

Feature article

# Advanced functional polymer membranes

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Received 13 October 2005; received in revised form 24 January 2006; accepted 25 January 2006

Available online 28 February 2006

## Abstract

This feature article provides a comprehensive overview on the development of polymeric membranes having advanced or novel functions in the various membrane separation processes for liquid and gaseous mixtures (gas separation, reverse osmosis, pervaporation, nanofiltration, ultrafiltration, microfiltration) and in other important applications of membranes such as biomaterials, catalysis (including fuel cell systems) or lab-on-chip technologies. Important approaches toward this aim include novel processing technologies of polymers for membranes, the synthesis of novel polymers with well-defined structure as ‘designed’ membrane materials, advanced surface functionalizations of membranes, the use of templates for creating ‘tailored’ barrier or surface structures for membranes and the preparation of composite membranes for the synergistic combination of different functions by different (mainly polymeric) materials. Self-assembly of macromolecular structures is one important concept in all of the routes outlined above. These rather diverse approaches are systematically organized and explained by using many examples from the literature and with a particular emphasis on the research of the author’s group(s). The structures and functions of these advanced polymer membranes are evaluated with respect to improved or novel performance, and the potential implications of those developments for the future of membrane technology are discussed.

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*Keywords:* Functional polymer; Polymer membrane; Membrane technology

## 1. Introduction

A membrane is an interphase between two adjacent phases acting as a selective barrier, regulating the transport of substances between the two compartments. The main advantages of membrane technology as compared with other unit operations in (bio)chemical engineering are related to this unique separation principle, i.e. the transport selectivity of the membrane. Separations with membranes do not require additives, and they can be performed isothermally at low temperatures and—compared to other thermal separation processes—at low energy consumption. Also, upscaling and downscaling of membrane processes as well as their integration into other separation or reaction processes are easy.

*Abbreviations:* 4Vpy, 4-vinyl pyridine; AAm, acrylamide; AFM, atomic force microscopy; ATRP, atom transfer radical polymerization; *-b-*, ...block (copolymer); BP, benzophenone; BSA, bovine serum albumin; CA, cellulose acetate; CMR, catalytic membrane reactor; *-co-*, ... (linear) copolymer; CVD, chemical vapor deposition; D, dialysis; DNA, deoxyribonucleic acid; ED, electrodialysis; EIPS, evaporation induced phase separation; EMR, enzyme-membrane reactor; *-g-*, ...graft (copolymer); GMA, glycidyl methacrylate; GS, gas separation; HEMA, hydroxyethyl methacrylate; *i*, isotactic; LB, Langmuir–Blodgett; LBL, layer-by-layer; LCST, lower critical solution temperature; *M*, molar mass; MEA, membrane electrode assembly; MF, microfiltration; MIP, molecularly imprinted polymer; MPC, methacryloxyethylphosphorylcholin; NCA, *N*-carboxyanhydride; NF, nanofiltration; NIPAAm, *N*-isopropyl acrylamide; NIPS, non-solvent induced phase separation; PA, polyamide; PAA, polyacrylic acid; PAH, polyallylamine hydrochloride; PAN, polyacrylonitrile; PBI, polybenzimidazol; PC, polycarbonate; PDMS, poly(dimethylsiloxane); PEEKK, polyetheretherketone; PEG, polyethyleneglycol; PEGMA, polyethyleneglycol methacrylate; PEM, polymer electrolyte membrane; PEMFC, polymer electrolyte membrane fuel cells; PES, polyethersulfone; PET, polyethylene terephthalate; PFSA, perfluorosulfonic acid; PGMA, polyglycidyl methacrylate; PH, poly(1-hexene); PI, polyisopren; PL, polylactide; PP, polypropylene; PS, phase separation; PSf, polysulfone; PST, polystyrene; PU, polyurethane; PV, pervaporation; PVC, polyvinylchloride; PVDF, polyvinylidene fluoride; PVP, polyvinylpyrrolidone; RhB, rhodamin B; RO, reverse osmosis; *s*, syndiotactic; SAM, self-assembled monolayer; SAXS, small angle X-ray scattering; SEM, scanning electron microscopy; SPSf, sulfonated polysulfone; SRNF, solvent-resistant nanofiltration; TEM, transmission electron microscopy; TFC, thin-film composite; TIPS, thermally induced phase separation; UV, ultraviolet; VIPS, vapor induced phase separation; VP, vinylpyrrolidone.

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After a long period of inspiration by biological membranes and scepticism about the ultimate technical feasibility, membrane technologies have now been industrially established in impressively large scale [1]. The markets are rather diverse—from medicine to the chemical industry—and the most important industrial market segments are ‘medical devices’ and ‘water treatment’. The worldwide sales of synthetic membranes is estimated at over US \$2 billion (in 2003) [2]. Considering that membranes account for only about 40% of the total investment for a membrane separation system,<sup>1</sup> the total annual turnover for the membrane based industry can be considered more than US \$5 billion. The annual growth rate for most membrane products are more than 5%, in some segments up to 12–15%. For example, the market of the by far largest commercial membrane process, the ‘artificial kidney’ (hemodialysis), represents a turnover of US \$1 billion, and >230 Mio m<sup>2</sup> membrane area are produced annually for that application. At the same time, the extremely high quality standards at falling prices<sup>2</sup> are only possible by a very high degree of automatization of the manufacturing process, integrating continuous (hollow-fiber) membrane preparation, all post-treatment steps and the assembly of the membrane modules into one production line [3].

In industrially established applications, some of the state-of-the-art synthetic membranes have a better overall performance than their biological counterparts. The very high salt rejections and water fluxes through reverse osmosis membranes obtained using transmembrane pressures of up to 100 bar may serve as an example for the adaptation of the membrane concept to technical requirements. However, relatively few of the many possible separation principles and processes have been fully explored yet. Consequently, a strong motivation for improving established membrane materials and processes is driving the current research in the field (cf. 3). Today this can be done on a sound technical and economical basis for the development and technical implementation of novel membrane materials and processes.

The membrane process conditions must be engineered very carefully, but the performance limits are clearly determined by the membrane itself. This will be briefly explained by giving an overview on the main membrane processes and separation mechanisms (cf. 2.1). Even when ceramic, metal and liquid membranes are gaining more importance, the majority of membranes are and will be made from solid polymers. In general, this is due to the wide variability of barrier structures and properties, which can be designed by polymer materials. Current (1st generation) membrane polymers are biopolymers

(mainly cellulose derivatives) or (less than 20 major) synthetic engineering polymers, which had originally been developed for different purposes. The typical membrane structures and manufacturing technologies will be briefly summarized (cf. 2.2).

The development of synthetic membranes had always been inspired by the fact that the selective transport through biological membranes is enabled by highly specialized macromolecular and supramolecular assemblies based on and involved in molecular recognition. The focus of this feature article will be onto improved or novel functional polymer membranes (the ‘next generation’ of membrane materials), and important trends in this field include:

- the synthesis of novel polymers with well-defined structure as ‘tailored’ membrane materials
- advanced surface functionalizations, yielding novel barrier structures or enabling the combination of existing barrier structure with ‘tailored’ modes of interactions (from ‘affin’ to ‘inert’)
- the use of templates for creating tailored barrier or surface structures for membranes
- preparation of mixed matrix or composite membranes for the synergistic combination of different functions by different (polymeric) materials
- improved or novel processing of polymers for membranes, especially thin-layer technologies or the miniaturization of membrane manufacturing.

The main part of this article will be organized into two sub-chapters, the most comprehensive one will be concerned with syntheses and/or preparation methods and resulting membrane structures (cf. 4) and thereafter the functions and/or performance of the improved or novel membranes will be discussed organized according to the different membrane processes (cf. 5). An attempt had been made to cover most important trends (at least by mentioning them in the respective context). However, due to the wide diversity of the field, selections had to be made which also reflect the particular interests of the author.

## 2. Membrane technology—state-of-the-art

### 2.1. Membrane processes and separation mechanisms

Passive transport through membranes occurs as consequence of a driving force, i.e. a difference in chemical potential by a gradient across the membrane in, e.g. concentration or pressure, or by an electrical field [4]. The barrier structure of membranes can be classified according to their porous character (Table 1). Active development is also concerned with the combination of nonporous or porous membranes with additional separation mechanisms, and the most important ones are electrochemical potentials and affinity interactions.

For non-porous membranes, the interactions between permeand and membrane material dominate transport rate and selectivity; the transport mechanism can be described by the solution/diffusion model [5,6]. The separation selectivity between two compounds can be determined by the solution

<sup>1</sup> Because membrane processes are typical examples for enabling technologies, it will become more and more complicated to ‘separate’ the membrane units from large and complex technical systems where the membrane still plays the key role. The best example for a field with a very large degree of integration along the value chain is the hemodialysis segment of the medical industry, where membrane companies form the high-technology core of a business which also owns complete hospitals for the treatment of patients suffering from kidney failure and related diseases.

<sup>2</sup> The current market price of one high-end dialysis module, for example with up to 15,000 hollow-fibers yielding up to 2.2 m<sup>2</sup> membrane area, is 7–10 US\$.

Table 1  
Classification of membranes and membrane processes for separations via passive transport

Membrane barrier structure	Trans-membrane gradient		
	Concentration	Pressure	Electrical field
Non-porous	Pervaporation (PV)	Gas separation (GS) Reverse Osmosis (RO)	Electrodialysis (ED)
Microporous pore diameter $d_p \leq 2$ nm	Dialysis (D)	Nanofiltration (NF)	Electrodialysis
Mesoporous pore diameter $d_p = 2$ –50 nm	Dialysis	Ultrafiltration (UF)	
Macroporous pore diameter $d_p = 50$ –500 nm		Microfiltration (MF)	

selectivity or by the diffusion selectivity. However, even for systems without changes of the membrane by the contact with the permeand—as it is the case for permanent gases with dense glassy polymers—a dual-mode transport model is the most appropriate description of fluxes and selectivities [7]. This model takes into account that two different regions in a polymer, the free volume and more densely packed domains, will contribute differently to the overall barrier properties. For a rigid polymer, especially in the glassy state, the contribution of free volume can become dominating. Moreover, with most other real mixtures—in particular for separations in liquid state—a strong coupling of transport rates for different components can occur. This is mainly due to an increase of (non-selective) diffusibility in the membrane due to swelling (plastification) of the membrane by the more soluble component. With non-porous membranes, a high transport-selectivity can be obtained for a limited number of molecule pairs or mixtures. An alternative approach towards molecule-selective non-porous membranes is the use of special (coupled) transport mechanisms, e.g. facilitated transport by affine carriers [8].

For porous membranes, transport rate and selectivity are mainly influenced by viscous flow and sieving or size exclusion [9]. Nevertheless, interactions of solutes with the membrane (pore) surface may significantly alter the membrane performance. Examples include the GS using micro- and mesoporous membranes due to surface and Knudsen diffusion, and the rejection of charged substances in aqueous mixtures by microporous NF membranes due to their Donnan potential. Furthermore, with meso- and macroporous membranes, selective adsorption can be used for an alternative separation mechanism, (affinity) membrane adsorbers are the most important example [10]. In theory, porous barriers could be used for very precise continuous permselective separations based on subtle differences in size, shape and/or functional groups.

In addition, ion-exchange membranes represent an important group of technical materials, and the best example for a well established application is the production of chlor and soda, where perfluorinated cation-exchange membranes have almost completely replaced older set-ups. Electrodialysis has—besides RO—also relevance for water desalination.

It is essential to mention that both membrane permeability and selectivity can be completely controlled by concentration polarization (due to the enhancement of the concentration of rejected species on the membrane surface as function of transmembrane flow) or membrane fouling (due to unwanted adsorption or deposition of matter on/in the separation layer of the membrane). These phenomena can significantly reduce the

performance, which would be expected based on intrinsic membrane properties. A high product purity and yield (by selectivity) and a high throughput (by permeability), i.e. the optimum membrane separation's performance, can only be achieved by process conditions adapted to the separation problem and the membrane material. Therefore, before it can come to real applications, optimizations of the membrane module configuration and design as well as of the process conditions will be most important [1].

One should note that in one of the technically most successful membrane processes, dialysis ('artificial kidney'), the transmembrane flux and hence the concentration polarization are relatively low. Consequently, also the fouling is much less pronounced than in other membrane processes for separation in liquid phase. The desired overall performance (high flux, i.e. throughput) is achieved by a very large membrane area (in hollow fiber modules [3]).

In conclusion, several completely different modes of separation can all be done very efficiently using membranes:

- removal of a small amount of substance(s) from a large feed stream yielding a large amount of purified product, by:
  - retention of the small fraction by the membrane, e.g. desalination of water by RO;
  - selective permeation of the small fraction through the membrane, e.g. solvent dehydration or azeotrope separation by PV;
- concentrating a small amount of a product by selective permeation of the solvent through the membrane, e.g. concentrating or/and desalting of valuable proteins by UF;
- separation of two or more components, present in low to moderate amounts in a solution, by their selective permeation through or retention by the membrane, e.g. fractionation of biomolecules by UF, NF, D or ED.

Membrane separation technologies commercially established in large scale are:

- D for blood detoxification and plasma separation ('medical devices');
- RO for the production of ultrapure water, including potable water ('water treatment');
- MF for particle removal, including sterile filtration (various industries);
- UF for many concentration, fractionation or purification processes (various industries including 'water treatment');
- GS for air separation or natural gas purification.

A more detailed overview on industrial separations using the main membrane technologies (cf. Table 1) can be found, for example, in Refs. [1,11,12] (cf. also 5). Important other membrane applications with significant activities in the development of improved or novel polymers are materials for controlled release or advanced package materials. While these special areas are not covered here, the development of membranes for fuel cells or as battery separators will be discussed in some more detail (cf. 4.2.1, 5.1.5).

## 2.2. Polymer membrane preparation and structures

Considering the large diversity of membranes suited for technical applications [12], it will be useful to introduce the following main classifications:

- *Membrane materials.* Organic polymers, inorganic materials (oxides, ceramics, metals), mixed matrix or composite materials.<sup>3</sup>
- *Membrane cross-section.* Isotropic (symmetric), integrally anisotropic (asymmetric), bi- or multilayer, thin-layer or mixed matrix composite.
- *Preparation method.* Phase separation (phase inversion) of polymers, sol–gel process, interface reaction, stretching, extrusion, track-etching, micro-fabrication.
- *Membrane shape.* Flat-sheet, hollow fiber, hollow capsule.

Membranes for pressure-driven molecule-selective filtrations (UF, NF, RO, GS) have an anisotropic cross-section structure—integral or composite—with a thin ( $\sim 50$  nm to a few micrometres) mesoporous, microporous or nonporous selective layer on top of a macroporous support (100–300  $\mu\text{m}$  thick) providing sufficient mechanical stability. By this means, the resistance of the barrier layer is minimized, thus ensuring a high membrane permeability.

Macroporous membranes with an isotropic cross-section (100–300  $\mu\text{m}$  thick) are typical materials for MF, but become also increasingly relevant as base materials for composite membranes, e.g. for membrane adsorbers. For niche applications, track-etched polymer membranes (8–35  $\mu\text{m}$  thick) with well-defined cylindrical pores of even size (between  $\sim 20$  nm and a few micrometres) are also available (cf. 4.1).

By far the most of the technically used membranes (including support membranes for composite GS, RO, NF and PV membranes) are made from organic polymers and via phase separation (PS) methods. Technically most relevant are four variants for processing a film of a polymer solution into a porous membrane with either isotropic or anisotropic cross-section:

- precipitation in a non-solvent (typically water)—non-solvent induced, NIPS;
- solvent evaporation—evaporation induced, EIPS;
- precipitation by absorption of non-solvent (water) from the vapor phase—vapour induced, VIPS;
- precipitation by cooling—thermally induced, TIPS.

For membrane technologies in general, the development of the first high-flux anisotropic RO membranes (via NIPS from cellulose acetate) by Loeb and Sourirajan [13] was one of the most critical breakthroughs. Today, extensive knowledge exists on how to ‘finetune’ the membrane’s pore structure including its cross-section morphology by the selection of polymer solvents and non-solvents, additives, residence times and other parameters during NIPS [4,14–21]. The key for high performance is the very thin ‘skin’ layer which enables a high permeability. This skin layer is non-porous for GS, RO, PV and NF membranes. All membranes with a mesoporous skin, prepared by the NIPS process and developed for D, UF and NF, have a pore size distribution in their barrier layer—which typically is rather broad—so that the selectivity for size-based separations is limited (Fig. 1).

