5 mm within 1.3 s
– lifetime at least 3000 hrs
– medium: automatic transmission oil

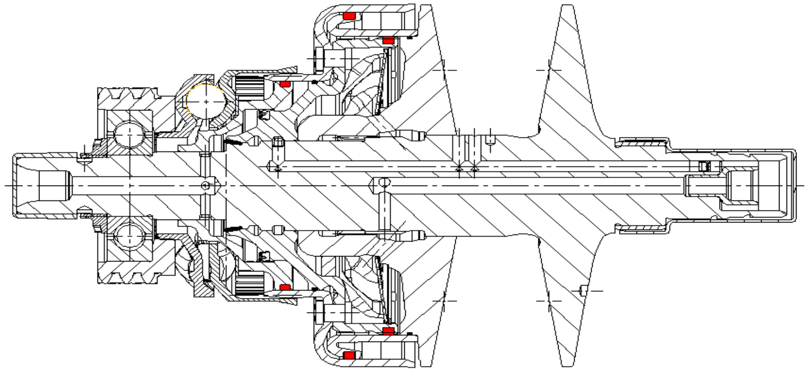

Figure 25: cross-section of a CVT transmission with red-colored rings

Figure 25 shows the cross-section of a CVT transmission. The core of the transmission is the variator consisting of two cone disks and an embracing medium (plate link chain). Due to the smooth changing in the axial distance between both cone disks, the transmission can also be regulated smoothly. The link chain transfers the actuated torque friction. The axial adjustment of the cone disks takes place hydraulically. PTFE slide rings are used to separate the two hydraulic chambers (Figure 26). In order to separate the two hydraulic chambers, PTFE slide rings with elastomer tension are used. The slide rings have to have very good pressure and wear resistance.

Figure 26: PTFE slide ring with o-ring support

Friction-optimized PTFE Shaft Seals for Formula 1

At the beginning of the development of shaft seals for the crankshaft of a Formula 1 engine, the aim was to develop a product that was well sealed, had very low engine friction and was up to the enormous demands of Formula 1. The technical requirements included:

– resistance in the face of high-tech synthetic oils
– bridging a short-term lack of lubrication in the sealing area
– leak tight up to 19,000 U/min - for a crankshaft diameter of 55 mm this corresponds to circumferential speed of up to 56 m/s
– lifespan over one single race of approx. 20 hours

First of all a flexible standard shaft seal with a dust lip was tested because due to its special construction it is suitable for high circumferential speeds of up to approx. 30 m/s. Tests showed that standard shaft seals were up to this task. After simulating several races on the engine test bench, no noticeable wear could be

discovered and thus the shaft seal met the leakage requirements made by formula 1. After this positive experience in testing this standard shaft seal, the requirements were modified. The aim was to reduce the weight and to use a lighter housing instead of the stainless steel housing made of V2A. In addition the friction loss was further reduced and the external measurements of the shaft seal adjusted to the housing.
The shaft seal (Figure 27) is now completely and solidly made out of PTFE. Thus the sealing lip is always exactly concentric - deviations resulting from assembling cannot happen. The housing form of the shaft seal is so designed that the sealing lip is specifically lubricated with oil and the shaft seal can be built into the crankshaft housing optimally and using the least space. An O-ring provides the static sealing. An increase of lifespan expectancy to two race weekends or a maximum of 100 hours is no problem with this shaft seal.

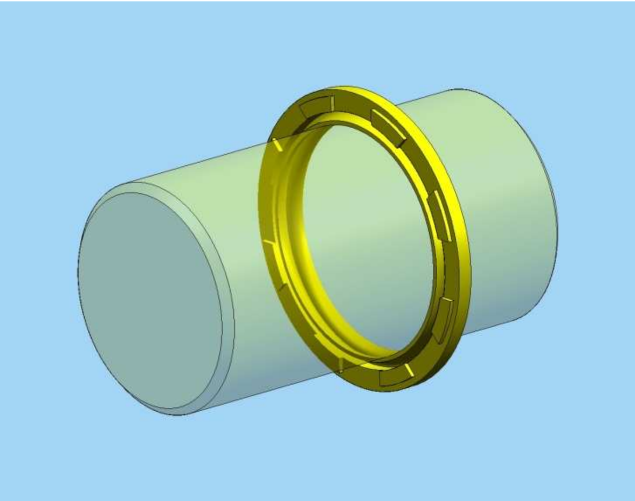

Figure 27: shaft seal for the crankshaft in a Formula 1 engine

PTFE Seals in direct-injection Gasoline Systems

In Otto engines with direct-injection gasoline systems, the air-fuel mix is formed directly in the combustion chambers. Only the air required for the combustion streams through the intake valve; the fuel is lead directly into the combustion chamber with a high-pressure injection valve. This preparation of the fuel-air mixture increases the engine performance, enables lower fuel consumption and results in lower toxic emissions.
Fuel pressures of up to 200 bar are achieved with the new direct-injection gasoline systems by means of a central high-pressure pump. The compromised fuel is lead directly to the high-pressure fuel injection valve. This fuel injection valve doses and atomizes the fuel in the combustion chambers in a very short time. PTFE gaskets are used both in the high-pressure pump (Figure 28) as well as in the high-pressure fuel injection valves.

Figure 28: test bench for seals in direct-injection gasoline systems

Piston pumps are often used as high-pressure pumps and their pistons are driven by the camshaft. This makes the following demands on the sealing elements:

- high wear resistance in order to endure the high, axial piston speeds of up to 3 m/s
- high pressure stability with pressure pulsations up to an amplitude of 24 bar in sealing area
- broad service temperature range of between -40^{0}C up to +150^{0}C typical in automotive construction
- very good sliding properties in order to avoid friction
- special sealing geometry for the separation of fuel and engine oil
- chemical resistance with all commercially available fuels and engine oils.

Due to the extreme demands mentioned above, only sealing materials which are very wear resistant, pressure stable and temperature stable come into question. In first development stages, pressed pieces (pressed powder type) were used. Changing to extruded rods with sufficient pressure stability simplified manufacturing significantly (Figure 29). PTFE as basic material brings chemical stability and good sliding properties and different combinations of organic fillers provide wear resistance and pressure stability.