Commercial MF membranes with a rather isotropic cross-section morphology are prepared via the TIPS process (most important for polyolefins as membrane materials [22,23]) and via the EIPS or, in some cases, the VIPS process [24]. Recently, more and more sophisticated variants, including combinations of various PS mechanisms have been developed in order to control the pore size distribution even more precisely. An example is a novel polyethersulfone MF membrane with a much higher filtration capacity, and that had been achieved by a modification in the NIPS manufacturing process leading a very pronounced anisotropic cross-section morphology with an internal separation layer ensuring that the rejection specifications are identical to the previously established materials (Fig. 2) [25].

Various composite membranes prepared by interface polymerization reactions or coating processes—mainly on asymmetric support membranes—had been established for RO, GS, PV, NF [26,27] and also recently for low-fouling UF. Pioneering work for the interface polycondensation or polyaddition towards ultra-thin polymer barriers on support UF membranes, a technique which is now technically implemented in large scale in several different variations, had been performed by Cadotte et al. [28,29]. The first protocol had been based on the reaction between a polyamine in water, filling the pores of the support membrane, with an aromatic diacid chloride in hexane. Alternatively, aromatic diisocyanates were also used. Similar chemistries had later been proposed for the surface modification of UF membranes [30,31] (cf. 4.3.4).

An overview of the state-of-the-art polymeric materials, used for the manufacturing of commercial membranes, is given in Table 2. A closer inspection reveals that most of the membranes currently on the market are based on relatively few polymers which had originally been developed for other engineering applications.

<sup>3</sup> A definition may be introduced here: while composite membranes are prepared by starting with a membrane (or filter) defining the shape of the final membrane (cf. 4.5), during preparation of mixed matrix membranes the two matrices can also be formed or synthesized simultaneously. Hybrid materials of organic polymers and inorganic fillers or networks are beyond the scope of this article.

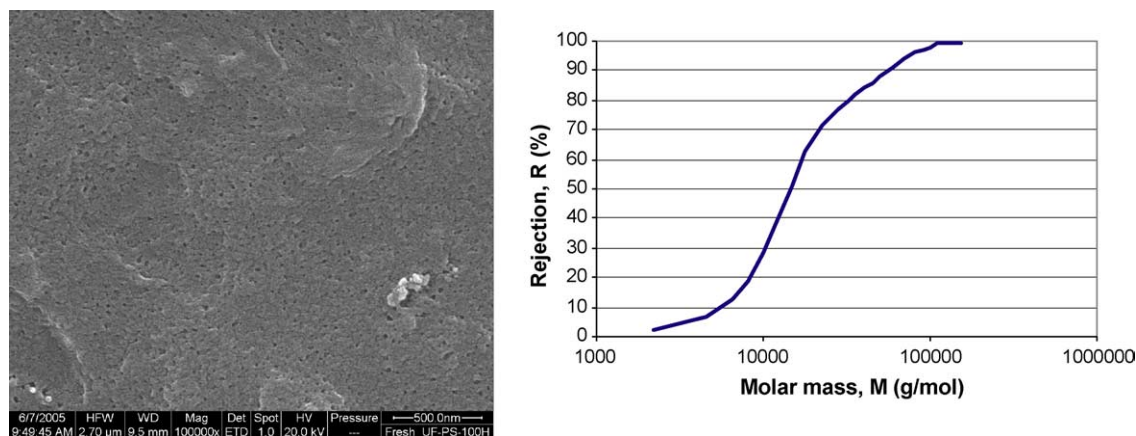


Fig. 1. Scanning electron microscopy (SEM) image of the outer surface ('skin' layer) of a commercial UF membrane made from polysulfone with a nominal molar mass cut-off of 100 kg/mol and separation curve analysis after UF of a dextran mixture with a broad molar mass distribution—both data reveal the broad pore size distribution of typical UF membranes prepared by state-of-the-art casting/immersion precipitation phase separation (NIPS) (data measured at Universität Duisburg-Essen, 2005).

### 3. Motivation and guidelines for development of advanced or novel functional membranes

In the last two decades, membrane technology had been established in the market, in particular for tasks where no technically and/or economically feasible alternatives exist. The successful implementation had been due to the unique separation principle based on using a membrane (cf. 1 and 2.1). By far the most processes in liquid separation are dealing with aqueous solutions, mostly at ambient or relatively low temperatures.

Technically mature membrane separations with a large growth potential in the next few years include especially UF and NF or D (with large membrane area modules) for concentration, fractionation and purification in the food, pharma and other industries [1]. Here, the selectivity of separation is still often limited, especially due to an uneven

pore size distribution of the membranes (cf. Fig. 1). GS with membranes is also industrially established for selected applications, some in large scale. Nevertheless, many more processes could be realized if membranes with high selectivities, competitive flux and sufficient long-term stability would be available. Emerging applications based on partially 'mature' membranes and processes which still need to demonstrate full commercial viability are PV and ED [1]. Here, main limitations are due to insufficient membrane selectivity and/or stability. In addition, membranes suited for all kinds of applications in organic media, including higher temperatures, are still rare. Progress in all these latter areas will open the doors into large scale membrane applications in the chemical industry [11].

Furthermore, the presumably largest potential for membrane technology is in process intensification, e.g. via implementation of reaction/separation hybrid processes

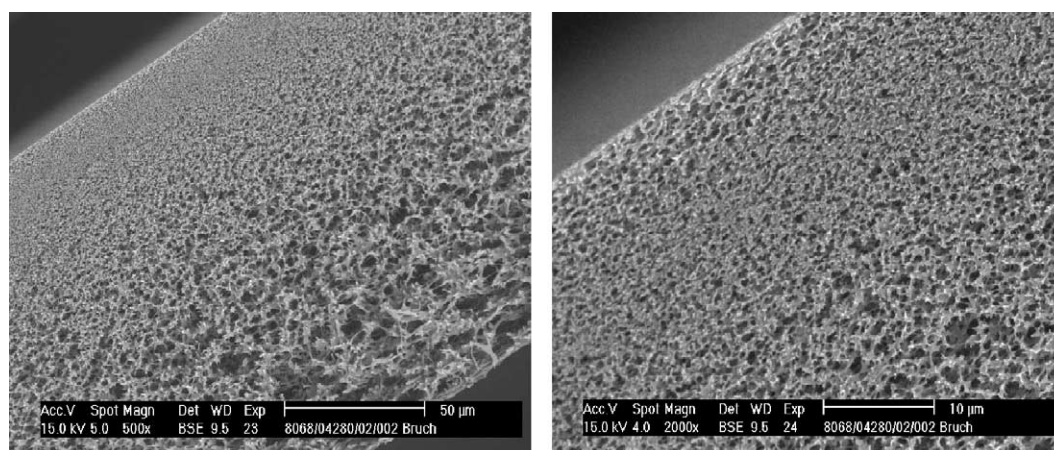


Fig. 2. SEM cross section images of a DuraPES<sup>®</sup> MF membrane (cut-off pore diameter 0.2 μm; Membrana GmbH Wuppertal): left, overview; right, detail—these membranes have a strongly anisotropic pore structure providing an 'internal protected separation' layer with the smallest transmembrane pores about 10 μm remote from the outer surface (cf. right) and a layer of up to 100 μm thickness with a very pronounced macropore volume which can be used as a depth filter with a high capacity at only small effects onto permeability (cf. left).

Table 2  
Polymers as materials for industrially established separation membranes

Polymer	Morphology			Membrane process
	Barrier type	Cross-section	Barrier thickness ( $\mu\text{m}$ )	
Cellulose acetates	Nonporous	Anisotropic	$\sim 0.1$	GS, RO
	Mesoporous	Anisotropic	$\sim 0.1$	UF
	Macroporous	Isotropic	50–300	MF
Cellulose nitrate	Macroporous	Isotropic	100–500	MF
Cellulose, regenerated	Mesoporous	Anisotropic	$\sim 0.1$	UF, D
Perfluorosulfonic acid polymer	Nonporous	Isotropic	50–500	ED, fuel cell
Polyacrylonitrile	Mesoporous	Anisotropic	$\sim 0.1$	UF
Polyetherimides	Mesoporous	Anisotropic	$\sim 0.1$	UF
Polyethersulfones	Mesoporous	Anisotropic	$\sim 0.1$	UF
	Macroporous	Isotropic	50–300	MF
	Macroporous	Isotropic track-etched	6–35	MF
Polyethylene terephthalate	Macroporous	Isotropic track-etched	6–35	MF
Polyphenylene oxide	Nonporous	Anisotropic	$\sim 0.1$	GS
Poly(styrene- <i>co</i> -divinylbenzene), sulfonated or aminated	Nonporous	Isotropic	100–500	ED
Polytetrafluoroethylene	Macroporous	Isotropic	50–500	MF
	Nonporous		$\sim 0.1$	GS
Polyamide, aliphatic	Macroporous	Isotropic	100–500	MF
Polyamide, aromatic	Mesoporous	Anisotropic	$\sim 0.1$	UF
Polyamide, aromatic, in situ synthesized	Nonporous	Anisotropic/composite	$\sim 0.05$	RO, NF
Polycarbonates, aromatic	Nonporous	Anisotropic	$\sim 0.1$	GS
	Macroporous	Isotropic track-etched	6–35	MF
Polyether, aliphatic crosslinked, in situ synthesized	Nonporous	Anisotropic/composite	$\sim 0.05$	RO, NF
Polyethylene	Macroporous	Isotropic	50–500	MF
Polyimides	Nonporous	Anisotropic	$\sim 0.1$	GS, NF
Polypropylene	Macroporous	Isotropic	50–500	MF
Polysiloxanes	Nonporous	Anisotropic/composite	$\sim 0.1 < 1-10$	GS PV, NF (organophilic)
Polysulfones	Nonporous	Anisotropic	$\sim 0.1$	GS
	Mesoporous	Anisotropic	$\sim 0.1$	UF
Polyvinyl alcohol, crosslinked	Nonporous	Anisotropic/composite	$< 1-10$	PV (hydrophilic)
Polyvinylidene fluoride	Mesoporous	Anisotropic	$\sim 0.1$	UF
	Macroporous	Isotropic	50–300	MF

(membrane reactors; cf. 5.6<sup>4</sup>). Therefore, membrane processes will largely contribute to the development of sustainable technologies [32]. Finally, using specialized support and/or separation membranes in cell and tissue culture will pave the road towards biohybrid and artificial organs for medical and other applications [33]. Here, ‘biomimetic’ synthetic membranes will be integrated into living systems, supporting and facilitating biological processes in order to directly serve human needs.

Many scientifically interesting, technically challenging and commercially attractive separation problems cannot be solved with membranes according to the state-of-the-art. Novel membranes with a high selectivity, e.g. for isomers, enantiomers or special biomolecules are required. Consequently, particular attention should be paid to truly molecule-selective separations, i.e. advanced membranes for NF and UF. Especially the development of NF membranes for separations in organic solvents will require a much better understanding of the underlying transport mechanisms and, hence, the requirements to the polymeric materials. In addition, a membrane selectivity which can be switched by an external stimulus or which can adapt to the environment/process conditions is an important vision. Such advanced or novel selective membranes, first developed for separations, would immediately find applications also in other fields such as analytics, screening, membrane reactors or bio-artificial membrane systems.

Specialized (tailor-made) membranes should not only have a significantly improved selectivity but also a high flux along with a sufficient stability of membrane performance. Of similar relevance is a minimized fouling tendency, i.e. the reduction or prevention of undesired interactions with the membrane. Furthermore, it should be possible to envision membrane manufacturing using or adapting existing technologies or using novel technologies at a competitive cost. The following general strategies will lead to a higher separation’s performance:

- non-porous membranes—composed of a selective transport and a stable matrix phase at an optimal volume ratio along with a minimal tortuosity of the transport pathways, thus combining high selectivity and permeability with high stability;
- porous membranes—with narrow pore size distribution, high porosity and minimal tortuosity (ideally: straight aligned pores through the barrier);
- additional functionalities for selective interactions (based on charge, molecular recognition or catalysis) combined with non-porous or porous membrane barriers;
- membrane surfaces (external, internal or both) which are ‘inert’ towards uncontrolled adsorption and adhesion processes.

In addition, minimizing the thickness of the membrane barrier layer will be essential. For certain completely novel membrane processes, e.g. in micro-fluidic systems, it should be

possible to fulfill special processing requirements. This can be envisioned considering the large flexibility with respect to the processing of polymeric materials. All these above outlined requirements can efficiently be addressed by various approaches within the field of nanotechnology.

#### 4. Synthesis or preparation routes towards functional polymer membranes

The various routes to functional polymer membranes are ordered in five categories. Advanced polymer processing, i.e. the preparation of membrane barrier structures using technologies beyond the state-of-the-art for membranes (cf. 2.2), is based on established polymers, and the innovations come from plastic (micro-)engineering (4.1). The synthesis of novel polymers, especially those with controlled architecture, and subsequent membrane formation is very promising. Some of the limitations due to the relatively low number of established membrane polymers (cf. Table 2) could be overcome because a wide variation of barrier structures and hence membrane functions will be also possible with the novel polymers (4.2). The surface functionalization of preformed (established) membranes has already become a key technology in membrane manufacturing; the major aim is to improve the performance of the existing material by either reducing unwanted interactions or by introducing sites for additional (tailored) interactions (4.3). The in situ synthesis of polymers as membranes barriers had already been established for selected commercial membranes (cf. 2.2), but the potential of this approach for tailoring the barrier chemistry and morphology as well as its shape simultaneously is definitely much larger (4.4). Composite membranes can be prepared using or adapting novel polymers (cf. 4.2), surface functionalizations (cf. 4.3) or/and in situ syntheses (4.4)—the ultimate aim is to achieve a synergy between the function of the base membrane and the added polymeric component (4.5). Ultimately, several of the above mentioned innovations could also be integrated into advanced processing (cf. 4.1) towards membranes with even more complex functions.

##### 4.1. Advanced polymer processing

In the context of microsystem engineering—largely driven by technologies originally developed for the semiconductor industries—a wide variety of methods had been established to create micro- or even nanostructures in or from established engineering polymers [34]. With respect to membranes, the ‘top-down’ fabrication of pores in barriers made from plastics may be considered a rather straightforward approach. Especially, attractive would be the possibility to control the density, size, size distribution, shape and vertical alignment of membrane pores, because this is not possible with all the other established membrane formation technologies (cf. 2.2).

Two different types of commercial membranes close to such an ‘ideal’ structure are already available, track-etched polymer and anodically oxidized alumina membranes. Even when the

<sup>4</sup> Note that fuel-cell systems will also fall into this category (cf. 5.1.5).

latter materials are clearly of inorganic nature, they should be briefly covered because such membranes belong to the state-of-the-art which could be improved by innovative polymeric materials and because such membranes can also be used as supports or ‘templates’ for the preparation of novel membranes with a selectivity determined by polymeric materials.

Track-etched polymer membranes are prepared from polycarbonate (PC; e.g. Nuclepore™) or polyethylene terephthalate (PET; e.g. RoTrac®) films with a thickness between 6 and 35  $\mu\text{m}$  [35,36] (cf. Table 2). The process involves two main steps: (i) the irradiation with accelerated heavy ions, and (ii) a controlled chemical etching of the degraded regions (nuclear tracks). The resulting membranes have a rather low porosity (up to 15%) or pore density (e.g.  $6 \times 10^8 \text{ cm}^{-2}$  for 50 nm and  $2 \times 10^7 \text{ cm}^{-2}$  for 1  $\mu\text{m}$  [35]), in order to reduce the probability of defects, i.e. double or triple pores. Under those conditions, the pore size distribution can be very sharp. Such membranes are commercially available with pore sizes from about 10 nm to several micrometres. There is some evidence that the pore geometry for the smaller pore size track-etched membranes may deviate from an ideal cylindrical shape what can be explained by the chemistry behind the manufacturing process [37]. In research labs, these manufacturing technologies have been further modified in order to obtain more specialized membrane structures, e.g. cone shaped track-etched polymer membranes [38]. Nevertheless, these membranes have their principal limitations because the preparation of pores with diameters in the lower nanometre range is not possible. The established ‘isoporous’ membranes have become favorite support materials for the investigation of novel (polymeric) barrier membranes as well as for exploring completely novel separation principles based on functional polymers (cf. 4.3, 4.4, 4.5).

Anodically oxidized alumina membranes have a much higher porosity (up to 50%) than track-etched materials. Barrier layer pore sizes can range between about 10 nm to a few 100 nm. Commercial membranes (e.g. Anopore™ [39]) have an anisotropic pore structure with a thin layer of smaller pore size on top of a thick macroporous support (pore size  $\sim 200$  nm) from the same material. Upscaling of the preparation (membrane area) is complicated, and the membranes are very expensive. Nevertheless, these membrane are also frequently used as support materials for novel polymeric separation layers or systems (cf. 4.2.5, 4.3.4, 4.5.1).

*Microfabricated membranes.* One important innovation in membrane manufacturing derived from microfabrication had to some extent already been commercialized. The very regular pore structure of so called ‘membrane sieves’ can be achieved via photolithography [40,41]. These membranes, typically from silicon nitride, are very thin (1–5  $\mu\text{m}$ ), have a very high porosity and the pore size can be adjusted from several micrometres down to a few 100 nm. In fact, those particle-selective filters with their extremely high permeabilities—orders of magnitude larger than track-etched or other MF membranes with the same cut-off pore size—impose completely new problems for membrane module and process design. Interestingly, irrespective the very regular pore

geometry, protein fouling via pore blocking can still be a major problem, so that surface modification of microsieve membranes with tailored functional polymer layers may be essential for certain applications [42].

Via ion beam aperture array lithography, microfiltration membranes with a similar pore structure (but still a lower pore density, up to  $4 \times 10^8 \text{ cm}^{-2}$ ) had been prepared for the first time from polymers [43]. Different from track-etched membranes, the highly uniform pores (diameters 350 or 200 nm) were equally spaced and without any overlap. Due to the lower thickness (only 600 nm), the permeabilities were much higher than those of equally rated track-etched membranes.

A very interesting replica technique towards ‘purely polymeric’ membranes had been introduced recently, the so called ‘phase separation micro moulding’ (PS $\mu$ M) [44,45]. Typical membrane polymer (e.g. polysulfone) solutions have been casted into microfabricated moulds (for a porous film), phase separated, and—due to some shrinking—relaxed without major defects from the mould. Again, a very high porosity could be combined with low thickness (a few 10  $\mu\text{m}$ ), and currently the smallest pore sizes (a few 100 nm) are determined by the photolithographic technologies for mould manufacturing. Until now, specific data about membrane properties are rather limited, but when this technology could be further improved, those membranes could become very attractive plastic counterparts of the expensive inorganic microsieves (cf. above). Another example for such micromolded membrane with a very regular array of pores having a diameter of 1  $\mu\text{m}$  had been demonstrated to show a very precise fractionation of microparticles [46].

A last illustration of the enormous potential of nanofabrication is a membrane system, prepared using high-end lithographic technologies, also involving polymeric components (as photo resists and components of the barrier structure)—ultimately pores with a diameter of a few nanometres have been prepared and their potential, e.g. for immunoisolation had been experimentally investigated [47,48]. Due to the complexity of the manufacturing processes and the resulting materials, the focus of further research and development will be on similar structures and functions achieved from less complicated processing of polymers (cf. 4.2.5).

## 4.2. Tailored polymer synthesis for subsequent membrane preparation

Important innovations are based either on particular intrinsic (bulk) properties of the polymers as a homogenous barrier phase, or on the formation of special morphologies—by phase separation or pore formation—in the barrier phase. In both cases, special surface properties could be also obtained. In this subchapter only examples will be covered where a special synthesis prior membrane formation (either conventional or unconventional) had been performed.



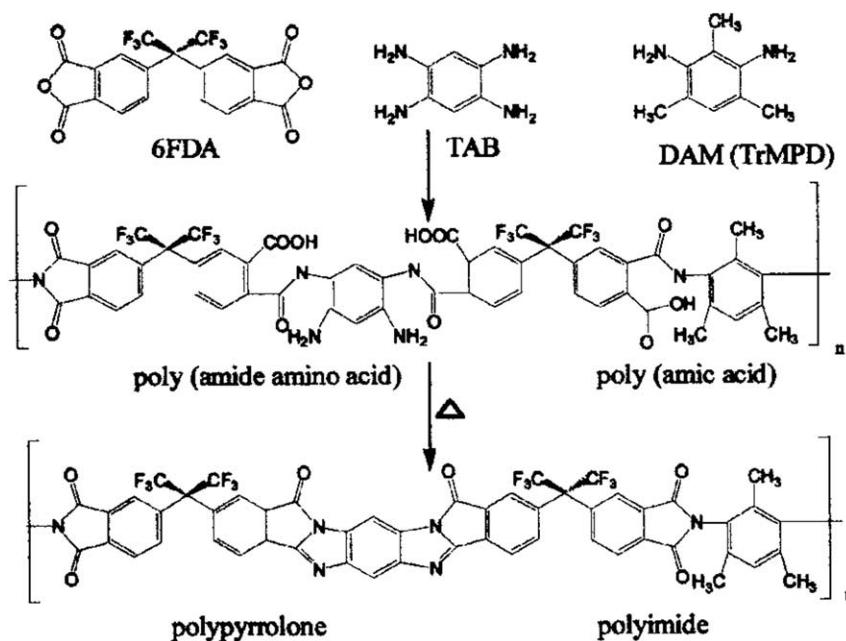


Fig. 3. Poly(pyrrolone-imide)s—ultrigid membrane polymers with a high gas selectivity (reprinted with permission from [55], Copyright (2003) American Chemical Society).

#### 4.2.1. Focus on barrier properties

*Polymer as non- or microporous barrier.* When a membrane is brought in contact with a gas or gaseous mixture, the interactions with the permeand are typically small. The much larger effects of plastification, e.g. with carbon dioxide, had also been studied largely [49,50]. In the last decade, very intense research efforts have been made to prepare polymer membranes for gas separations which show a performance beyond the trade-off curve between permeability and selectivity, also known as Robeson's upper bound [51,52]. This upper bound reflects the transport mechanism; polymers with high sorption have typically also a large segmental mobility leading to a high permeability but a low selectivity, and vice versa. Other reasons for a reduced performance include the limited temperature-stability and plastification at high permeand concentrations. Therefore, polymers with a high free volume at minimal segmental mobility under a broad range of conditions would be very attractive materials.

Modification of established polymers, e.g. polysulfones, is still an important approach, the comprehensive work of Guiver et al. is an excellent example [53]. Among the most promising novel polymer materials are poly(pyrrolone-imide)s which have an ultra-rigid backbone structure (Fig. 3) [54,55]. Those polymers are called 'polymeric molecular sieves' because they exhibit entropic selectivity capabilities, similar to carbon molecular sieves or zeolites.<sup>5</sup> In addition to the rigidity, it is necessary to attempt to alternate 'open' regions and 'bottleneck' selective regions, and this had been achieved by fine-tuning the polymer matrix

through the use of suited building blocks and optimized stoichiometry. In particular, the inter-macromolecular packing of the extended condensed ring segments and the free volume created by the aliphatic chain segments can serve as explanations for the achieved high performance beyond the 'upper bound' [55]. A schematic comparison of these polymers with conventional polymers and carbon molecular sieves is shown in Fig. 4. Consequently, the transport through those polymers can be described with similar models as used for microporous materials. Instead of the pore size distribution of a material with a permanent porosity, the distributions in the free volume—created by different inter-macromolecular packing—may be used to explain differences in selectivity for polymers with varied structure [27,55].

Following the same guideline, novel polymers with 'intrinsic microporosity' (PIMs) have recently been synthesized and characterized by McKeown et al. [57–60]. Their highly rigid, but contorted molecular structure (Fig. 5) leads to a very inefficient space-filling. The polymers which are soluble in many common organic solvents form rather robust solids—including flat-sheet membranes—with very high specific surface areas (600–900 m<sup>2</sup>/g) [59]. First examples for their use as membrane materials indicating a promising combination of high selectivities and fluxes in organo-selective PV have been reported recently [60].

Further alternatives include polymers with a 'tailored' crosslinking architecture, including macromolecules which can undergo intermolecular crosslinking reactions after membrane formation [61,62]. Moreover, the development of mixed matrix membranes, e.g. with molecular sieves in a polymer to achieve a true synergy between the two materials, has become a special field in membrane research that will not be covered here (for an overview cf. [63,64]).

<sup>5</sup> Note, that alternative attempts to prepare high performance gas separation membranes similar to carbon molecular sieves have been done via carbonization through controlled pyrolysis of suited precursor polymers [56].

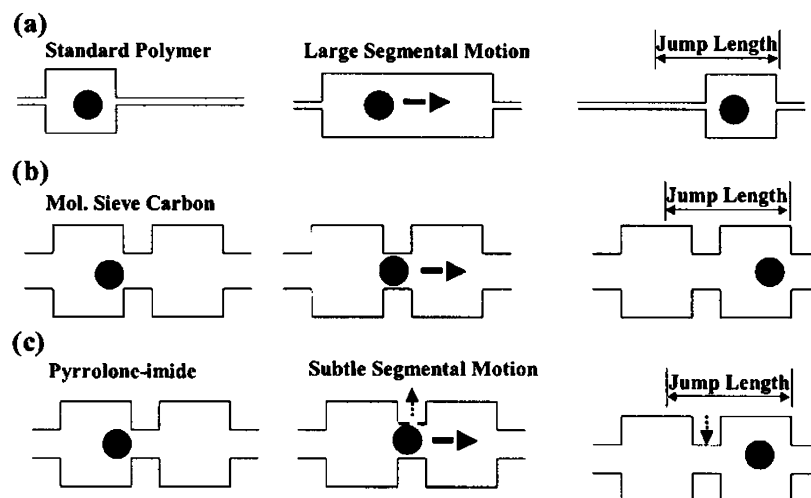


Fig. 4. Idealized transport mechanism through ultrarigid polymers in comparison with molecular sieving carbon materials and conventional polymers (reprinted with permission from [55], Copyright (2003) American Chemical Society).

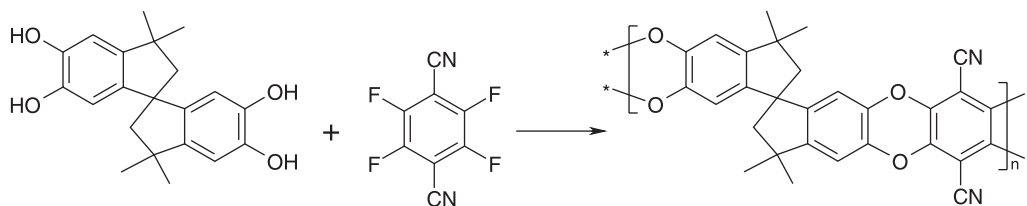


Fig. 5. Synthesis of a polymer with intrinsic microporosity (PIMs) [60].

It should also be mentioned that the molecular modeling of intrinsic transport properties had been quite successful for polymers used for gas separation, especially for systems with weak (negligible) interactions between polymer and permeand [65].

*Polymer as plasticized or swollen barrier.* During PV, NF (or RO), the membrane is in contact with a liquid phase, and, consequently, interactions with the membrane material are much stronger than for GS. Effective materials and applications had been established for aqueous systems, and the main attention had now been focused on materials for separation in organic media, including selectivity for small molecules [66,67]. Here, a tradeoff between a high affinity (sorption; as a basis for high permeability) and simultaneous deterioration of the barrier selectivity (due to excessive swelling) occurs. Mechanical stability of the membrane polymer is another, related problem. Straightforward strategies are to explore ‘high-performance’ engineering polymers as membrane materials, to develop crosslinked polymers or to prepare polymer composite membranes.<sup>6</sup>

Several main groups of solvent-stable polymers have been investigated in more detail: polyimides, polysiloxanes,

polyphosphazenes, (meth)acrylate-based polymers and some special crosslinked polymers. High-performance solvent-resistant nanofiltration (SRNF) membranes with an anisotropic cross-section, which are already applied in technical processes (cf. 5.1.2) have been prepared from commercial polyimides via the NIPS process (Fig. 6) [68–71]. Solvent-stable silicone rubber composite membranes had been obtained by crosslinking with polyisocyanates, polyacid chlorides or silanes [72]. Peterson et al. had explored a large variation of polyphosphazenes as membrane materials with especially high thermal and chemical stability [73]. The first commercial solvent-stable polymer membranes had been based on thermally crosslinked polyacrylonitrile, but the detailed chemistry had not been fully disclosed [74]. Alternatives for special solvents can also be based on phase-separated polymers (polymer blends or block copolymers) or on polymers stabilized by embedded nanoparticles acting as crosslinker [75].

Polyurethanes (PU) are a class of polymers with a very wide variability in structures and properties what could be useful also for membrane separations [76–79]. Nevertheless, PU had not yet been established as a major membrane polymer. The synthesis of chemically crosslinked PU using commercial precursors has been studied with respect to variations in the crosslinking density, and conditions have been identified where the swelling in different organic solvents could be adjusted in a range which should be suitable for NF [80]. Based on the knowledge about conversion rate and gelation point, it was possible to cast prepolymerized solutions and to allow

<sup>6</sup> Examples for the last strategy will be also discussed later, because the processing can have a major influence onto composite membrane structure and performance (cf. 4.5). Note that in order to prepare thin-film composite membranes for organic solvent processes, the (ultrafiltration) support membranes must be also stable.

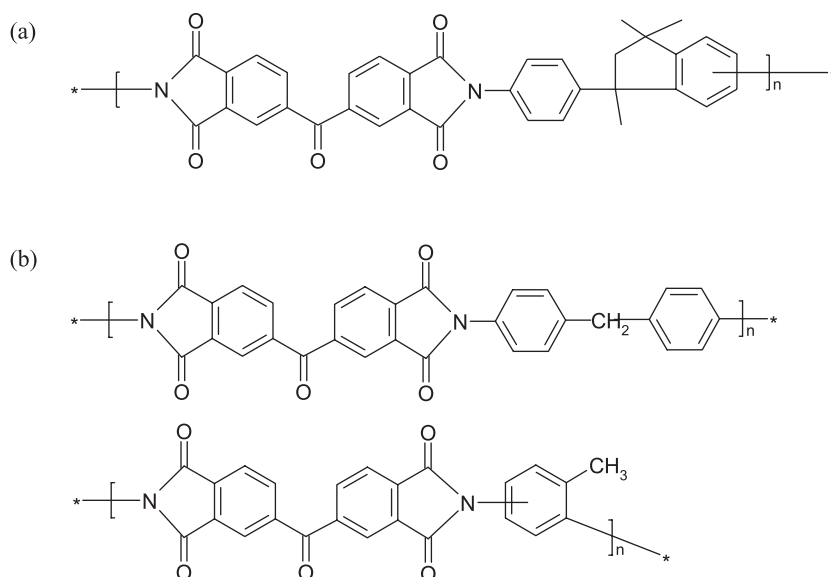


Fig. 6. Commercial polyimides as materials for solvent-stable NF and UF membranes (a) Matrimid 5218, (b) Lenzing P 84 (cf. [70]).

the completion of the crosslinking polyaddition and simultaneous solidification in the film. Thus novel thin-film composite membranes for SRNF with PU layer thickness of 2–3  $\mu\text{m}$  have been prepared. Quite high fluxes at rejections of up to 80% for a dye with a  $M \sim 350$  g/mol had been measured for various organic solvents, and the fluxes correlated very well with the equilibrium volume swelling for thick films from the same synthesis method and conditions [80].

*Polymer with a stable mesoporous barrier morphology in presence of organic solvents.* Most of the solvent-stable polymers mentioned above (cf. Fig. 6) can also be processed into porous (UF) membranes, by changing the conditions for the phase separation process. Current UF membranes for filtration of mixtures in organic solvents are mainly based on polyimides [81,82].

Approaches for post-crosslinking reactions of UF membranes had also been proposed, but this can be rather complicated because the fine pore structure formed in the processing step (NIPS) should be preserved. One of the most promising strategies for such a post-formation stabilization of UF membranes, with a pore structure ‘tailored’ by NIPS, had been proposed recently [83,84]. A copolymer of polyacrylonitrile (PAN) with a relatively small content of glycidyl methacrylate (GMA) had been synthesized so that the membrane formation was still controlled by the properties of the PAN, which is a most versatile membrane polymer (cf. Table 2). Via the reaction with ammonia as bi- or three-functional crosslinking agent, the pore structure could be stabilized in a three-dimensional network, because the reaction could be performed in aqueous solution (thus the pore morphology of the membrane was not changed by an organic solvent), and the very small size of the reactant ensured a high conversion also in the bulk of the solid polymer (cf. Fig. 7). The resulting crosslinked membranes had the same cross-section pore structure (SEM) and only a somewhat reduced water

permeability. However, the chemical stability was so much increased that these membranes could be even used for UF separations of strongly acidic and alkaline aqueous solutions as well as with most organic solvents. For example, it was possible to fractionate polystyrene dissolved in DMF (the solvent what had been used for the membrane casting step before the post-crosslinking!) [83]. The properties of the crosslinked PAN-*co*-PGMA membranes can be adapted to the requirements of various UF or NF processes where both high separation performance (selectivity and flux) and stability of the membrane are critical.