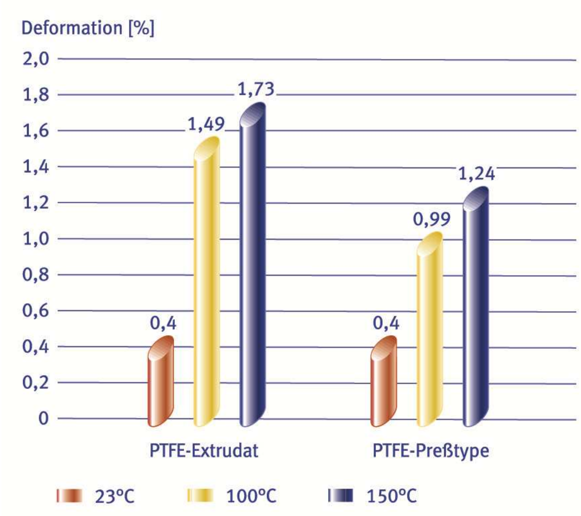

Figure 29: PTFE deformation comparisons of different manufacturing procedures;

test parameters:
pressure 5N/mm^2
test temperatures: 23^{0}C, 100^{0}C, 150^{0}C
test time: 24 hrs
test piece measurements: 11.2 x 2 mm
As the seals in high-pressure piston pumps additionally have to separate the media fuel and engine oil, special requirements are made on the design and geometry of the seal. Double effect sealing systems are used. On the fuel side, PTFE sealing lips are supported by stainless steel spring elements in order to guarantee that the contact pressure of the sealing lips on the pistons remains constant in the whole service temperature range. On the engine oil side, sealing lips with memory effect are used - PTFE compounds can be equipped with a memory function. The sealing lips on the engine oil side are so formed in thermal processes that radial contact pressure

is generated on the mating surface. In this way both media are reliably separated from each other. The spring-energised seals available in various geometrical variations and made of high wear resistant PTFE compounds enable a secure sealing of the high-pressure piston pumps over a very long lifespan of more than 4000 hours of automotive operation.

PTFE Seals in Pneumatic Spring Compressors

Pneumatic spring compressors are used in pneumatic springs or in automatic level control systems in middle or upper class passenger cars but also in light commercial vehicles and SUVs in order to produce the required compressed air. The pneumatic spring has the task of increasing driving comfort. Moreover the level of the car can be lowered at high speed in order to improve road holding and therefore provide more safety. Especially for station wagons and light commercial vehicles, the automatic level control results in a constant vehicle construction level and thus for constant suspension levels even with high loads. This significantly improves the driveability of the vehicle.
Vehicle manufacturers make the following demands on the sealing elements for pneumatic spring seals:

- compression pressure up to maximum 20 bar
- temperature resistant from -40^{o}C to +200^{0}C
- lifespan of 1000 hrs
- able to operate in dry applications

A difference is made between wobble compressors and reciprocating compressors. In wobble compressors the piston (Figure 30) makes a wobbling motion of maximum 9^{0} in the cylinder. Special gas-tight, round piston rings or memory packs are used here.

These have the task of ensuring the sealing of the compressor chamber from the crank chamber so that the necessary pressure can be produced in the compressor. In this application it is a single-step compressor which means that the air is compressed to the required pressure of maximum 20 bar in one step.

Figure 30: reciprocating compressor solution for compressors in automotive industry

In the case of reciprocating compressors the piston makes a linear movement in the cylinder. Special gas-tight piston rings and memory packs are used here. A piston ring with a gas-tight thrust is chosen due to the minimal amount of leakage (Figure 31). In addition the piston is lead into the cylinder with PTFE guide rings.

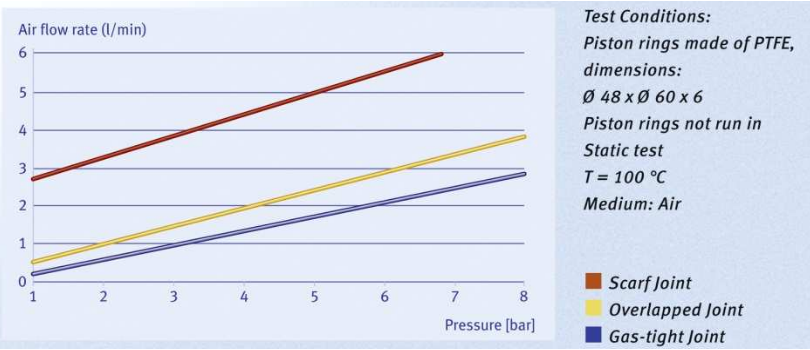

Figure 31: degree of efficiency of various types of piston ring thrust

Contrary to the wobble compressor, the reciprocating compressor in this application is a two-step compressor. In the first step the air is compressed at a pressure of between 4 and 6 bar. This compressed air goes straight into the second step when the end pressure of maximum 20 bar is reached.

Due to the compression, the sealing elements in both systems heat up to a temperature of up to 200^0C at high pressure. This alone is a huge challenge for the material. Even at -40^0C and at an altitude of 4000 metres the compressor has to have the required pressure available within a given time. If the time limit is exceeded, a fault is displayed in the vehicle and this would mean an unscheduled trip to the garage. Thanks to the specially designed PTFE high-performance materials, these demands can be met.

Sensor Technology for the Automotive Industry

PTFE Components in Lambda-Sensors in Exhaust Gas Catalytic Convertors

In order to minimize toxic emissions from Otto engines, the most accurate preparation of the air-fuel mix is required. This can only be achieved if the exhaust gas composition is measured constantly and the fuel supply adjusted according to the result measured. The Lambda sensor is the most important measuring sensor in the regulating loop for the catalytic exhaust gas cleansing. Installed in the exhaust manifold or the collection pipe, it gives information on whether the air-fuel mix has to be adjusted to be richer (higher proportion of fuel) or leaner (higher proportion of air). This provides the continuous optimal combustion of the air-fuel mix.

The most common construction of Lambda sensor is the Nernst sensor. The core is formed by a ceramic element which has one side in the exhaust gas flow and the other side is in contact with external air. The oxygen concentration is therefore different on both sides of the ceramic element. Due to the special properties of ceramic, an electrical voltage is detected in the sensor which depends on the concentration difference defined according to the Nernst equation. Depending on the measured sensor voltage, the mix preparation is adjusted constantly and correspondingly.

Due to the extremely high temperatures in the ceramic element of up to 300^0C, high-temperature resistant plastics are needed for the cable routeing (grommets) and protective tube (blow molded). (Figure 32)

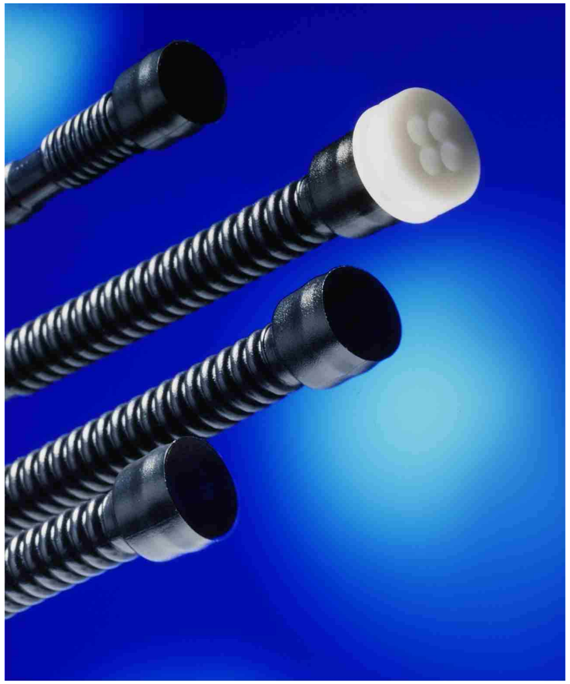

Figure 32: blow molded tube with grommet in a lambda sensor

PTFE offers the ideal preconditions for this application such as, for example:

- high temperature resistance, short-term up to 300^{0}C (Figure 30)
- very good chemical resistance against exhaust gas particles
- very good electrical insulating properties
- high form stability during pressure on the PTFE grommets for cable routeing and insulation
- high flex-life of the PTFE form hose