*Polymers as macroporous barrier.* One example shall illustrate that improving the structural control of established polymers may also provide new opportunities for membrane development. ‘Tailor-made polypropylenes’—syndiotactic PP (sPP) [85] and copolymers of PP with 1-hexene (PP-*co*-PH) [86], with isotactic PP (iPP) of same molecular weight for comparison—had been synthesized via metallocene catalysis, and the formation of porous membranes via the TIPS process had been investigated in detail. Pronounced differences in pore morphology as well as bulk and surface properties had been found which could be related to the changes of the phase diagrams of PP and solvent, and the phase separation kinetics as well as reduced crystallinity of sPP and PP-*co*-PH: the sPP and PP-*co*-PH membranes were much more ductile than iPP membranes with similar pore structure.

*Polymers as ion-conductor* are currently most interesting as materials for fuel cell applications (polymer electrolyte membrane fuel cells, PEMFC) [87,88]. The direct methanol fuel cell is one of the preferred technical systems—here, the aim is a maximum proton conductivity and selectivity at minimized methanol permeability. State-of-the-art materials for such PEMFCs are perfluoro sulfonic acid (PFSA) polymers, with Nafion<sup>®</sup> as the ‘standard’ material (cf. Table 2). Key problems with the existing membranes are related to their

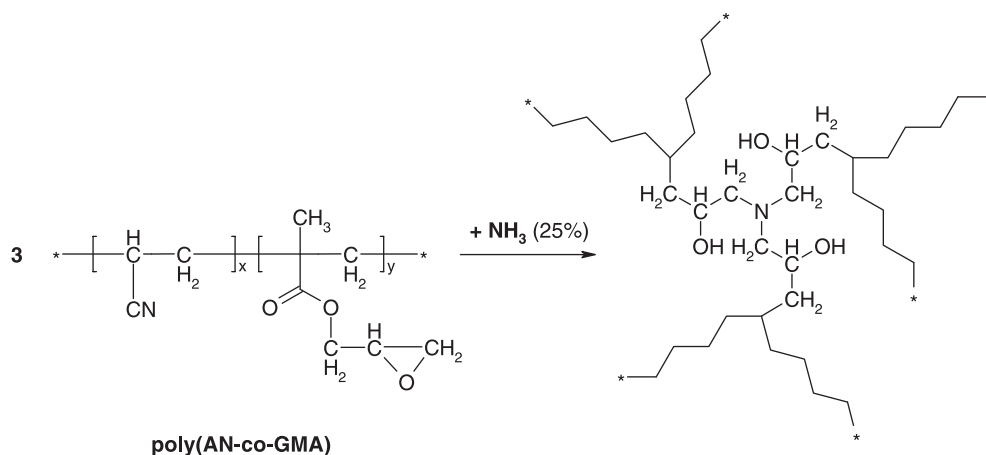


Fig. 7. Schematic depiction of the crosslinking reaction of poly(acrylonitrile-*co*-glycidylmethacrylate) after membrane formation, yielding highly solvent-stable UF membranes (a GMA content in the copolymers of 7 mol% will be sufficient for achieving the required stability; cf. [83]).

limited stability against temperature (beyond 80 °C) and the consequences for the barrier properties which have impact onto the overall performance. The current development of improved or novel materials can be classified as follows [87]:

- modified PFSA polymers (some materials with minor structural variations are commercial and known as Flemion, Dow or Aciplex; Fig. 8);
- alternative sulfonated polymers and their composite membranes;
- acid–base complex membranes (may include polymers from either of the above groups as components).

The structure of the PFSA polymers had been investigated in very much detail in the last decades (cf., e.g. [89], and references therein), and the special properties of these polymers are due to a nanoscale phase separation into (Fig. 9 [90]):

- a hydrophobic subphase, including the perfluorinated polymer backbone and side chains, except the sulfonic acid groups;
- a hydrophilic subphase, containing to sulfonic acid groups, mobile counter ions, and water.

The slight modification of the established Nafion structure by omitting all CF<sub>3</sub> group in the side chains (cf. Fig. 8) lead to a stable high performance at temperatures up to 120 °C. Those membranes form the basis of the advanced PEMs commercialized by 3 M [91].

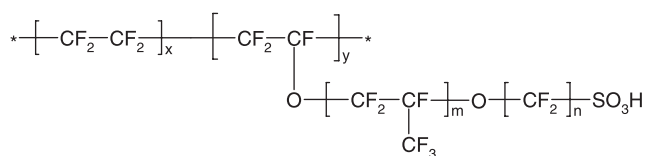


Fig. 8. Structure of commercial perfluoro sulfonic acid (PFSA) polymers—Nafion (DuPont):  $m=1$ ;  $n=2$ ;  $x=5-13.5$ ;  $y=1$ ; Flemion (Asahi Glass):  $m=0,1$ ;  $n=1-5$ ;  $x=5-13.5$ ;  $y=1$ ; Aciplex (Asahi Chemicals):  $m=0$ ;  $n=2-5$ ;  $x=1.5-15$ ;  $y=1$ ; Dow (Dow Chemical):  $m=0$ ;  $n=2$ ;  $x=3.6-10$ ,  $y=1$  (cf. [87]).

Stable ‘alternative’ backbone polymers which had been functionalized via sulfonation include polysiloxanes, various polyphenylenes, polyphenylene sulfide, polyphenylene oxide, polyphenylene sulfone, polyetheretherketone, polysulfones, polyphenylquinazoline derivatives, and poly(2,2′-*m*-(phenylene)-5,5′-biphenylimidazole) (PBI, Fig. 10 [87]). Other examples of ‘tailored’ copolymers had been also reported [92–96].

For these sulfonated polymers, a similar micro-phase separated morphology than for PFSA polymers had been discussed (cf. Fig. 9). Differences in terms of barrier performance could be related to slight differences with respect to contents and connectivity of the hydrophilic domains. In particular the hydrophilic domains may be tailored by the addition of various electrolytes yielding acid base complex membranes. One of today’s most advanced PEM material is based on sulfonated PBI and phosphoric acid, and the working range had been extended to 200 °C without sacrificing the membrane performance when compared with Nafion at lower temperature [97].

Further routes towards modified PFSA based membranes include surface modifications, mainly in order to reduce the methanol permeability (cf. 4.3.3), the preparation of ‘re-enforced’ (e.g. ‘pore-filled’) composite membranes, in order to improve the barrier stability (cf. 4.5.2), and the preparation of mixed matrix membranes, especially hybrid materials of organic polymers with inorganic fillers<sup>7</sup> (cf. 2.2 and 4.5).

Beyond these developments which currently attract most attention, there are also other applications of ion conducting polymer membranes, which in fact have a quite large market (today still larger than for PEMFC). Most important are membranes as battery separators [98]. For advanced systems such as lithium batteries, the functions of such barrier polymers should be co-ordinating and conducting cations in combination with a high-dimensional and electrochemical stability. Poly(ethylene glycol)s have been proven to be very promising, and many different copolymer and polymer blend

<sup>7</sup> Those hybrid materials are beyond the scope of this article.

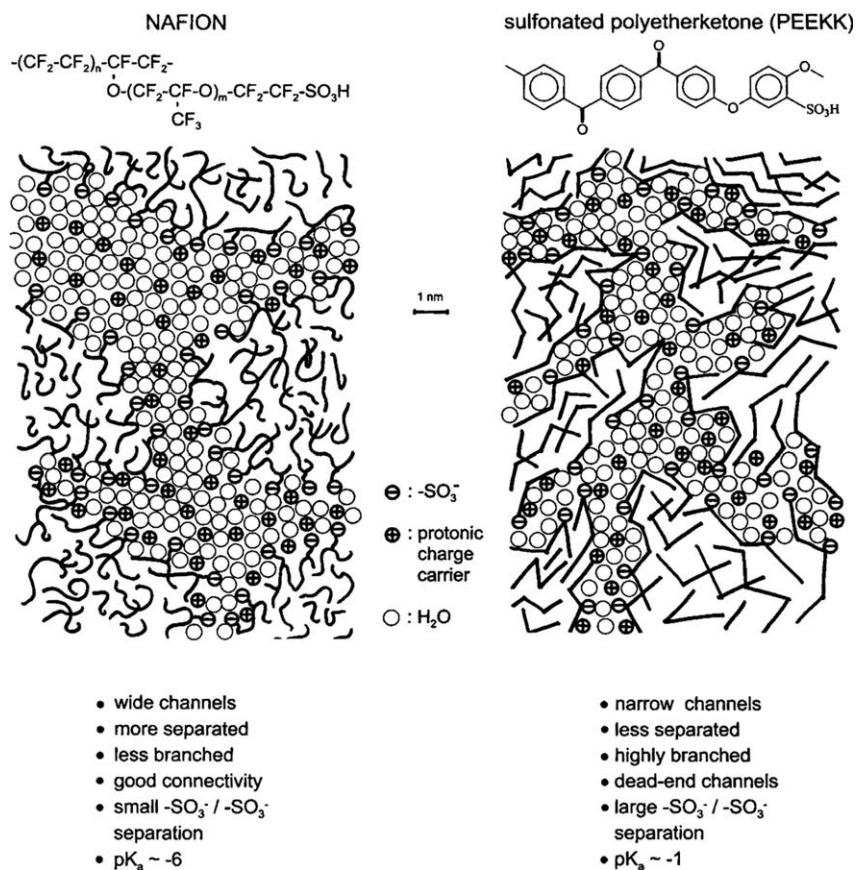


Fig. 9. Schematic illustration of the microstructures of Nafion and a sulfonated ‘alternative’ polymer (sulfonated PEEKK; reprinted with permission from [90], copyright (2001) Elsevier).

compositions and architectures had been investigated in order to optimize the materials for that purpose (cf., e.g. [99]).

#### 4.2.2. Focus on surface properties

In order to achieve special surface properties by using a ‘tailored’ macromolecular structure, two approaches may be chosen:

- (i) preparing the membrane from one special functional polymer;
- (ii) using such functional polymer as component of a blend or as an additive during membrane formation.

The first alternative will inevitably also lead to (often completely) different bulk properties of the membranes. Among the many different attempts, the work of Kang et al. [100–103] featuring functional graft copolymers of PVDF or fluorinated polyimides, or the research of Xu et al. [104] exploring acrylonitrile-based copolymers containing phospholipid moieties may serve as examples.

Regarding the second alternative, blends from an established ‘matrix polymer’—for a tailored and stable pore structure—and a ‘functional polymer’—for special (tailored) surface properties—would be very attractive from the membrane preparation point of view. If a macromolecular additive would show a pronounced surface segregation along with sufficient surface coverage, it should be possible to change

the surface characteristics with only minor influence onto bulk (including pore) morphology and properties.

The addition of hydrophilic polymers such as polyvinylpyrrolidone (PVP) has become a standard method; commercial UF and MF membranes from so called ‘hydrophilized’ polysulfone (PSf) or polyethersulfone (PES) are mostly produced using this approach. The PVP addition had originally also a function in order to tune the pore structure formed in the NIPS process [17,105]. In addition, a fixation of the PVP in the membrane matrix can occur statistically, with a slight preference for the interface because PVP is better soluble in the aqueous precipitation bath than PSf or PES. This resulting interphase structure had found to be heterogenous [106]. Furthermore, the modification is not permanent, at least a fraction of the PVP will be washed out during the use. In clinical applications of those membranes, e.g. in hemodialysis, this release of PVP may be a critical problem [107].

Tailored functional macromolecules may offer an attractive alternative. Surface active amphiphilic block or comb copolymers—with blocks from, e.g. polyethylenglycol (PEG) or a fluorinated polymer—had been added during membrane formation [108–111]. Mixing of the compatible blocks with the matrix polymer lead to an efficient anchoring, while the surface segregation of the functional blocks lead to a modified membrane surface. Such membranes were hydrophilic [108], or they had a low surface energy [109,111]. Matsuura et al. had explored various different syntheses, e.g. based on

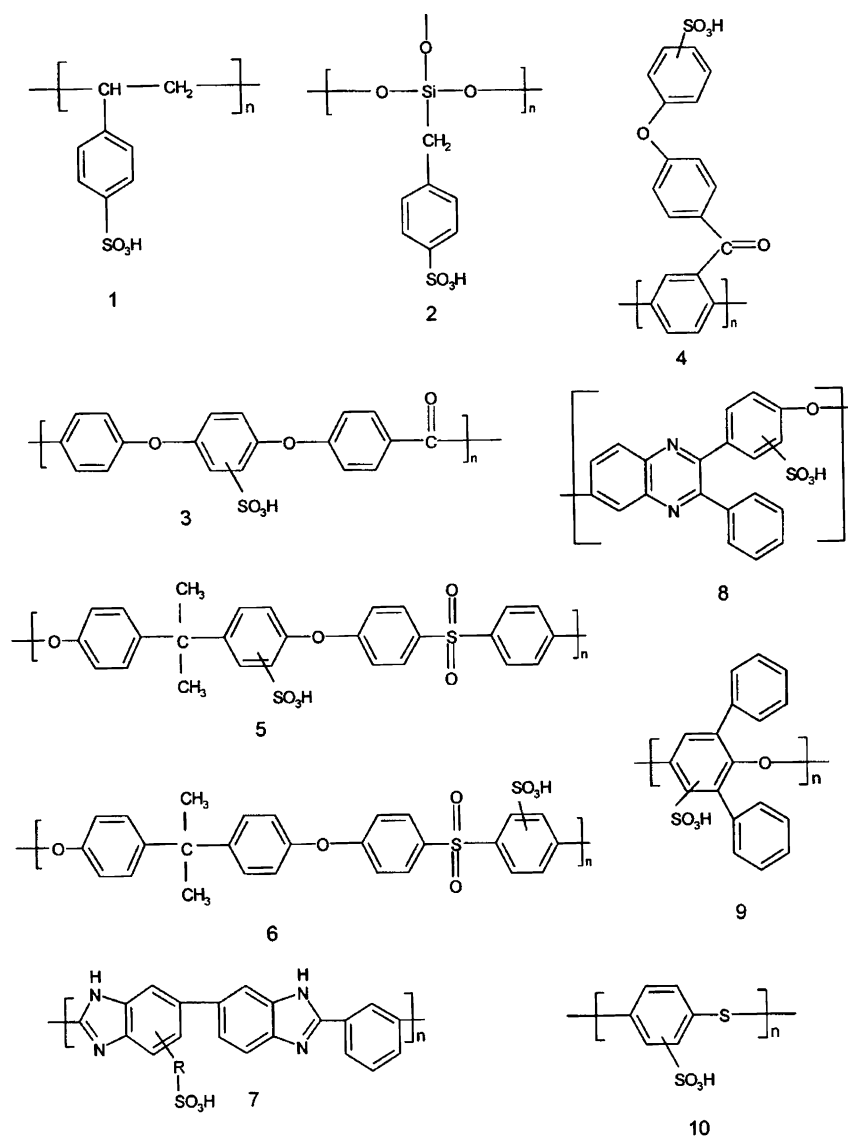


Fig. 10. Overview on sulfonated polymers as membrane materials for proton-conducting membranes (reprinted with permission from [87], Copyright (2003) American Chemical Society).

polyurethane chemistry, yielding different ‘surface modifying macromolecules’ to significantly improve membrane performance in various UF or MF processes [108–110]. A significantly improved performance in PV separations had also been obtained [111]. Also copolymers with special side groups such as phosphorylcholine had been used as surface-modifying additives in formation of membranes for UF or D [112,113].

Hester et al. had prepared very interesting block copolymers, via controlled (ATRP) graft copolymerization of PEG methacrylates onto the membrane polymer PVDF (Fig. 11 [114]). Such polymers had not only been rather promising additives for a surface modification [115], but they could also be used as bulk material for advanced NF membranes (cf. 4.2.5).

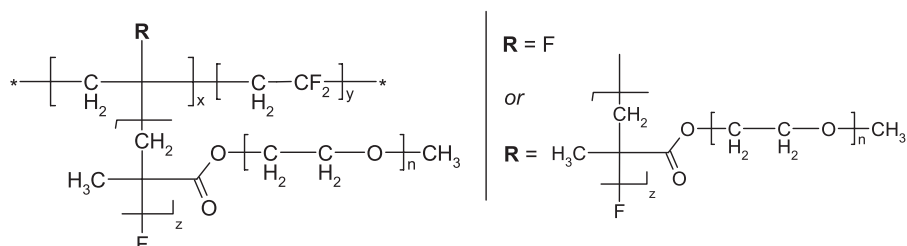


Fig. 11. Graft copolymer (PVDF-g-PEGMA) synthesized via ATRP using commercial PVDF as macroinitiator; the molar mass of the PEG in the macromonomer was  $\sim 400$  g/mol ( $n \sim 8.5$ ) (cf. [114]).