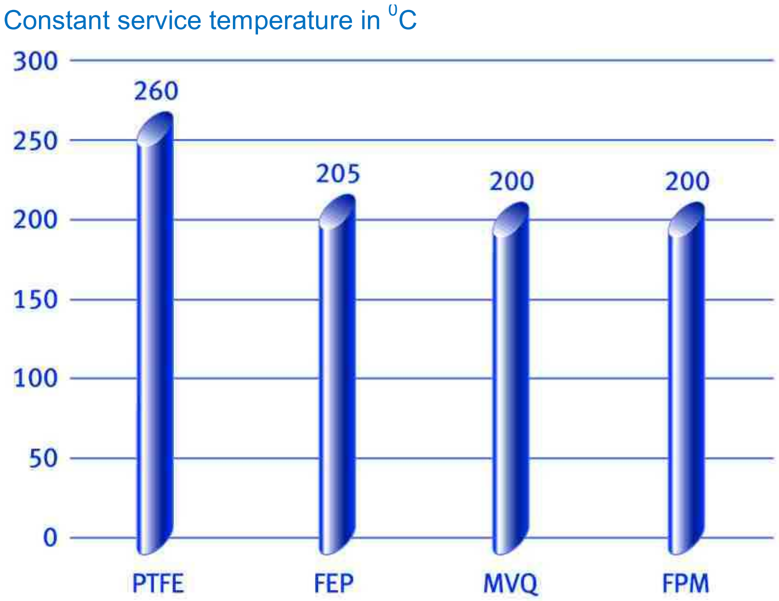

Figure 33: range of temperature applications for PTFE compared with other plastics

PTFE grommets are used for cable routeing and cable insulation in the lambda sensor. They serve as electrical insulators and at the same time as sealing elements against the atmosphere. Dimensionally stable PTFE glass fibre compounds are very often used because, on the one hand, they insulate very well and, on the other hand, they retain their shape under temperature stress. PTFE form hoses are used to prevent cable kink and as a sealing against external influences such as, for example, water spray, cold cleaners and engine oil. They are manufactured by means of a special blow molding process. A PTFE tube manufactured by paste extrusion and molded into a blow molded tube by special tool. Both components are together extremely important in order to protect the lambda sensor from kinking, to guarantee temperature resistance from the catalytic convertor and the leak tightness of the Lambda sensor.

PTFE Protective Caps for Steering Angle Sensors

Modern electronics and steering angle sensors enable various calibrations of electric and electro-hydraulic power-assisted steering systems. In its basic function the steering angle sensor determines the angle position of the steering wheel without making contact and thus also the steering angle of the wheels.
New steering systems, such as, for example, active steering, provide optimised steering and driving and the stabilization of the vehicle. The steering transmission is designed variably, that means at lower driving speeds the vehicle reacts directly to the steering movement but increasingly indirectly as speed increases. Thus together with an electronic stability program (ESP) over-steering tendencies are recognized and the vehicle is stabilized by automatic counter-steering.
Steering angle sensors require a protective cap especially when the sensor is directly coupled with the steering gear. The protective cap has to fulfil the following requirements:

- protect the sensor electronics against steering gear oil
- diffusion tightness against steam and steering gear oil
- temperature resistance from -40^{0}C up to +150^{0}C
- low dynamic friction coefficient as a magnet makes a swing movement over the protective cap
- connection possibilities with sprayable silicon or pouring materials

In the application described here a PTFE protective cap made of an special diffusion resistant PTFE material is used (Figure 34). Its contours are manufactured in a PTFE form molding process. In this process a PTFE film is heated and molded into a form under heat and under pressure. In this way nearly every contour can be manufactured with little material waste and economically. In order to enable a connection possibility to the injection material - e.g. silicon - the inner contours of the PTFE protective cap are roughened in a plasma process, so to say, etched. Only in this way can the anti-adhesive PTFE be connected to other materials. This described manufacturing process of form molding techniques and using special PTFE basic materials enable the special requirements of the automotive industry to be met economically.

Figure 34: steering angle sensor with mounted protective cap

Diaphragms for the Pump and Valve Industries

Diaphragms are hermetic seals between two areas which usually contain different media and/or are under different pressures. As opposed to piston seals and rod seals, no delay leakage occurs on the diaphragm. Low demands are made on the tolerances and surfaces of neighbouring parts.
The form diaphragm described as follows has to meet the following demands in the filing valve of a bottling plant (Figure 35):

- good flex-life
- nearly universal chemical resistance
- very easy to sterilize
- temperature resistant from -60^{0}C to +200^{0}C
- FDA-approved material
- high flexibility
- lowest diffusion

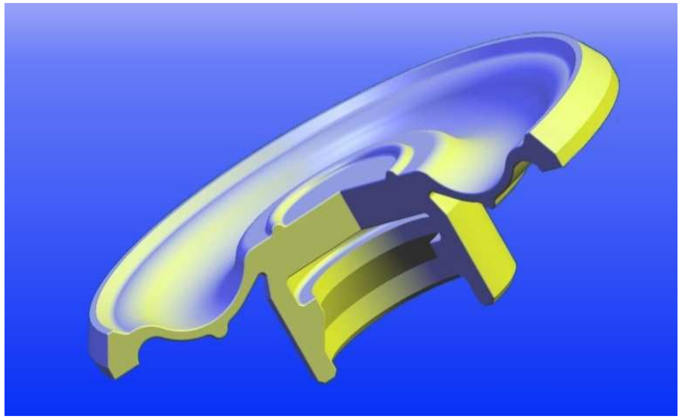

Figure 35: form diaphragm for bottling plants

Up to today a purely elastomeric diaphragm or a PTFE elastomeric connecting diaphragm are used as form diaphragms in the filling valve of a bottling plant. The development of a multi-layer diaphragm is however complex. Due to the complexity of the manufacturing, deviations in the diaphragm properties which could lead to a premature failure of the component can occur. Because special tools are required, such diaphragms are also very expensive. Special problems occur in filling beer: froth remains stick to the diaphragm and crystallize. As a result the diaphragm can stick. This causes very quickly in the elastomeric parts to tear very quickly in the switching operation. The user is then also confronted with another weak point: aggressive media can attack the upper surfaces of the elastomers, despite a PTFE coating, because these media diffuse through the mostly thin films. The layers often separate themselves from each other anyway in normal operation when, due to different elasticity modulus (E-module) and shear modulus (G-module), the materials used result in inhomogeneous tension distributions which put pressure on the boundary layer. This characteristic often limits the lifespan of the connecting diaphragm. Therefore it is sensible to use pure PTFE diaphragms in the food industry. The mechanical and anti-adhesive properties are essentially better and the material has FDA approval. The extreme resistance of PTFE to frequent flexing - this property makes PTFE the preferred material for diaphragms and is unknown from any other thermo-plastic material - is a great advantage for applications such as filling valve diaphragms.
Optimized PTFE material can meet all the required values for endurance strength. Therefore this material exceeds standard PTFE 3-fold in its endurance strength and modified PTFE even 10-fold (Figure 36). The advantages of modified PTFE including low permeation, reduced cold flow and a smoothly machinable surface remain. The optimal geometry of the PTFE diaphragm depends on

the kind of manufacturing - molded or machined. As a result of optimizing the diaphragm material and the diaphragm geometry, the filling valve works trouble-free: in practical use a lifetime of over 20 million operating cycles.

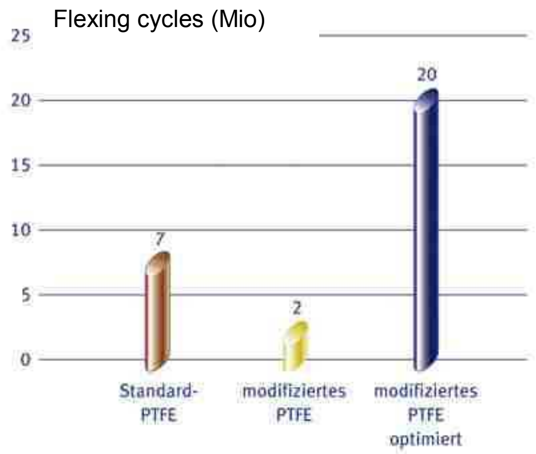

Figure 36: flex-lifetest of various qualities of PTFE: a 1 mm thick film piece (test piece) standardized according to SPI is bent to 90^0 in both directions by 4 Hz. If there is a complete break at the flexing point, the test apparatus stops

Extinguishing Nozzles for High Voltage Switches

The extinguishing and/or quenching nozzles of high voltage switches are a decisive component in circuit breaker units. The quenching gas (SF_6) streaming out of the control chamber is lead into it and then blown into the upper switch area. When the voltage switch is

separated, an electric arc occurs on the circuit voltage which is quenched with the help of the gas.
The PTFE extinguishing nozzle illustrated in Figure 37 consist of a PTFE compound which is totally resistant to chemicals (acids, alkalis), temperature resistant up to 260^0C in constant operation (short-term up to 300^0C), incombustible and - very important for use in the switch - an excellent insulator.

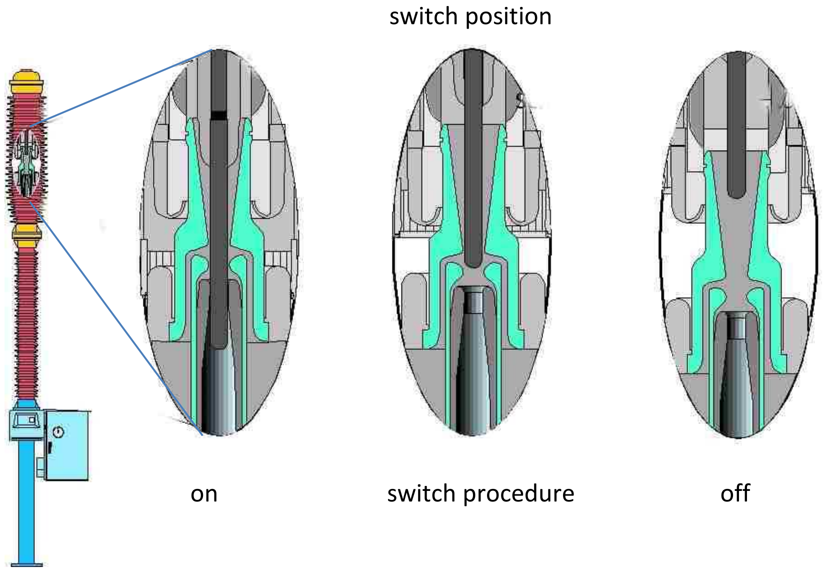

Figure 37: extinguishing nozzles (left) in various switch positions: when switching (middle), a high arc erosion resistance is required due to the high thermal and mechanical demands. In switch position “off”, the dielectric demands are high.

A special filler is added to the PTFE which is decisive for the switch-off capacity, the lifespan of the switch and in addition, the coloring of the jet. The composition of this filler is a heavily guarded secret of each switch manufacturer. In order to minimize material wear, test pieces are pressed isostatically, sintered and finally turned / milled into the final form (Figure 38).

Figure 38: extinguishing nozzle for high-frequency switches

Special Products for medical Technology and chemical Analysis

PTFE tubing for flexible endoscopes

In medical technology precision tubes are mainly used in the field of endoscopy e.g. in catheters to extract gallstones. It is possible to extrude PTFE tubing with several channels (Figure 39).

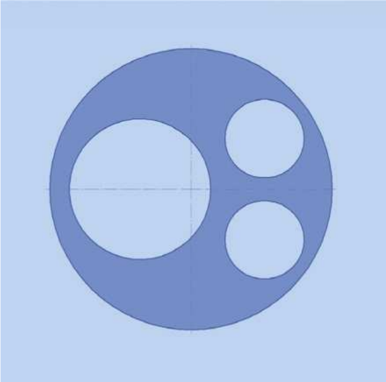

Figure 39: 3-lumen tubing

Such multi-lumen tubing can therefore take over more than one function. This means not only that processes can be more user-friendly but also that the assembly is easier as individual components can often be dispensed with.
Above all in bronchoscopes is tubing with tapering (Figure 40) used more and more as this enables even deeper penetration into damaged areas.

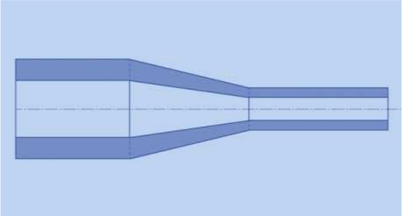

Figure 40: tubing with tapering

Very advanced constrictions of the respiratory tract can thus be passed through better and tumours or lymphomas can be treated specifically. Colored markings on the tubing help to be able to define corresponding working areas and /or positions (Figure 41). In addition this technology is often used to put markings or letterings on the tubing according to customer specifications. For X-ray applications, the PTFE matrix can be altered by mixing contrastable additives so that a color coding of the tubing is easily recognizable.

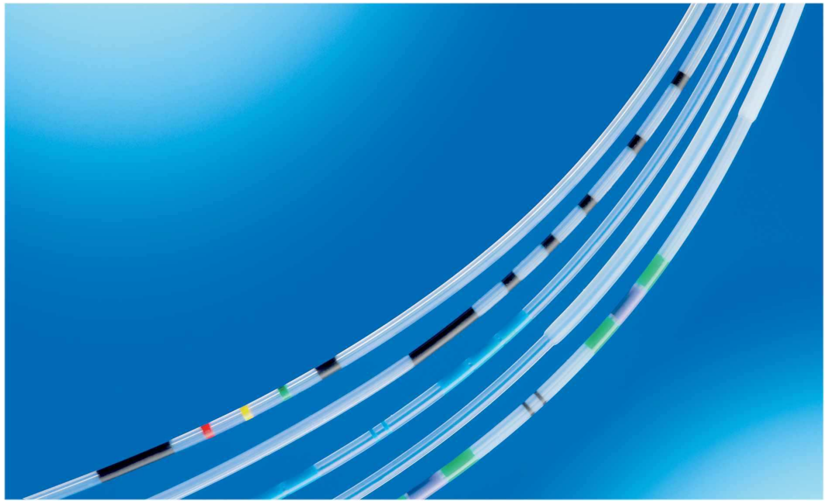

Figure 41: color-coded tubing with X-ray contrast capability

Above all in the medical sector the surface qualities of the tubing play an important role. High demands are made on the adhesive technology when connecting systems or metal or ceramic bushings have to be connected with the tubing. Such connecting systems often require a long-term durability regarding the adhesive strength. In order to create such a stable connection with PTFE, a modification of PTFE is required. The aim in this case is to increase the surface

energy so that surface wetting can take place. The processes used for this are wet etching or dry plasma etching. Further demands made on the tubing are:

- biocompatibility
- UV resistance
- high wear hardness
- able to be sterilized

PTFE tubing modules as venting units in liquid chromatographs

Liquid chromatographs are used in analytics in order to break down the liquid material mixture to be analyzed into its component parts. In this case the liquids to be analyzed have to be absolutely free from dissolved gases. This task is taken over by the venting unit.
In this example the venting of liquids takes place through a tubing module (Figure 42) which consists of a number of thin PTFE tubes through which the liquid to be analyzed is fed. PTFE plastic is permeable for gases. The tubing bundle has a large surface area for effective venting with a minimal wall thickness. The tubing bundle is in an evacuating chamber. Due to the difference in pressure, the dissolved gas particles escape from the liquid to be analyzed through the walls of the tubing into the chamber and are there extracted by the pump. The vented liquid to be analyzed is then further transported to the liquid chromatograph and analyzed.

Figure 42: tubing module for liquid chromatograph

The following demands are put on the PTFE tubing modules:

- chemical resistance to nearly all media such as, for example, acids, alkalis and solvents
- no water absorption allowed
- specific gas permeability of the tubing
- very smooth internal surfaces in order to avoid residue
- FDA approved materials suitable for the food and medical industries
- high-purity materials so that the measuring results are not adulterated.

Only PTFE meets these demands. In production, in each case several PTFE tubes are welded in a connector into a tubing bundle. Couplings at both ends allow the tubing module to be installed directly. Last but not least the extremely good chemical resistance of PTFE to nearly all solvents, acids and alkalis predestines this material for this special application. Venting modules for liquid chromatographs would not be possible without PTFE tubing modules.

PTFE sealing gaskets for respiratory air compressors

Small compressors used as respiratory air compressors in medical applications have to have a low weight, be maintenance free and long-lasting. A known application in respiratory air therapy is to produce compressed air in inhalers: the small, light compressors compress the air to the required pressure which then enables an effective vaporization of the materials.
In the respiratory air compressor illustrated in Figure 43 it is a radial piston compressor with a plastic cylinder. Such small compressors are constructed from only a few components and are nearly maintenance free. The produced air is pure, oil-free and neutral in taste.

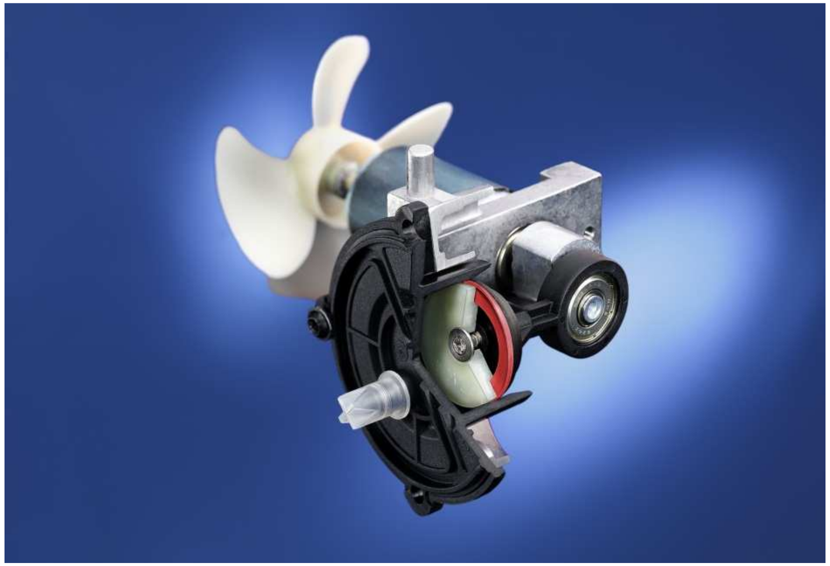

Figure 43: respiratory air compressor with mounted memory packing (colored red)

The following demands are made on the sealing element of the respiratory air compressor:

- low friction for low motor current draw since the machine is partly used in battery operation
- wear resistance for a long lifespan and low abrasion of the seal and the mating surface
- material with approval for medical applications.

The material used for the sealing element of the illustrated radial piston compressor is a PTFE compound whose components are non-toxic/harmless. The sealing element withstands temperatures from -

40^{0}C to +200^{0}C, pressure up to 5 bar and a sliding velocity of up to 3m/s.
The memory cup packing is a simple cost-effective construction. The radial piston can be sealed well with this construction. The sealing gasket adapts itself to the changing available space which is caused by the tumbling motion. The radial lip initial tension is achieved by only one thermal molding process without additional springs. It can be adapted to the application. The advantages of this seal such as low wear, low friction, no stick-slip effect and thus low start-up energy even after a longer standing period make it very suitable for applications in small compressors.

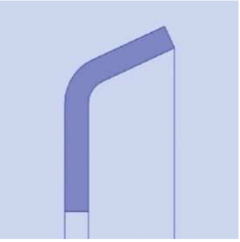

Figure 44: cross-section of memory cup packing

Reflectors and Diffusers for the optics Industry

Ulbricht integrating spheres are widely used in lighting technology and in spectroscopy. With internal diameters ranging from a few centimeters up to three meters, the preferred coating on the interior side used to be barium sulphate. The reflectors manufactured in this way have, however, a yellow discoloration over a period of time, tend to accumulate dirt particles and become sensitive to mechanical damage. This means that they have to be regularly recoated.

These disadvantages can be avoided if porous PTFE is used as the reflecting surface. As a result of its nearly perfect Lambertian behavior, porous PTFE is very well suited for coating the interior surfaces of Ulbricht integrating spheres. Lambertian behavior means the ability of a material to reflect projected light in the same intensity in any direction (Figure 45).