The integration of the surface modification via tailored macromolecular additives into the continuous technical manufacturing of membranes has the advantage, that no additional process step would be necessary. A high surface activity would also result in low additional material cost. However, due to the interplay between barrier and surface properties of a membrane, such a membrane ‘modification’ may in reality be equivalent to the development of a novel membrane, i.e. a modified base membrane with a functional surface [100–105,116,117].

#### 4.2.3. Polymer membranes for chiral separations

The discrimination of enantiomers is a particular challenge in separation technology, and using a membrane is most promising because—different from conventional crystallization or chromatographic methods—such separations could be performed continuously. As with all other membrane processes, the overall performance and practical feasibility will depend on both (enantio)selectivity and permeability. Two different types of membranes have been explored for this purpose:

- (i) liquid membranes containing selective carriers;
- (ii) solid polymer membranes.

A typical configuration for type (i) is the immobilization of the liquid phase in a porous membrane, but the problems of membrane stability have still not been solved sufficiently for practical applications.<sup>8</sup> Further, different functionalizations of the pore surface or volume with macromolecules in order to immobilize chiral selectors have been performed (yielding composite membranes; cf. 4.5.3). In most cases the function of such membranes had been a membrane adsorber (cf. 5.5). However, enantio-selective (facilitated) transport had also been observed for combinations of porous membranes with chiral selector groups, including biomacromolecules [118–126]. Proteins, such as BSA, immobilized in the pores of UF or MF membranes are presumably the best studied example [125,126]. The surface modification of a MF membrane with chiral polyglutamates (cf. 4.3.3) had also yielded membranes with some enantioselectivity [127]. Because all these membranes had a permanent pore structure including macropores, the selective transport should be more similar to pore immobilized liquid membranes or membrane assisted homogeneous chiral resolution (cf. above).

Research towards membranes of type (ii) had focused on two alternatives: the use of chiral or achiral polymers. In both cases, the preparation of molecularly imprinted polymers (MIPs; for a review cf. [128]) is one option to introduce enantioselectivity.

Enantioselective permeation through a polymer membrane had been first demonstrated using poly-L-glutamates with amphiphilic *n*-nonylphenoxy-oligoethyleneglycol side chains [129]. In diffusion experiments with tryptophan and tyrosin,

selectivities of >8 for the D vs. the L isomers had been observed. The temperature-dependency of permeability and selectivity, an increase in selectivity in the first period of the experiments and additional spectroscopic data suggested that an ordered structure of the polymer (presumably a nematic liquid crystalline phase) should be the reason for the remarkably high selectivity.

Aoki et al. had performed comprehensive investigations on various chiral polymers as membranes for optical resolution ([130–138], for a review cf. [135]). Several different macromolecular architectures had been studied in detail:

- polymers with bulky chiral pendant groups; e.g. pinanyl, on a poly(prop-1-in) backbone (cf. Fig. 12);
- blends of chiral polymers with achiral polymers;
- graft copolymers with chiral macromolecular side chains on an achiral backbone;
- polymers with a chiral main chain; e.g. poly(amino acids).

Remarkable selectivities had been obtained in diffusion dialysis, but a changed (reduced) selectivity as a function of time (due to saturation of the membrane) had been observed more or less pronounced in all cases. Nevertheless, clear conclusions about an ‘intrinsic’ enantio-selective transport through the polymers could be made. In most (but not all) cases, the enantio-selective transport correlated with an adsorption selectivity, and with increasing permeability of the membrane a decreasing selectivity had been correlated.

Two significant deviations from those trends had been confirmed. For the pinanyl side chain homopolymers, an enantio-selectivity for a relatively broad range of molecules (from various amino acids to 2-butanol) had been observed; and the selectivities and fluxes were lower for the smallest solute (2-butanol). For this polymer, no adsorption enantioselectivity could be measured in batch experiments. Hence, it had been concluded, that ‘enantio-selective permeation was achieved not by selective dissolution at the membrane surface but by selective diffusion through the chiral space formed by the pinanyl groups in the membrane’ [134,135]. Membranes with the selective polymer in a thin layer on the membrane surface (from the graft copolymers with chiral macromolecular side chains; cf. above) had a much larger ratio between selectivity and permeability than all homogeneous polymer films. The analysis of the transport data in the framework of the solution-diffusion model suggested that a selective sorption contributed largely to the selective (i.e. faster) transport [133,135].

A remarkable discovery had been made recently: membranes made from the polymer with the chiral pinanylsilyl side groups had been prepared and then the side groups had been removed via selective hydrolysis (‘depinanylsilylation’; Fig. 12) [137,138]. The resulting films were still chiral, and this ‘chiral memory’ had been explained by the retention of a helical conformation of the polymer main chain irrespective the loss of the pendant chiral side groups. With those membranes, diffusion- or pervaporation-driven permeation experiments with racemic tryptophan or 2-butanol had been

<sup>8</sup> Discussing immobilized liquid membranes is beyond the scope of this review.

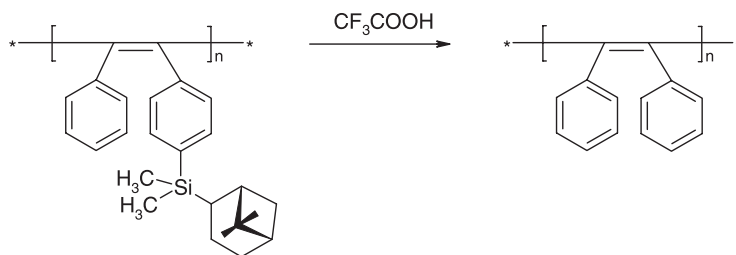


Fig. 12. Polymer with chiral side groups and its conversion via ‘depinanylsilylation’ in solid state to a polymer with ‘chiral memory’ (cf. [137]).

performed, and significant enantioselectivities had been achieved. In addition the permeability had been much increased due to the hydrolysis (Table 3) [137]. This was considered the first evidence for a membrane selectivity based a helical conformation of the polymer chain, with ‘molecular-scale voids generated by the depinanylsilylation’ acting as transport pathways. It had also been noted that this preparation resembled the molecular imprinting of polymers [137].

A few further variations of selective polymers and methods for film preparation had been reported by other groups. Crosslinked polyalginates had been successfully used to prepare membranes which could be used in enantio-selective diffusion and ultrafiltration separations [139]. Using the layer-by-layer (‘LBL’) technology (cf. 4.3.4), charged and chiral poly(amino acids) in combination with other chiral or achiral polyelectrolytes had been used for the preparation of transport-selective membranes for chiral resolution, but until now the characterization of the very thin membranes had only been done with the films directly on an electrode [140].

Until today, there had been only relatively few attempts to adopt the molecular imprinting for the preparation of polymer membranes for chiral separation (for recent review on such MIP membranes, cf. [141]). This was mainly due to problems to directly apply the established imprinting methods for the preparation of mechanically stable films ([142], cf. 4.4.2). The group of Yoshikawa has done very comprehensive work to establish an alternative approach towards molecular imprinting: Specifically synthesized polystyrene resins with chiral oligopeptide recognition groups in a blend with a matrix polymer PAN-*co*-PSt had been used for the membrane formation via a EIPS process, by casting a polymer solution and subsequent evaporation of the solvent, and chiral amino acid derivatives had been used as the template [143–148]. Systematic variations of the peptides on the resin indicated that imprinting specificity was indeed influenced by structure, size

and architecture of the recognition group [148]. Diffusion studies revealed the role of the template as porogen, and the observed transport selectivity—slower transport of the template—was explained by a retardation due to specific template binding to the ‘pore walls’. However, the same membranes showed an opposite selectivity in electro dialysis, and electro dialysis performance was also very much susceptible to the applied voltage. The MIP membrane behaviour was summarized in a phenomenological relationship where the flux monotonically increased with the difference in chemical potential while the selectivity was  $\sim 1$  at about 20 kJ/mol (corresponding to a concentration difference of 1 mmol/l), showed a pronounced maximum (up to 6) in the range of 200 kJ/mol and levelled off again to  $\sim 1$  at very high potential values [145]. The authors also argued that by applying a pressure difference such as in membrane filtration, a similar increase in selectivity could be expected. This, however, is hindered by the microporous structure of the thick MIP membranes.

Remarkably, cellulose acetate [146] and even the fully synthetic, achiral carboxylated polysulfone [144] could also be used to prepare enantio-selective membranes via imprinting with a chiral amino acid derivative, but the selectivities were very low ( $\leq 1.2$ ). Grafted polypeptides—via NCA activated monomers—on polysulfone were also used as MIP membrane polymer [149]. Recently, a highly enantio-selective MIP membrane based on a poly(amide-imide) and using electrical potential as gradient had been reported [150].

Van der Ent et al. had proposed a classification of non-porous polymer membranes for enantioseparation: diffusion-selective vs. sorption-selective [151]. Chiral discrimination during diffusion had been considered ‘the summation of chiral interactions’ so that one enantiomer diffuses faster than the other. Irrespective the presence of ‘some sorption selectivity’ in those membranes, it had been pointed out that this sorption is ‘not caused by a one-to-one molecular interaction’ (e.g. the membranes by Aoki et al. [134,135,137,138]—cf. above—would fall into this group). Based on an analysis of performance data in the literature and due to the inevitable inverse proportionality between flux and selectivity for diffusion-selective membranes, it had been proposed to focus further research onto sorption-selective membranes (e.g. MIP membranes). Those, however, could only be efficient if the selectively adsorbed population of molecules is also mobile and if non-selective diffusion through the membranes is minimized. The authors had also pointed out that the increase

Table 3

Enantio-selective transport via pervaporation of 2-butanol through membranes from a polymer with chiral side groups before and after its conversion via ‘depinanylsilylation’ in solid state (cf. Fig. 12 [137])

Membrane	Permeation coefficient, $P$ (m <sup>2</sup> /h)	Selectivity, $\alpha$ (–)/ee (%)
Before depinanylsilylation	$1.76 \times 10^{-11}$	9.24/80.5
After depinanylsilylation	$1.45 \times 10^{-9}$	3.83/58.6



in enantioselectivity of the membranes by Yoshikawa et al. with increasing transmembrane potential gradient [145] (cf. above) would be in line with such increased ‘mobility’. It should be mentioned that similar structures and transport mechanisms can also be used for other highly selective separations, as it had been demonstrated recently for the resolution of xylene isomers with polymer membranes containing cyclodextrins as fixed receptors/carriers [152].

In conclusion, the relationships between transport rate and selectivity for enantioselective polymer membranes should be further analyzed in detail. This is possible using variations of the gradients (concentration vs. pressure or electrical field), but using these options will depend on the structure (pores, stability) of the membranes and/or the analyte (e.g. its charge). Especially a more detailed pore analysis of the membranes will be indispensable.

#### 4.2.4. Porous affinity membranes by molecular imprinting of polymers

Besides the focus on chiral separations, molecular imprinting of polymers has been explored to prepare membranes with a pre-determined affinity for a variety of molecules. All these approaches have in common that a polymer solution containing a template (and a blank solution as control) are used to form a film; depending on the phase separation conditions, different pore morphologies are obtained. The evaporation induced phase separation (EIPS) with the systems of Yoshikawa et al. [143–150] had lead to mainly microporous membranes (cf. 4.2.3).

Kobayashi et al. had done pioneering work to use the well-established precipitation separation (NIPS) [153–157]. In their first studies they had used copolymers of acrylonitrile with acrylic acid for a NIPS process yielding anisotropic porous membranes [153,154]. The same copolymer and methodology had been successfully adapted by other groups [158]. Binding sites for a variety of small molecules have been obtained. However, the obtained porous membranes had been typically characterized as adsorbers.

The selection of polymers had been extended to many of the commonly used membrane materials (cf. Table 2): cellulose acetate [146], polyamide [155,156], polyacrylonitrile (PAN) [157], polysulfone (PSf) [157], but also including polystyrene (PSt) and PVC [157]. The exceptions are the hydrophobic—and almost non-functional—polymers (polyolefines, PVDF, or Teflon). However, because both recognition sites and pore structure are ‘fixed’ at the same time within the same material, a comparison of the efficiency of different MIP membranes, and thus polymer materials, was rather complicated. Nevertheless, Reddy et al. [157] had found, that the affinity of MIP membranes for dibenzofuran showed the following order: PVC > PSf > PSt > PAN (binding from methanol), while for all MIPs higher affinities than for blanks had been observed.

Another alternative, the use of a polymer blend in order to tailor both pore structure and binding sites had been explored recently (Fig. 13, [159–161]). Porous membranes had been prepared by immersion precipitation (NIPS) of cellulose acetate/sulfonated polysulfone (CA/SPSf) blends with varied

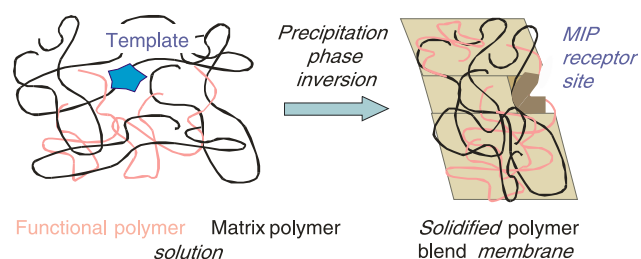


Fig. 13. Porous molecularly imprinted polymer blend membranes via phase separation—a matrix polymer provides a (membrane) pore morphology, and the functional polymer enables additional stronger non-covalent interactions with a template which is extracted after the fixation of the ‘imprint’ receptor sites during the solidification step.

compositions. MIPs, prepared with the fluorescent dye Rhodamine B (RhB), and Blanks, prepared without RhB, had been analysed by atomic force microscopy (AFM), scanning electron microscopy (SEM) and gas adsorption isotherm method (BET). RhB binding data from solid phase extraction experiments allowed an estimation of imprinting efficiency as a function of blend composition: 95:5 > 85:15 > 100:0. SEM revealed an anisotropic cross-section morphology with nodules in the top layer and macrovoids in the support layer which indicated instantaneous demixing as overall mechanism of polymer solidification [161]. SEM at high resolution and AFM enabled a detailed analysis of the top layer morphology, in particular the estimation of the nodule size. Overall, significant differences in pore structure between MIP and Blank, and as a function of the polymer blend composition had been found; the magnitude of these differences, measured by SEM, SFM and BET, clearly correlated with the imprinting efficiency. In particular, for the CA/SPSf 95:5 blend, the characteristic nodule size was much smaller for the MIP than for the Blank. Hence, the fixation of imprinted sites occurred mainly in small polymer particles, which were formed during a very fast demixing upon contact with the non-solvent. Further, the addition of the template to the CA/SPSf blend solution seemed to facilitate the demixing after contact with the precipitation bath water, presumably via a complexation of the RhB with the sulfonic acid groups of SPSf. Hence, another interesting aspect of this study was that the detailed morphologies in correlation with the well-studied mechanisms of membrane formation via NIPS (cf. [161] and 2.2) had been successfully used to shed light onto the detailed mechanism of molecular imprinting by solidification of functional macromolecules.

#### 4.2.5. Novel ‘nanoporous’ barrier morphologies

One of the first examples for self-assembled porous membrane barrier layers were the ‘S-layer’ membranes introduced by Sleytr et al. [162]. The cell wall protein of bacteria had been isolated and purified, then reconstituted (crystallized) as an ultrathin layer on a porous support (MF) membrane and finally stabilized by crosslinking with glutaraldehyde [163,164]. The pore size, based on the highly ordered S-layer protein array structure, was in the range of 5 nm. The corresponding UF membranes showed a very sharp size selectivity. For a S-layer UF composite membrane,

manufactured according to above procedure, the transition between 0 and 100% rejection was between 30 and 40 kg/mol; i.e. the separation curve was much steeper than for typical UF membranes obtained by the NIPS process (cf. Fig. 1). There had been attempts to commercialize this membrane. However, this was not successful yet, mainly due to the problems to upscale the process of biopolymer isolation, purification, reconstitution and realization of a reproducible and defect-free large scale film formation. Therefore, synthetic polymers with similar properties, i.e. self-assembling into well-defined porous structures, would be very attractive.