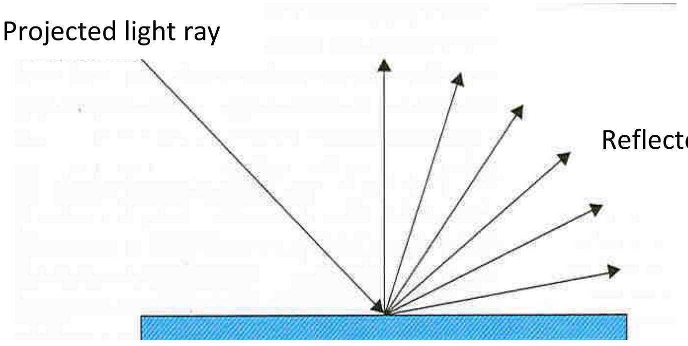

Figure 45: the design of reflectors

General properties of porous PTFE which are suitable for optical applications are:

- high reflectivity (reflecting degree of >99% in wavelength range of 400 to 1500nm, >95% in wavelength range of 250 to 2500nm)
- Lambertian behavior in wavelength range of ultra-violet and visible light as well as in close infrared
- hydrophobic
- thermally stable up to 300^{0}C

- nearly universal chemical resistance with only few exceptions needing consideration
- non combustible; LOI >95%
- flammability according to DIN4102, class A2
- no tendency to age, yellow discoloration or brittleness (long-term resistance also to ultra-violet rays)
- physical properties adjustable over a wide area (Figure 46)
- possibility to change the color by adding fillers

Figure 46: the design of reflectors based on porous PTFE can be adapted to the demands of the application

PTFE is extremely suitable as a diffuser for transmitted light in wavelengths ranging from ultra-violet over visible light to close infra-red. Typical applications for this are, for example, background lighting of instruments, screens and display equipment. In order to create a suitably high light intensity, the typical thicknesses of films for diffuser applications range between 100 µm and 1 mm. The transmission degrees under these conditions can be varied within a very broad range, for example, between 5 and 70%.

Rollers and rolls for high performance Printers

High performance printers have both fuser roller systems as well as feed roll systems. In the following application examples, the use of PTFE in fuser roller systems is described in more detail.
When fusing, the toner particles have to be melted and firmly fixed to the print material (e.g. paper or film). Fuser roller systems usually consist of the heated fuser roller and the pressure roller which provides the necessary counter pressure. The following demands are made on such a roller system:

- constant temperatures of 220^0C for melting the toner
- high wear resistance as paper as well as the other materials which are to be printed are very abrasive
- good thermal conductivity as the radiant heater is in the roller core
- excellent anti-adhesive behavior as no toner particles should stick to the roller

Rollers coated with a PTFE film have proved to be the optimal solution for these high demands (Figure 47). A PTFE film etched with a special high temperature resistant adhesive is applied to the aluminium base body with its excellent thermal conductivity. Finally the PTFE film is ground down to a thickness of 500 to 250 µm.

Figure 47: fuser rollers coated with high-performance PTFE

The choice of the PTFE compound as film material is always a compromise between abrasion resistance, thermal conductivity (Figure 48) and anti-adhesive properties. The correct coating allows high performance printers with an average of 1200 sheets per minute to print up to 10 million sheets without requiring any maintenance.

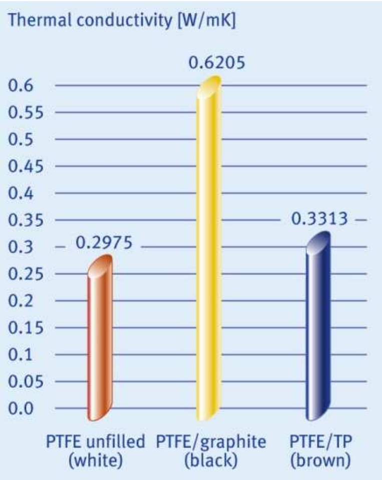

Figure 48: thermal conductivity of coatings for fuser rollers: TP thermoplastic (e.g. PPS, PEEK)

Large-sized Shaft Seals for Wind Power Plants

Large machines and plants usually place high demands. This also applies to sealing elements in wind power plants. The first problem is in manufacturing the large diameters. As PTFE is a molded, sintered material, the pressing tools have to be filled with PTFE powder by hand (Figure 49).

Figure 49: a tool to manufacture a ring-formed test piece is filled with PTFE powder

The maximum external diameter is 3000 mm. This necessitates large-sized sintering ovens in order to sinter the test pieces. The seals are then manufactured under tension on a special lathe (Figure 50). As PTFE has a large thermal expansion coefficient, the seals are measured at defined temperatures of 23 ^{0}C. Due to tensions in the material and temperature fluctuations, there is the danger that the diameter changes, i.e. usually shrinks. In order to guarantee stable measurements, for certain applications the rings are stored on a spike.

Figure 50: the finished test piece is processed on a lathe

The radial diameter of the rotary shaft seal for wind power plants as shown above is 1200 mm and the circumference speed reaches 1.6 m/s.
The seal has to retain the fat application during storage and prevent the fat from escaping. Further demands are:

- long lifespan
- low friction
- ozone resistant

Since it is extremely difficult to disassemble such rotary shaft seals, the seal is expected to run for many years. A spring energised seal as illustrated in Figure 51 has proved to be best for this application.

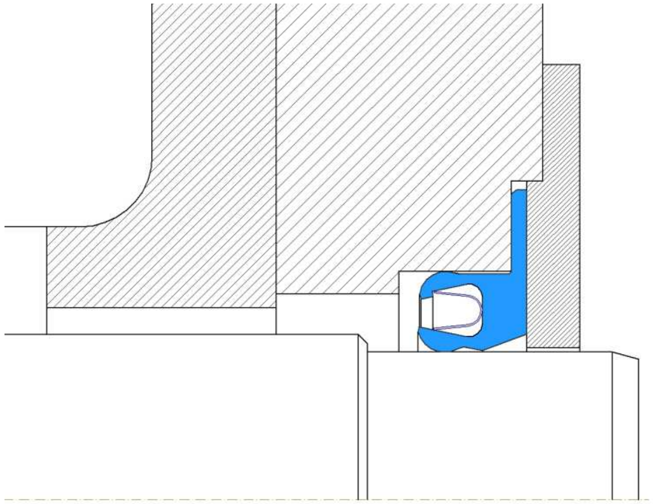

Figure 51: spring-energized seal as rotary shaft seal in wind power plants

Approvals and Guidelines

As well as the technical feasibility of system solutions, the legal approval of such systems is nowadays of increasing importance. This is especially true of applications which effect people and their safety.

Approvals for contact with foods

The basic legal requirements on materials or objects which come into contact with foods are laid down in EU countries by regulations from the European Commission and national laws. Due to the very advanced harmonization process within the EU, EU regulations are increasingly brought to bear on applications in the plastics sector. The FDA (US Food & Drug Administration) is the most important regulatory system for food applications in the world. Providers of components which come into contact with foods should take the requirements of the EU as well as the FDA into consideration, independent of the aspired sales market, and, moreover, observe the specific country specifications.
In Germany the legal stipulations for materials or objects that come into contact with foods are laid down in the regulation governing articles of daily use (LMBG). In addition, the plastics recommendations from the Federal Institute for Consumer Health Protection and Veterinary Medicine (BgVV), which was dissolved on 01.11.2002, also apply. The newly formed Federal Institute for Risk Assessment (BfR) has taken over responsibility for the areas food safety and consumer protection since that date.
Dangers to foods and drinking water especially emanate from the migration of plastics elements. The following can migrate from virgin PTFE:

- monomers (e.g. TFE, HFP, PPVE)
- oligomers with low molecular weight

As well as the above-mentioned monomers and oligomers, fillers such as, for example, glass fibres, graphite or E-carbons, can also migrate from virgin PTFE. The following do not usually migrate from virgin PTFE:

- additives (not usual in PTFE)
- antioxidants
- lubricants
- plasticizers
- stabilizers (flame-retardant additives, UV absorbers)

Due to its described properties and its special purity, PTFE is preferred for applications placing the highest demands on the purity and physiological harmlessness in contact with foods but is also chosen for applications in the pharmaceutical industry and when bio-compatibility is required.
Table 6 classifies important PTFE materials for use in contact with foods corresponding to its principle suitability according to the regulatory systems LMBG, EU and FDA. The overview is only intended as information. Concrete approval must be collected from the manufacturers of the raw materials in each individual case.

Table 6: PTFE and PTFE compounds for applications in the food industry

Product	LMBG	EU	FDA
S-PTFE (virginal)	yes	yes	yes
Modified PTFE (virginal)	yes	yes	yes
E-PTFE (virginal)	yes	yes	yes
Modified E-PTFE (virginal)	yes	yes	yes
PTFE-E carbon compound	yes	yes	no
PTFE graphite compound	yes	yes	no
PTFE carbon-graphite compound	no	no	no
PTFE glass fibre-compound	yes	yes	yes
PTFE glass fibre-graphite compound	yes	yes	no
PTFE electro-static dissipating	yes	yes	no
PTFE electro-static dissipating «FDA»	yes	yes	yes
PTFE bronze compound	no	no	no

Approvals for the automotive Industry

The background to the introduction of the International Material Data System (IMDS) is national and international environmental protection laws which stipulate that every manufacturer is responsible for the ecological effects of their product (incl. EU Regulation 2000/53/EG governing old vehicles, Life-Cycle Resource Management Law and Integrated Product Policy ISO 14040 ff). In order to meet this regulation, among other things, exact knowledge of the components in motor vehicles as well as the materials and substances used in them is required.
The Association of the Automotive Industry (VDA) therefore decided in 1996 to extend the initial sample inspection report according to the VDA handbook with the data sheet "constituents of purchased

parts (material data sheet)". The board of the VDA furthermore decided to create a system which allows material data sheets to be compiled and processed electronically.
The internet-based IMDS establishes a concept which allows the necessary data to be compiled electronically. The system makes use of the following lists:

- list of pure materials
- list of materials that must be declared
- Global Automotive Declarable Substance List (GADSL)

Further information on IMDS can be found in the internet.

Approvals for Contact with Oxygen

Substances, materials and components which are destined for use in systems which transport oxygen have to be suitable from a safety aspect and therefore have to undergo special tests. Many substances, which are not combustible in the atmosphere, burn in an atmosphere which has been enriched with oxygen. Not only lightly combustible oil and fat, rubber and plastic but also aluminium, steel and bronze can combust in an oxygen atmosphere. PTFE and PTFE compounds are often used as sealing materials due to their inert behavior in contact with oxygen for, among other things, sealing elements in fittings (valves and pressure controllers) and for pipes in flange connections and screw connections.
The Federal Institute for Material Research and Testing (BAM), one of the testing institutes recognized by the Employers' Liability Insurance Association, has developed testing processes and assessment principles for the safe operation of oxygen systems as

well as for non-metallic seals over the past five years. Components made of PTFE and PTFE compounds for specific applications in systems transporting oxygen are assessed according to the following criteria:

- ignition temperature in compressed oxygen
- resistant to ageing in compressed oxygen
- impact of oxygen pressure surges
- testing of flat gaskets for flange connections
- reactivity with liquid oxygen in the case of impact stress

Table 7 gives an incomplete overview of BAM tested sealing materials made of PTFE and PTFE compounds including the BAM test procedures used. The results are usually only good as an orientation. The above-mentioned tests should always be carried out on the finished components for a final assessment.

Table 7: PTFE and PTFE compounds for applications in contact with oxygen

Product	**Test procedure**					**BAM listing**
	a)	b)	c)	d)	e)	
S-PTFE (virginal)	yes	yes	yes	yes	no	yes
Modified PTFE (virginal)	yes	yes	yes	yes	no	yes
PTFE glass-fibre compound	yes	yes	yes	yes	yes	yes
PTFE glass-fibre graphite compound	yes	no	yes	no	no	yes
PTFE E carbon compound	yes	yes	yes	yes	no	yes
PTFE carbon-graphite compound	yes	yes	yes	yes	no	yes
PTFE electro-static dissipating	yes	yes	yes	yes	no	yes
PTFE graphite compound	yes	yes	yes	no	no	yes
PTFE bronze compound	yes	yes	yes	yes	no	yes
PTFE bronze carbon compound	yes	yes	yes	no	no	yes

Approvals for explosion endangered Areas

On 01 July 2003 the ATEX directive 94/9/EG came into effect as EN 13436 according to which non-electric appliances have also to receive approval for use in explosion endangered areas. This directive stipulates the explosion protection of non-electric systems, appliances and components in explosion endangered areas and thus the responsibilities for the manufacturer. It defines an *explosion endangered atmosphere* as a “mixture of air and combustible gases, vapor, mist or dust under atmospheric conditions where the combustible process is transferred to the whole unburned mixture after successful combustion”. The ATEX conformity certificate refers

to appliances and components. Corresponding certificates are not required for substances, however relevant substance characteristics are provided by the raw material producers in order to support ATEX applications.
As well as the time and effort for identification markings, conformity declarations, approval and certification of appliances to meet ATEX specifications, the choice of the suitable material is of top priority for manufacturers. An important criterion for selecting the material is that is has to avoid electrostatic discharges (ESD) between objects with different electric potentials. In the case of discharges, electric arches could cause an explosive atmosphere to ignite. One way to prevent this is to use materials with special physical properties, especially with specific electrostatic dissipation properties. The choice of a suitable material with the necessary properties is the responsibility of the appliance manufacturer and is in accordance with the corresponding categories of appliances.
The material properties relevant for ATEX applications as well as typical values for PTFE can be seen in table 8. High quality PTFE and PTFE compounds qualify for ATEX applications due to their excellent long-term temperature resistance, chemical resistance and stability against ultra-violet rays (light resistance). An LOI above 95 and its classification as Flame Class 94V-0 also qualify the products in the area of combustibility on a very high level.

Table 8: PTFE and PTFE compounds are suitable for ATEX applications

Property	Test Regulation	Unfilled PTFE
Composition		free of additives
Temperature resistance	IEC 216 or UL 746 B	RTI = 180^{0}C
Surface resistivity	EN 50014	$10^{17}\Omega$
Volume resistivity	IEC 60093	$10^{18}\Omega$
Dielectric strength	IEC 243	65 to 85 kV/mm
Combustibility	EN 50018, ISO 1210, IEC 707	94V-0
Chemical resistance		nearly universal, few restrictions
Light resistance		yes

High quality conductible PTFE compounds are available as they meet increased demands for creep resistance, surface resistivity and electric strength. The temperature resistance is also on a high level, around 180^{0}C (RTI after UL) or above. All those properties support the demands of law-makers that non-electric systems, appliances and components must not become ignition sources neither in a new condition nor during the whole lifetime.