Block copolymers as building blocks for ordered three dimensional structures had been reviewed recently [165]. The bicontinuous phase separated morphologies can be transferred into ‘nanoporous’<sup>9</sup> structures by using them as template for the formation of an inorganic material, as shown for example by Thomas and coworkers [166]. In this review, however, the focus is onto potentially novel polymeric barriers with well-defined micro- and mesoporosity.

The first example for the preparation of regularly spaced nanochannels in a glassy polymer matrix had been reported by Hashimoto et al. [167]. A film had been prepared by casting from a solution of a mixture of a polystyrene-*block*-polyisopren (PSt-*b*-PI) blockcopolymer and a PSt homopolymer—at a composition that the overall volume fraction of the PSt was 0.66—in a good solvent for both polymers (toluene), followed by slow solvent evaporation leading to a microphase separation into a bicontinuous gyroid morphology. The 100–300  $\mu\text{m}$  thick films had then been subjected to ozonolysis in order to selectively degrade the PI blocks. The nanochannels had additionally been plated with nickel to enhance the contrast in electron microscopy (TEM). The channel diameters in the bicontinuous structure were about 25 nm. An analogous morphology had been obtained by the same approach but using a blockcopolymer of PSt and poly(dimethylsiloxane) (PDMS) and selective removal of the PDMS by etching with hydrofluoric acid [168].

Liu et al. [169] had prepared a film with ordered nanochannels from a triblock copolymer polyisopren-*block*-poly(2-cinnamoyl ethyl methacrylate)-*block*-poly(*tert*-butyl acrylate) (ABC). The copolymer had been mixed with the homopolymer poly(*tert*-butyl acrylate) (homo-C) and films were casted from solutions in a common solvent. After drying and annealing, the block ‘B’ could be used for UV-crosslinking of the ‘AB’ phase. Thereafter, the ‘homo-C’ had been extracted, and a regular pore morphology had been visualized by TEM. Gas permeability measurements confirmed the highly porous nature of the films, but the lack of water permeability

suggested that the nanochannels might be discontinuous on a macroscopic level, e.g. due to ‘grain boundaries’ in the film.

Hillmyer et al. had found that polystyrene-*block*-poly lactide (PSt-*b*-PL) copolymers can form hexagonally packed nanocylinders of PL in PSt which can then be converted into pores by selective hydrolysis of the PL (Fig. 14 [170,171]). Based on that work they had prepared highly porous and ordered monoliths with connected and hydrophilic pores (e.g. average pore diameter  $\sim 20$  nm, average spacing  $\sim 30$  nm) [172]. Here, the base material was a PL-poly(*N,N*-dimethylacrylamide)-PSt triblock copolymer with a low polydispersity. Alignment of the phase separated polymer was achieved using cooling from the melt in a channel die. Finally, the polylactide was removed quantitatively, leaving the PSt matrix with the hydrophilic polyacrylamide covering the pore surface.

First results towards a responsive nanoporous membrane based on a polystyrene-*b*-poly(2-vinylpyridine)-*b*-poly(*tert*-butyl methacrylate) have recently been reported [173–175]. The phase separated gyroid morphology corresponds to a matrix of PSt, which is perforated by nanoscopic channels of poly(*tert*-butyl methacrylate), which can be removed by UV irradiation. Thereafter, inner walls of the nanochannels are coated by the poly(2-vinyl pyridine) middle block, which can change its conformation reversibly as function of pH.

Another step towards a better orientation via a ‘pore-filled’ composite technique (cf. 4.5.2) had been achieved by

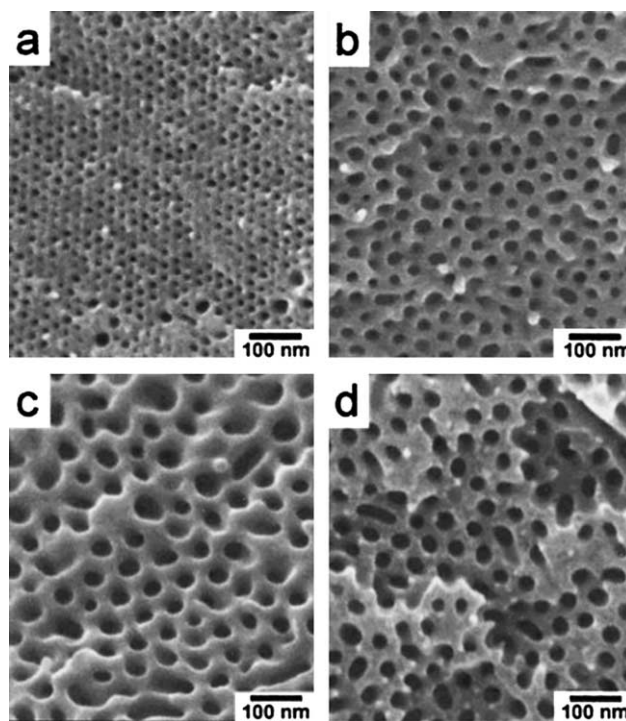


Fig. 14. ‘Nanoporous’ membranes from phase separated polystyrene-*block*-poly lactide (PSt-*b*-PL) copolymers with varied copolymer structure (molar mass in kg/mol, molar fraction of PL), after selective hydrolysis of the PL phase: (a) 32, 0.28 ( $D_{\text{cyl}}=15$  nm), (b) 58, 0.38 ( $D_{\text{cyl}}=31$  nm), (c) 92, 0.36 ( $D_{\text{cyl}}=45$  nm), (d) 40, 0.42 ( $D_{\text{cyl}}=42$  nm)—the diameter of the cylinder,  $D_{\text{cyl}}$ , as determined by SAXS agrees well with the pore diameter found from SEM (reprinted with permission from [171], Copyright (2002) American Chemical Society).

<sup>9</sup> The term ‘nanoporous’ is not consistent with the IUPAC nomenclature for pore structures. However, in their original papers, all authors from the macromolecular community call the materials discussed here nanoporous based on their pore dimension in the lower nanometre range. It should be kept in mind that in the membrane community, the IUPAC terminology is also not used so consistently as done in this article (except chapter 4.2.5 and subsequent reference to these materials).

introducing a melt of a microphase-separated polystyrene-*block*-polybutadiene into the pores of an Anopore membrane via capillary action [176]. The polymer, which forms cylindrical microdomains in the bulk, presents those cylindrical domains aligned parallel to the pore walls in the membrane.

Rubner had obtained special morphologies from thin polyelectrolyte ‘LBL’ films (cf. 4.3.4) as a function of certain formation and posttreatment conditions which seem to have regular microporous structures, and it could be possible to use those also as membrane barriers [177].

However, for all above attempts, methods to process the interesting nanoporous structures into membranes for practical separations must still be developed. A promising example for such a transfer of microphase-separated morphologies of well-defined block copolymers into a ‘real-world’ separation membrane had been given by Mayes et al. [178]. Using the graft-copolymers of PVDF with poly(PEG methacrylate) synthesized via ATRP [114] (cf. Fig. 11), they had prepared composite membranes by coating thin films on a support PVDF UF membrane and subsequent phase separation. Both, the structural characterization by high resolution electron microscopy and NF experiments suggested that hydrophilic ‘nanochannels’ in a hydrophobic matrix as transmembrane barrier in the skin layer and a hydrogel-like outer membrane surface had been obtained (Fig. 15). This membrane showed very high NF flux and molecule-selectivity according to size in the range of  $M < 500$  g/mol, along with a minimized fouling tendency when used for concentrating oil/water emulsions. In a direct comparison the membranes had been much better than a state-of-the-art NF membrane [178].

#### 4.3. Surface functionalization of membranes

The intention of a surface modification of a membrane is either to minimize undesired (secondary) interactions (adsorption or adhesion) which reduce the performance (membrane fouling), or to introduce additional interactions (affinity, responsiveness or catalytic properties) for improving the selectivity or creating an entirely novel separation function (Fig. 16).

A key feature of a successful (i.e. ‘tailored’) surface functionalization is a synergy between the useful properties of the base membrane and the novel functional polymer (layer). This is best achieved by a functionalization, which essentially preserves the bulk structure of the base membrane. Here, the focus will be onto truly surface selective processes.<sup>10</sup> In a more general context, surface modifications of and with polymers had attracted much attention in last decade (for reviews cf. [179–184]). Often, two alternative approaches are distinguished. ‘Grafting-to’ is performed by coupling polymers

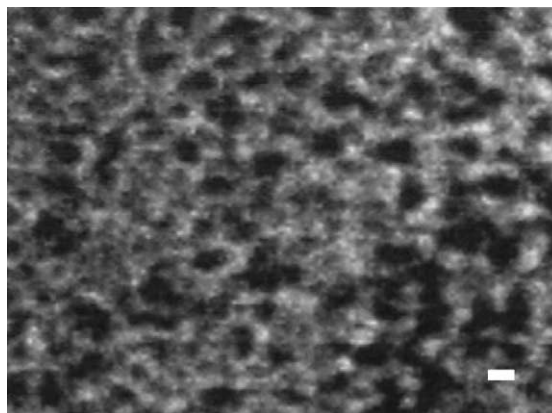


Fig. 15. TEM image of the outer (skin) surface of a composite membrane consisting of a micrometre-thin separation layer of PVDF-*g*-PEGMA (cf. Fig. 11) on a PVDF UF membrane; the length of the scale bar is 2 nm (reprinted with permission from [178], Copyright (2004) American Chemical Society).

to surfaces, while during ‘grafting-from’ monomers are polymerized using an initiation at the surface. ‘Grafting-to’ methods have the potential advantage that the structure of the polymer to be used for surface modification can be well controlled by synthesis and also characterized in detail. However, the grafting densities on the surface, which may be achieved are limited, and the coupling reactions typically require special efforts. In contrast, the synthesis of surface-anchored polymers via ‘grafting-from’ is often less controlled with respect to polymer structure, but a very wide variation of grafting densities and chain lengths can be obtained under relatively convenient reaction conditions. In order to achieve the ultimate aim of a membrane surface modification—an improved or entirely novel function of an already established membrane—a large variety of alternative methods exists, and often only a two- or multi stage methodology will provide an optimum solution.

##### 4.3.1. Heterogeneous reactions of the membrane polymer

Chemical reactions on the surface of the membrane material could be classified as follows:

- derivatization of or grafting onto the membrane polymer via reaction of intrinsic functional groups without material degradation (no polymer chain scission or change of bulk morphology);
- controlled degradation of the membrane material for the activation of derivatization or grafting reactions (at minimized polymer chain scission or change of bulk morphology).

For reaction-controlled modifications, a penetration into the base materials will be facilitated by either the intended chemical reaction itself or by an influence of reaction conditions (temperature, solvent) onto the base polymer [185]. Therefore, a ‘decoupling’ of activation—e.g. via controlled degradation (b)—and the actual functionalization reaction—under conditions which do not influence the base

<sup>10</sup> We will distinguish a ‘surface modification’ from other membrane modifications not primarily by the thickness of the functional layer but by the fact that the nature of the barrier of the original membrane will remain essentially unchanged (this is, for example, not the case when a RO thin-film composite membrane is prepared based on an UF membrane support; cf. 4.5.1).

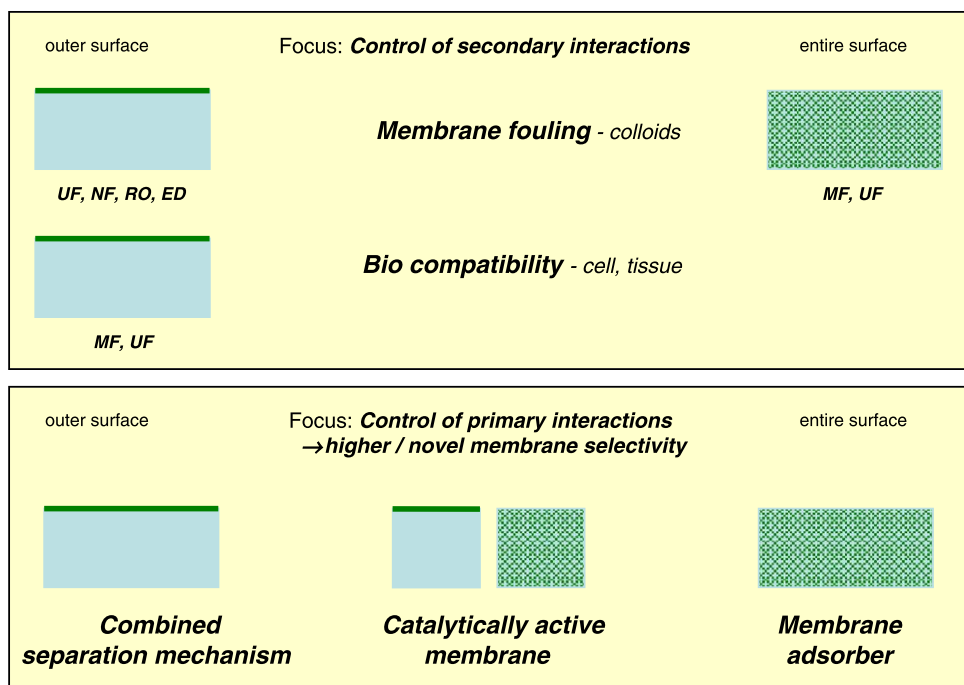


Fig. 16. Improved or novel membrane performance via surface modification of membranes: a thin functional layer (green)—depending on pore structure and separation function either on the outer or the entire surface—leads to effective solutions for problems or to novel principles. ‘Secondary’ interactions (occurring also without a separation) should be controlled without sacrificing the separation function of the membrane. Controlling ‘primary’ interactions can be used to tailor the separation function of a membrane or to ‘integrate’ them with other processes.

material—is the preferred approach towards truly interface selective modifications.

For reactions according to (a), biopolymers, especially the ‘traditional’ membrane polymers based on cellulose (cf. Table 2) offer many possibilities [185–188], and those had also been used extensively for the surface functionalization of membranes [188,189]. However, most of the other established membrane polymers are chemically rather stable, and, therefore, controlled heterogenous functionalizations are complicated or even impossible. Reactions according to (a) may be based on end groups of the membrane polymer (e.g. amino or carboxylic groups in polyamides or hydroxyl groups in polysulfone). Considering the low surface concentrations of such groups, this method would only be efficient in combination with the synthesis or attachment of macromolecular layers [189] (cf. 4.3.2). Heterogenous derivatizations of MF or UF membranes such as a sulfonation or carboxylation of PSf [190,191] or the conversion of nitrile groups of polyacrylonitrile (PAN) [192] had been used for surface modification, but they had always been accompanied by side reactions and changes of the membrane pore morphology. However, an example for a very facile controlled degradation reaction according to (b) is the ‘oxidative hydrolysis’ of polyethylene terephthalate, which had been established for a surface functionalization of track-etched membranes without significant changes of their pore structure (Fig. 17, [193,194]).

Many more possibilities for a chemically controlled surface modification can be based on using special (reactive) copolymers as membrane material (for draw-backs of this approach cf. 4.2.2)—the surface coupling of poly(ethylene

glycol)s [195] or the introduction of phospholipid-analogous groups to membranes from PAN copolymers may serve as examples [196].

Physical activation of chemical reactions, especially via controlled degradation of polymers [197], is possible by:

- high energy radiation, e.g.  $\gamma$ - or electron beam;
- plasma;
- UV irradiation.

The excitation with high energy irradiation has a low selectivity, and bond scissions in the volume of a membrane material cannot be avoided. Various technically relevant membrane modifications, especially the preparation of ion exchange membranes (cf. 4.2.1) via graft copolymerization, are initiated using electron beam, but typically this is not a surface modification of the base membrane (for a recent review, cf. [198]).

The excitation with plasma is very surface selective [199]. However, the ablation tendency of the base polymer may be significant [200]. Also, the contribution of the high-energy deep-UV radiation during a direct plasma exposition may lead to uncontrolled degradation processes. Typically, the treatment of the materials must be performed in vacuum. Modifications in small pores (diameter < 100 nm) are complicated because this dimension is smaller than the average free path length of the active species in the plasma. Alternative sources for the activation of the polymer surface are free radicals in the gas phase (one of the ‘remote plasma effects’) or the deep-UV excitation (cf. above) [201]. Therefore, an even modification of

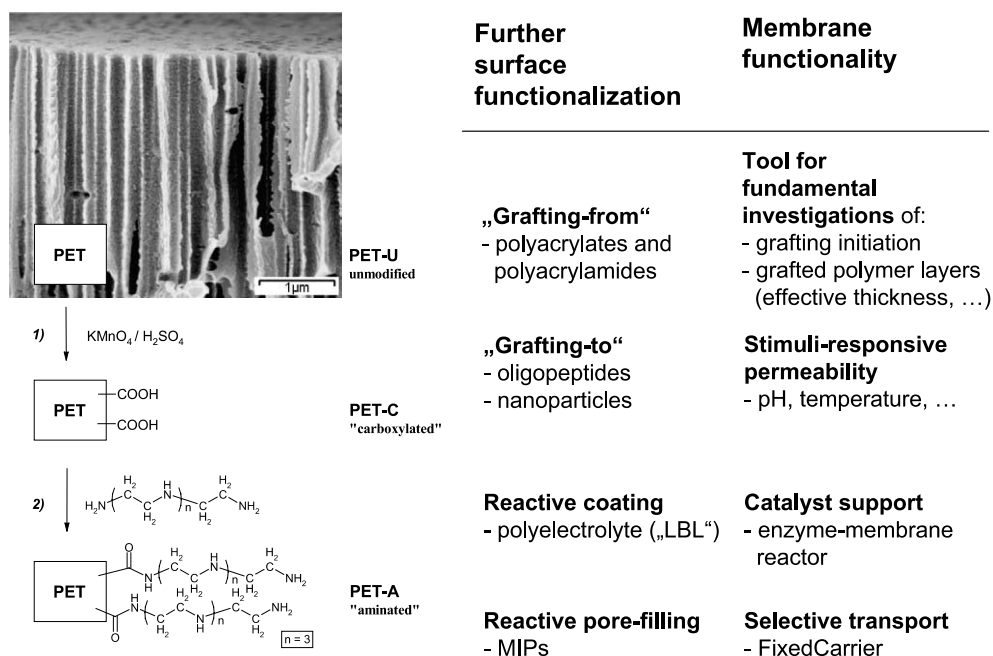


Fig. 17. Examples for surface functionalizations of track-etched capillary pore membranes made from polyethylene terephthalate (PET)—these can be done either directly with the as-received membranes or may be facilitated by a premodification, i.e. a heterogeneous polymer-analogous reaction preserving the membrane's pore structure.

the internal surface of MF membranes is problematic. Most recently, however, a novel commercial hollow-fiber membrane for dialysis had been announced where the porous structure on the outer fibre surface had been functionalized via plasma excitation [202]. For surface modifications of membranes (for a review cf. [203]), the plasma treatment had been studied very intensively. Typical applications are a hydrophilization (oxygen or inert gas plasma with subsequent exposition to air will initiate polymer-analogous oxidations of the membrane material [200]), or the introduction of special functional groups on the surface (e.g. an amination in an ammonia plasma [204]). For UF membranes it is possible to modify exclusively the outer surface, but a degradation of the micro- and mesoporous structure of the skin layer with consequences for the separation selectivity of the membrane can usually not be avoided. PAN UF membranes can be an exception, because under well-defined plasma conditions a hydrophilization occurs in parallel to a stabilization of the membrane material via an intramolecular cyclization of the PAN [200]. The excitation with plasma is frequently used also for the initiation of heterogeneous graft copolymerizations (cf. 4.3.3). Alternatively, a coating can be performed via a plasma polymerization, i.e. the deposition of a polymer from plasma (cf. 4.3.4).

The excitation with UV irradiation has the great advantage that the wavelength can be adjusted selectively to the reaction to be initiated, and, hence, undesired side reactions can be avoided or at least reduced very much [197]. Photoinitiation can be used without problems also in small pores. The UV technology can be integrated into continuous manufacturing processes simply and cost-efficiently. Photo-initiated processes have their largest potential when surface-selective functionalizations of complex polymer morphologies shall be performed

with minimal degradation of the base membrane, and when they are used to create macromolecular layers, via 'grafting-to' or 'grafting-from' (cf. 4.3.2 and 4.3.3).

#### 4.3.2. 'Grafting-to' reactions

In order to introduce macromolecular functional layers to the surface of membranes, the following strategies had been investigated:

- direct coupling on reactive side groups or end groups of the membrane material (e.g. for cellulose derivatives [189,205], polyamides or polysulfones [189,206]);
- primary functionalization of the membrane—introduction of amino, aldehyde, epoxide, carboxyl or other reactive groups on the surface—and subsequent coupling;
- adsorption on the membrane surface and subsequent physically activated coupling—alternatives are a non-selective fixation, e.g. via plasma treatment (by this means, even teflon [207] or polypropylene [208] membranes had been functionalized) or—when using photo-reactive conjugates as adsorbate—a coupling via selective UV irradiation [209,210]; also membranes from photo-reactive specialty polymers [211] or with a photo-reactive coating for the coupling of any (macromolecular) adsorbate had been proposed [212].

These 'grafting-to' reactions had been used to functionalize membranes—mostly UF or MF membranes—with hydrophilic macromolecules (e.g. PEG [207,209] or PVP [208]) or with other functional polymers (e.g. polypeptides [205] or polysaccharides [189,206]). The intentions had been to control the interactions with the membrane surface (e.g. minimizing the

adsorption of protein [209,210], binding of metal ions [205] or covalent coupling of ligands [189,206]). Starting with track-etched membranes from PET after a primary functionalization via oxidative hydrolysis, polypeptides had been synthesized in the membrane pores—sequentially according to Merrifield or via fragment condensation [193] (cf. Fig. 17).

#### 4.3.3. ‘Grafting-from’ reactions

For the synthesis of macromolecular layers via ‘grafting-from’ the polymer membrane surface, radical polymerization reactions had been used almost exclusively until now (Fig. 18). A very large variety of functional monomers such as acrylates, acrylamides or other vinyl monomers with all kinds of functional groups which could be interesting for adjusting surface properties—strong or weak anion or cation exchanger, hydrophilic, hydrophobic or fluorinated groups, reactive groups, etc.—is commercially available. These monomers can be polymerized—either from aqueous or organic solutions—very efficiently via the radical route if termination reactions are well controlled (especially by excluding or controlling the oxygen concentration).

Physical activation (electron beam, plasma treatment or direct UV excitation) had been explored from early on because this excitation can be applied to many membrane polymers (cf. 4.3.1). Subsequently, a graft copolymerization can be started by radicals of the membrane polymer [182–184,197]. For a surface modification of membranes, the ‘sequential’ variant has advantages because excitation and reaction conditions can be optimized separately. Radicals formed by physical excitation can be converted—e.g. via contact with oxygen in air—into peroxide groups on the membrane material. Those can then—in the presence of monomer—be used to create starter radicals for a polymerization [208,213,214]. Via a direct UV excitation it is possible to functionalize UV-sensitive membrane polymers, such as polyethersulfone, also under ‘simultaneous’ conditions, i.e. in direct contact with

the monomer; the starter radicals are formed via scission of the main chain of the membrane polymer [215–219] (cf. Fig. 18(a)). Almost all membrane polymers have already been functionalized via ‘grafting-from’ using physical activation [180,182–184]. Depending on the sensitivity of the membrane material and the excitation conditions, the main limitations of this technology result from unwanted changes of membrane morphology and/or an uneven modification in the interior of porous membranes.

Chemical methods for the generation of radicals on the membrane surface can also be used. Using surface hydroxyl groups, either intrinsic or introduced by plasma treatment, the initiation of a graft copolymerization with cer ions is a feasible method for membrane modification [220–222]. Via decomposition of peroxides in a solution in contact with the membrane, a radical transfer to the membrane material can also yield starter radicals (cf. Fig. 18(b)). Via such a method, the polyamide separation layer of a commercial RO composite membrane had been functionalized with grafted hydrophilic polyacrylates [223,224]. Such ‘grafting-from’ functionalizations without additional activation by external means could also be applied for the modification of membranes in modules. A primary functionalization of the membrane surface with a covalently coupled monomer can also be used to covalently attach the polymer—growing during a polymerization in solution—to the surface [225]. In all these cases, branching or crosslinking of the grafted chains by reactions in solution cannot be avoided.

Ulbricht et al. had developed UV-assisted methods for a heterogeneous graft copolymerization, mainly with the intention to improve the ‘decoupling’ of effects of the activation and the grafting reactions [194,226–232]. Added photoinitiators which can be selectively excited by certain UV energies are used. An especially easy and effective two-step approach is based on (i) the adsorption of a ‘type II’ photoinitiator (e.g. benzophenone, BP) on the membrane

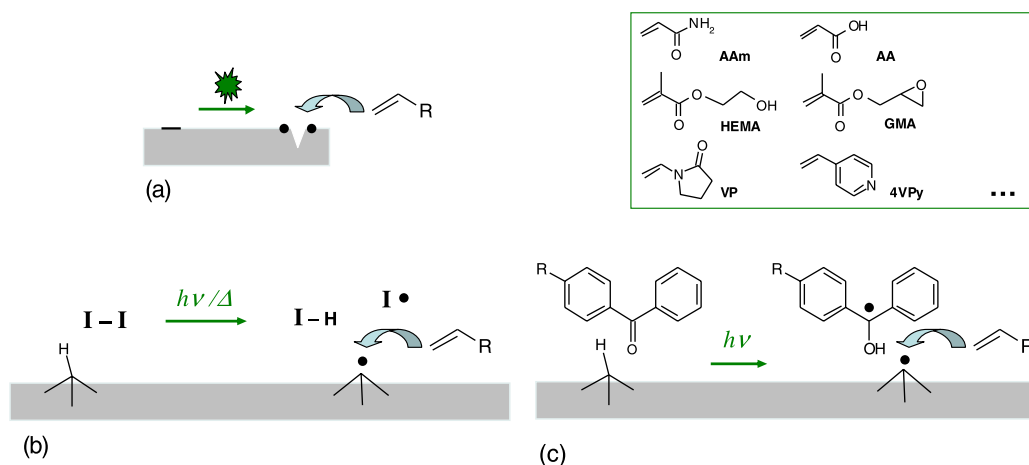


Fig. 18. Heterogeneous radical graft copolymerizations (grafting-from) of functional monomers on membrane polymers can be initiated (formation of starter radicals) via: (a) degradation of the membrane polymer (main chain scission or cleavage of side groups), via physical excitation with radiation or plasma, (b) decomposition of an initiator in solution and radical transfer (here hydrogen abstraction); radicals in solution may initiate a homopolymerization as a side reaction or leading to grafting via radical recombination, (c) adsorption of a type II photoinitiator (e.g. benzophenone derivative) on the surface and selective UV excitation (the reactivity of the benzpinakol radical is too low to start a polymerization in solution)—surface-selective ‘grafting-from’.

surface and (ii) the subsequent UV initiated hydrogen abstraction reaction to yield polymer radicals on the surface of the membrane in the presence of monomer [226] (cf. Fig. 18(c)). It had also been demonstrated that both surface selectivity and overall efficiency of this surface functionalization can be improved by using ionic bonding between primary-functionalized membrane surfaces (e.g. ‘carboxylated’ or ‘aminated’ PET [194]) and ionic ‘type II’ photoinitiator derivatives (cf. Fig. 17). Recently, another option to improve the surface selectivity by confining the initiator had been demonstrated: The photoinitiator BP had been ‘entrapped’ in the surface layer of polypropylene (PP) by using a solvent which can swell the PP in the coating step (i). By selecting suited BP concentration and time the uptake in the surface layer of the PP can be adjusted, and after change to a more polar solvent such as water or alcohol a fraction of the BP is immobilized but can still initiate a graft copolymerization [232]. The particular potential of this variant is the possibility to perform surface selective ‘grafting-from’ functionalizations in organic solvents where the simple physical adsorption to the surface is not effective [233]. Another achievement of UV-initiated ‘grafting-from’ had been the first synthesis of thin-layer MIPs on the entire surface of a hydrophobic polypropylene MF membrane [234]—this had been the basis for further work towards tailored thin-layer MIP composite membranes (cf. 4.5.3).

UF and MF membranes, e.g. from PP, polyamide, polysulfone, PET, PAN or PVDF, had been functionalized via such photo-grafting without degradation of the membrane morphology, and either on their outer or on their entire surface [194,226–234]. Several other groups have successfully used this approach [235–237]. Recently, the methodology had been also applied to the modification of hollow-fiber membranes made from polysulfone; in this study the aim was a photografted ion-selective layer polymer layer on the outer surface of the fibers which could be obtained in a straightforward manner by UV irradiation of the outer fibre surface [238]. However, it is also possible to modify selectively the interior of such hollow-fiber membranes via UV initiated grafting if photoinitiator and/or monomer are supplied only to the lumen of the fibers [239].

Inspired by the progress in the field of ‘controlled’ polymerizations, more interest has been devoted to special grafted polymer architectures—having a controlled grafting density, a narrow chain length distribution and/or special block structures—on the outer surface or in the pores of separation membranes. However, the adaptation of such methodologies to technically established membranes is still in the early stage. Detailed studies on chemistries for a more controlled grafting towards the functionalization of porous membranes and the impact of the grafted layers on their structure and function had been performed using inorganic membranes as base material. Examples are the studies by Cohen et al. with silica or titanium dioxide membranes [240–242].

Two other examples with polymer membranes as substrates had been based on a pre-modification of PP MF membranes. A two-step UV-assisted grafting methodology used the photo-

grafting of BP on the polymer surface yielding benzpinacol moieties as the first step, followed by a ‘pseudoliving’ iniferter graft copolymerization from the pore surface yielding a degree of grafting or block copolymers via UV irradiation time or change of the monomer solution, respectively [243]. A potential disadvantage of this method is that the benzpinacol must be excited at high UV energies and that the yield of photocleavage is rather low. A primary functionalization towards an amino-surface on the entire PP pore surface had been achieved by treatment with an oxygen plasma followed by a silanization to introduce amino groups on the surface. Those amino groups were the starter for a ring-opening polymerization of the *N*-carboxyanhydride (NCA) derivatives of chiral amino acids, yielding grafted polymer chains with a defined—here helical—secondary structure on the membrane surface [244]. The grafting of polyglutamate via their NCA derivative onto PVDF MF membranes [127] had already been mentioned before (cf. 4.2.3).

Using an initiator grafted to an Anopore membrane, ATRP had been used to prepare composite membranes with an ultrathin selective layer [245]. The surface functionalization of PVDF MF membranes via ATRP had been done after a premodification of the membrane with a reactive polymer layer in order to introduce the initiator groups [246].

#### 4.3.4. Reactive coating

Via an in situ synthesis of a polymer on the membrane surface or via coating a membrane with another polymer it is possible to obtain layers which are attached to the membrane material via one (or more) of the following mechanisms:

- adsorption/adhesion—the functional layer is only physically fixed on the base material; the binding strength can be increased via multiple interactions between functional groups in the macromolecular layer and on the solid surface;
- interpenetration via mixing between the added functional polymer and the base polymer in an interphase;
- mechanical interpenetration (macroscopic entanglement) of an added polymer layer and the pore structure of a membrane.

The thickness of the layer depends on the selected strategy, it can be significantly larger than for surface modifications controlled by interfacial reactions (cf. 4.3.1, 4.3.2 and 4.3.3).

For the modification of membranes, physically assisted methods such as plasma polymerisation, chemical vapor deposition (CVD) or sputtering of metals or nonmetals had often been applied. When using plasma-assisted methods, interphase layers between modified base polymer and the added polymer are always involved (b). All these methods are typically restricted to the coating of the outer surface of the membrane. In most cases, thin barrier layers—e.g. a hydrophobic barrier plasma polymer on a hydrophilic membrane [247], or a catalytic metal layer on an ion exchange membrane [248]—are created, so that the resulting membranes should be considered as composite membranes (cf. 4.5.1).

The two mentioned examples are typical for a tailored surface coating modification of membranes for low-temperature fuel-cell applications (cf. 4.2.1 and 5.1.5).

Further methods, which may in principle be adapted also to the coating of the entire internal surface of porous membranes, are the coating with polymers [249,250], a polycondensation [251], other reactive coatings [30,31,252] and the electrolytic or currentless deposition of metals, all from solutions. For fundamental studies, one variant of the last method—the modification of commercial isoporous track-etched membranes from polycarbonate with gold [37]—had received special attention (cf. 4.5.3).

Below, one established and one novel strategy for reactive coating are discussed in some more detail.

In situ crosslinking copolymerization of hydrophilic acrylate monomers in macroporous membranes from hydrophobic materials such as polypropylene or polyvinylidene fluoride is the by far most important surface coating modification in technical scale [253–255]. The reaction leads to a permanent hydrophilization of the pore surface by a thin polymer layer. Even if a coupling to the surface via radical reactions would be possible (cf. 4.3.3), the main mechanism for the fixation is the mechanical interpenetration between the added polymer network and the base membrane pore structure (c). Such surface modified membranes are commercial materials, and the coating technology provides also the basis for the development of further novel products such as membrane adsorbers (cf. 5.5). Surface functionalizations towards thin-layer MIP composite membranes via photo-initiated crosslinking polymerization and subsequent deposition from solution are based on the same general methodology (cf. 4.5.3).