TRENDS AND FUTURE PROSPECTS

The use of fluoropolymers is increasing overproportionally to global economic growth. If the reasons are analyzed, the following driving factors can be seen in individual market segments: in the *automotive sector* the constant demand for reduced emissions with increased engine performance leads to significantly higher demands on emission sensors, signal lines and signal processing. An

intelligent use of performance reducing units such as, for example, for cooling or air conditioning, is strived for. The increasing need for comfort and additional safety requirements necessitate electronic load levelling systems or equipping with multiple airbags. Most of this equipment is directly next to the engine, takes up signals from this hot area or is in contact with aggressive fuels or lubricants. Because the required lifespan has tripled in the last 25 years, only fluoropolymers or compounds based on these are increasingly used. In the *medical sector* there is a rapid mechanization and automation of diagnostics and therapy methods. PTFE is increasingly used everywhere where high tissue tolerability is required as well as universal media resistance. High power density in connection with increasing miniaturization in the *electronics sector* increasingly demand materials with better and better insulation and absorption. The low dielectric constants of PTFE enable always tighter packing densities of electronic components and low electric loss factors enable a significant increase in the signal frequency of computer and broadcasting performances. In *the construction of chemical installations* the demand for longer lifespans and the higher availability of installations lead to an increased use of fluoropolymers, not only as materials for seals but also increasingly for whole installations such as reactors or pipe systems made wholly of plastics. Last but not least fluoropolymers are therefore an economic alternative to stainless steel.
The introduction of meltprocessable PTFE effectively counteracts the current main disadvantages of the subsequent machining of PTFE: while in the case of complex geometries of components, up to 90% waste has often had to be accepted up to now, thanks to injection molding or extrusion manufacturing, the net yield from plastics can be increased to nearly 100%. Sprues or remains from injection molding can be recycled and made into the same or similar products. All of the mentioned advantages can be applied to compounds based on meltprocessed PTFE.

The increase in lifespan is most effective measure to protect resources. Good wear and sliding properties are best achieved by developing compounds based on PTFE, modified PTFE or meltprocessed PTFE. When modern compounds in addition preserve counter direction mating surfaces, then, for example, heavy steel can be exchanged for lighter aluminium - a plus factor which is especially cost-saving in automotive applications.

TECHNICAL TERMS AND ACRONYMS

amorph	structureless configuration of atoms and solid bodies
ATEX	Atmosphères Explosibles
BAM	Bundesanstalt für Materialforschung- und prűfung (Federal Institute for Material Research and Testing)
BfR	Bundesinstitute für Risikobewertung (Federal Institute of Risk Assessment). Successor to BgVV
BgVV	Bundesinstitute für gesundheitlichen Verbraucherschutz und Veterinärmedizin (Federal Institute for Consumer Health Protection and Veterinary Medicine)
CVT	Continuously Variable Transmission
dielectric	electrical insulating material in which an opposing field is built up against the external electrical field by electrical polarization
DIN	Deutsches Institut für Normen e.V. (German

	Institute for Norms and Standards)
DoE	Design of Experiments
E-carbon	electro-graphite carbon
EN	European Norm
ESD	Electronic Static Discharge
FDA	Food & Drug Administration
FEP	Fluorinated Ethylene Propylene
FEP-G	Fluorinated Ethylene Propylene, solvent-based polymerization process
Flame Class 94V-0	term used within UL 94
FTP	Fluorothermoplast
GADSL	Global Automotive Declarable Substance List
GFK	Glass Fibre reinforced Plastic
HDPE	High density Polyethylene
HFP	Hexafluoro- propylene
IEC	International Electrotechnical Commission
IMDS	International Material Data System
ISO	International Standard Organization
Cold flow	deformation (of PTFE) under load
CFK	Carbon Fibre reinforced Plastic
LCP	Liquid Chrystal Polymer
LMBG	Lebensmittel- und Bedarfsgegenstandgesezt (law governing foods and articles of daily use)
LOI	Limited Oxygen Index
MFA	Perfluoro methoxy modified PTFE
monomer	basic chemical molecule for polymerization
MVQ	silicone rubber
oligomer	polymer with low degree of polymerization n, e.g. n = 2...........12
PA	polyamide
PAEK	polyaryl ether ketone
PAI	polyamide-imide

PBT	polybutylene terphthalate
PC	polycarbonate
PEEK	polyetheretherketone
PEI	polyetherimide
PES	polyether sulphone
PET	polyethelene terephthalate
PFA	perfluoralkoxy modified PTFE
polymer	basic molecule for plastics manufactured by joining very many single monomers
POM	polyoxymethylene
PP	polypropylene
PPE	polyphenylene ether
PPS	polyphenylene sulphide
PPVE	perfluoproplyvinylether
PSU	polysulphone
PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride
RTI	Relative Temperature Index
SPI	Society of Plastics Industry
SUV	Sports Utility Vehicle
TFE	tetrafluoroethylene
VDA	Verband der Automobilindustrie (Association of the German Automotive Industry)
virginal PTFE	unprocessed PTFE powder
UL 94	safety norm of the Underwriters Laboratories Inc. (UL®) called “Tests for Flammability of Plastic Materials for Parts in Devices and Appliances”
UV	ultraviolet

Appendix Table

Physical properties	**Unit/ factor**	**Fully fluorinated plastic**					
		Stan-dard PTFE	**Modi-fied PTFE**	**melt proc. PTFE**	**PFA**	**MFA**	**FEP**
GENERAL							
Permanent service temperature	^0C	260	260	260	250	240	205
Specific density	g/cm^3	2.13-2.20	2.13-2.19	2.14-2.18	2.12-2.17	2.12-2.17	2.12-2.17
Combusti-bility (UL flame class)	-	V-O	V-O	V-O	V-O	V-O	V-O
Oxygen index	%	>95	>95	>95	>95	>95	>95
Water absorption	%	<0.01	<0.01	<0.01	<0.03	<0.03	<0.01
THERMAL							
Melting point	^0C	327	327	317-324	300-310	280-290	253-282
Thermal conductivity	W/(m-K)	0.22-0.23	0.22-0.23	0.22-0.23	0.22	0.22	0.2
Thermal expansion coefficient	10^{-5} K^{-1}	12-17	12-17	12-16	10-16	12-20	8-14
Spec.thermal capacity at 23^{0}C	10^3 J/(kg K)	1.01	1.01	1.03	1.09	1.09	1.17
MECHANICAL							
Tensile strength at 23^{0}C	MPa	29-39	29-39	23-32	27-32	22-36	19-25
Tensile elongation	%	200-500	300-600	150-450	300	300-360	250-350
Tensile E-modulus at 23^{0}C	MPa	400-800	650	400-630	650	440-550	350-700
Hardness (shore D)		55-72	59	55-65	60-65	59	55-60
Dyn, friction coefficient (steel,dry)		0.05-0.2	0.05-0.2	0.05-0.2	0.2-0.3	0.2-0.3	0.2-0.35
ELECTRICAL							
Spec. volume resistance	Ωcm	10^{18}	10^{18}	10^{18}	10^{18}	10^{18}	10^{18}
Dielectric constant at 10^6Hz	-	2.0-2.1	2.0-2.1	2.0-2.1	2.1	2.0	2.1
Dielectric loss factor at 10^6Hz	10^{-4}	0.7	0.7	0.7-1.1	<5		<9
Surface resistance	Ω	10^{17}	10^{17}	10^{17}	10^{17}	10^{17}	10^{16}
Dielectric strength	kV/mm	40-100	50-110	50-100	50-80	34-38	50-80