Layer-by-layer (LBL) adsorption of polyelectrolytes is a relatively new coating method based on supramolecular assembly [256]. The particular feature of the LBL technique, however, is the vertical organization and stabilization of the layers in combination with the potential to design both outer surface and internal layer structures on a wide range of base materials. The LBL multilayers are not ideally ordered, but the building principle enables the compensation of defects in surface coverage at very low total layer thickness [256]. All these features contribute to the significant robustness of the coating technology and of the fabricated layers under application conditions. As a precondition for the use of the LBL technology, the base membrane must be able to adsorb the first polyelectrolyte layer via (multiple) ionic bonds (a); however, the required density of charged functional groups on the surface, is moderate. Examples for suited base membranes include plasma-treated polyacrylonitrile UF membranes [257], surface-modified polypropylene membranes [258] or Anopore<sup>®</sup> membranes from aluminium oxide [259]. Some overviews on membranes prepared via LBL have been published recently [259–261]. The particular focus had been onto the creation of very thin barrier layers, so that ultimately thin-film composite membranes can be obtained (4.5.1). Besides the efforts towards thin-film composite membranes, at least three other types of membranes via LBL technologies are under investigation.

First, it should also be possible to perform intraporous modifications using LBL coatings. However, the conditions for the functionalization of pore surfaces with a ‘concave shape’ should be especially carefully controlled. On the one hand, results with premodified macroporous PP MF membranes suggested that the main modifications had taken place on the outer surface [258]. On the other hand, the pores of primary-functionalized PET track-etched membranes (either carboxylated or aminated; cf. Fig. 17) had been functionalized by step-wise alternating adsorption of poly(acrylic acid) and poly(allyl amine) [262]. This had been proven by the alternating sign of the trans-membrane streaming potentials as well as the step-wise reduction of membrane permeabilities (Fig. 19). While the first data clearly show that the surface charge of the pores is determined by the properties of the respective functional macromolecule in the outer layer, the latter data indicate that the decrease of average pore radius (between 5 and 15 nm per bilayer, calculated using the Hagen–Poiseuille model) was larger than expected for ideal self assembly at the pore surface. The deviations could be explained by an increasing contribution of pore bridging.

Hollman and Bhattacharya [263] had also modified track-etched membranes (pore diameter 200 nm)—after a pre-modification via gold coating [37], thiol SAM formation to introduce aldehyde groups and covalent coupling of the first

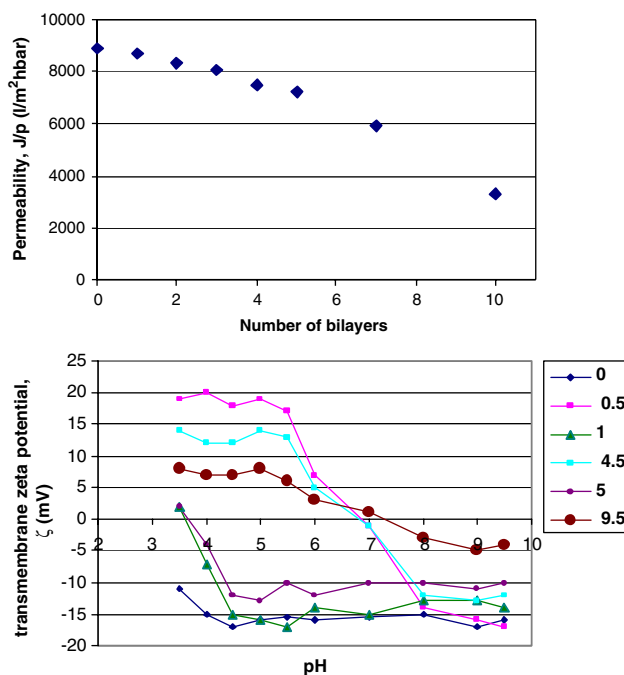


Fig. 19. Intra-porous surface functionalization of ‘carboxylated’ PET track-etched membranes (pore diameter 200 nm; cf. Fig. 17) via LBL coating using polyallylamine hydrochloride (PAH;  $M_w \sim 15$  kg/mol, 1.0 g/L in water, pH 5.6) as polycation and polyacrylic acid (PAA;  $M_w \sim 30$  kg/mol, 0.7 g/L in water, pH 5.6) as polyanion, via step-wise filtration through the membranes and subsequent washing with water (pH 5.6)—1 bilayer corresponds to a first coating with PAH (‘0.5 bilayers’) and subsequent coating with PAA: (a) water permeability and (b) apparent zeta potential from trans-membrane streaming potential measurements for various numbers of bilayers (data based on the Masters Thesis of K. Vuthicharn; experimental work at University Essen, submitted to Aalen University of Applied Sciences, Germany, 2002).



aminopolymer layer—via ‘LBL’ deposition using convective transport of the respective polyelectrolytes, polyglutamic acid and polylysine or polystyrene sulfonate and polyallylamine, through the membranes. However, after only two bilayer cycles, the pore diameter had already been reduced to about 50% indicating very strong bridging. On the other hand, the resulting membranes had very interesting properties because high salt rejection had been observed at a very high flux. Recently, other examples of the internal coating of porous membranes had been reported: Ai et al. concluded that the obtained much thicker layers than expected for ideal LBL coating may be caused by the concave surface of the pores [264], while the data of Hou et al. seemed to suggest that the LBL coating in their 126 nm diameter pores proceeded identical to deposition on a flat surface [265].

Second, special phase-separated (porous) morphologies had been obtained from thin LBL films from weak polyelectrolytes, in particular with the combination of polyacrylic acid and polyallylamine, depending on the pH during deposition and a post-treatment at a different pH [177,266] (cf. 4.2.5).

Third, via LBL deposition of polyelectrolytes on a particle and subsequent dissolution of this template, hollow capsules can be prepared [267]. This preparation method and several subsequent studies reveal also information about the permselective properties of the walls made from polyelectrolyte complexes, e.g. their sieving properties [268]. Obviously, for the convex surfaces of particles, the limitations observed for concave (pore) surfaces do not play a role.

#### 4.4. *In situ synthesis/preparation of polymers as membranes (barriers)*

Most polymer membranes for practical applications are obtained by methods of polymer processing, i.e. from (pre-synthesized) polymers (cf. 2.2). The *in situ* synthesis of polymers could be an alternative in attempts to prepare improved or novel membranes. In order to provide sufficient mechanical stability, those membranes should be self-supported—‘monolithic’—or stabilized by a suited support material. While various types of composite membranes will be discussed separately (cf. 4.5), we will here focus on the relatively few approaches using *in situ* polymerizations for the formation of entire membranes with different kinds of barrier structures.

##### 4.4.1. *Interfacial polymerization*

The best-known examples for *in situ* synthesis of thin non-porous polymer membranes are the salt-rejecting barrier layers of RO and NF membranes (cf. 2.2 and 4.5.1). For more detailed characterizations, those ultrathin polyamide layers had been prepared separately, laminated with different supports (silicon wafer or electrodes), and swelling as well as the sorption and diffusion of solutes have been studied. The data have then been correlated with the performance of the composite membranes [269]. If the lateral dimensions of the membrane barrier are only in the microscale, the mechanical properties of such a self-supported material becomes less important. Consequently, successful attempts have been made to prepare nonporous, thin

and free-standing membrane barriers in micro-devices via the same interface polycondensation chemistry as established for RO or NF membranes (cf. 5.8).

Many *in situ* polymerization or polymer crosslinking methods had been developed and technically established for the preparation of thin films for sensor systems; the polymer films can function as a selective barrier or/and as matrix for receptors. Those films can be either non-porous, gel-like (swollen) or porous. Because the separation function of such ‘membranes’ is integrated into a more complex function (cf. 5.7), and the structures of the films are typically not well characterized, thin-film sensor systems will not be discussed in more details here.

Free-standing monomolecular polymer film membranes, with a thickness of 10 nm, had been prepared from triblock copolymer poly(2-methyloxazoline)-*block*-poly(dimethylsiloxane)-*block*-poly(2-methyloxazoline), and polymerizable endgroups could be used to further crosslink these films so that the final mechanical properties were very promising [270]. Among thin sensor films, there also examples where molecules had been used as ‘template’ during fixation of the layer structure and had then been removed. Investigations of such ultrathin self-assembled and ‘molecularly imprinted’ monolayers with voltammetry suggested that imprinted sites—‘perforations’ in an insulating matrix—could discriminate the transport of different redox active molecules to the electrode [271].

A novel strategy towards macroporous membranes with a high porosity and an even pore size distribution had been based on a template process using (nano)particles in a thin (acrylate-based) polymerization mixture on a water surface; the underlying principle had been named ‘particle-assisted wetting’ [272,273]. A typical preparation used the hydrophobic monomer trimethylolpropane trimethacrylate and monodisperse silica particles (e.g. 320 nm diameter) which had been hydrophobized by a silanization. The mixture of both components with an added photoinitiator formed a regular monolayer of the particles on a water surface in a Langmuir trough; subsequent UV irradiation was used for curing, and after removal of the particles with hydrofluoric acid, a thin porous membrane had been achieved (Fig. 20). Further experiments indicated that those membranes on a suited support could indeed be used for size-based separations [273]. Based on the same principle but using multilayers of particles, the strategy had been extended to the preparation of three-dimensional porous structures with monomodal size distribution [274] (cf. 4.4.2).

The self-assembly of monodisperse nanoparticles with diameters below 10 nm at liquid interfaces had been combined with crosslinking reactions so that ultrathin membranes had been obtained [275]. The interstitial space between these nanoparticles could enable size-selective separations. With the very recently described two-dimensional membranes from viruses (bionanoparticles) having a very precise size, shape and additionally various chemical functionalities [276], also affinity based or other separations could be envisioned.

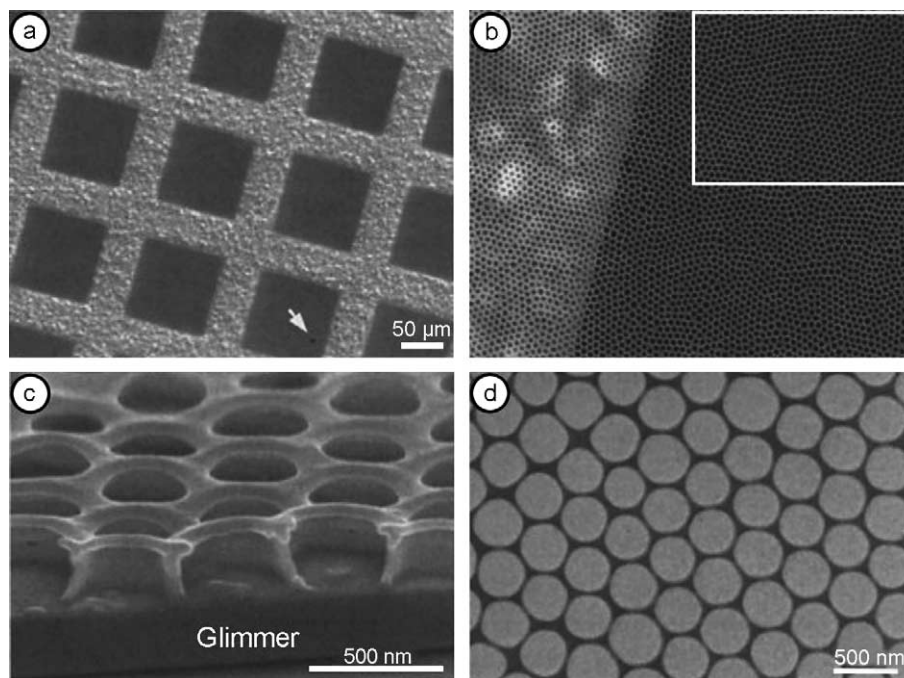


Fig. 20. Thin-film macroporous membrane prepared via 'particle-assisted wetting' of an aqueous subphase by a dispersion of nanoparticles in a monomer mixture, followed by in situ crosslinking copolymerization and subsequent removal of the nanoparticle templates: (a) and (b) SEM pictures of thin self-supported porous membranes on a metal grid with 100  $\mu\text{m}$  wide windows, (c) high-resolution SEM cross-section picture of a porous membrane on a mica support, (d) TEM picture of a self-supported porous membrane (reprinted with permission from [273], Copyright (2003) Wiley-VCH).

#### 4.4.2. Bulk (crosslinking) polymerization

Because the thickness of the barrier is crucial for the overall separation performance, the preparation of dense and self-supported membranes via in situ polymerization has only limited relevance.<sup>11</sup> However, swollen or porous films are more interesting.

Polyacrylamide hydrogels, prepared via an in situ cross-linking polymerization, are established materials for the analysis of biomacromolecules in electrophoresis; and the typical format is a flat sheet film. The combined effects of electrophoretic mobility and size exclusion by sieving through the swollen polymer network had been developed to a membrane-like separation technology [277–279]. Due to their limited mechanical stability, such polymers have been studied in more details in a 'pore-filled' composite membrane format (cf. 4.5.2).

Macroporous polymeric monoliths have since two decades attracted increasing attention from fundamental and practical point-of-view [280,281]. These materials can be synthesized in a 'mold' of (almost) any shape via an in situ polymerization of reaction mixtures containing three important components, a functional monomer, a crosslinker monomer and a porogen (selective solvent). After completion of the reaction, a crosslinked porous polymer with the shape of the mold and a pore structure with a bimodal size distribution is obtained. Macropores serve as transport pathways allowing fast permeation while a large fraction of micro- and mesopores can yield very high specific

surface areas (for some compositions more than 500  $\text{m}^2/\text{g}$ ). Additional functionalities ('affinity' to the pore wall, e.g. via ion-exchange) can be also introduced by the selection of functional monomers. 'Nanoporous' organic–inorganic hybrid 'monoliths' had also been prepared [282]. Thin monolith discs ('membranes') had been an interesting format from early on [283]. Those materials, e.g. the CIM<sup>®</sup> discs, had recently a 'renaissance' for very fast chromatographic separations [284].

Typical reaction mixtures for the synthesis of polymeric monoliths and molecularly imprinted polymers (MIPs) are very similar [128]. In both cases, high contents of crosslinker monomers are used; with monoliths the clear focus is onto the pore structure while for MIPs it is the affinity by templating. Until now only the first attempts to use synergies between the respective knowledge had been made. Nevertheless, in the past decade, some preparations of MIP membranes via in situ polymerization of liquid monomer films had been reported. Typical examples for the obtained thick and self-supported materials will be discussed below (for a recent review cf. [141]).

Mathew-Krotz and Shea [285] had prepared free-standing membranes by thermally initiated cross-linking copolymerization of a mixture of methacrylic acid and ethylene dimethacrylate. From SEM studies, a regular porous structure built up by polymer nodules with 50–100 nm diameter was discussed. The properties of the membranes were very interesting because a selective (facilitated) permeation of the template molecule and its derivatives could be observed. Kimaro et al. [286] had prepared free-standing membranes by thermally initiated cross-linking copolymerization of styrene monomers followed by leaching of a polyester used as 'pore former' at a concentration of a few percent

<sup>11</sup> Such thick polymer layers, also prepared by in situ polymerization or curing, are of interest when the barrier action for any substance should be maximized, but those systems are out of the scope of this article.

in the reaction mixture. SEM pictures suggested the presence of isolated pores with diameters of up to 1  $\mu\text{m}$  at a low density (<2%). In line with permeation data showing a very large selectivity for the template uranyl ion, it could be speculated that trans-membrane channels had been obtained, induced by the presence of a removable macromolecular pore former in the reaction mixture. Sergeeva et al. [287,288] had used an oligourethane-acrylate macromonomer in imprinting polymerization mixtures in order to increase the flexibility and mechanical stability of the membranes; self-supported MIP membranes with a thickness between 60 and 120  $\mu\text{m}$  could be prepared. The membranes had been characterized as barrier in a sensor system, and the response could be explained by a ‘gate’ effect, i.e. the binding of the template changed the membrane permeability.

The use of ‘supramolecular templates’ for the preparation of porous materials had been explored in many variations [289]. ‘Supramolecular channel’ membranes with pores mimicking biological ion-channels are an interesting, purely organic chemistry-based example, reported by the group of Beginn and Möller [290]. The approach had been based on the gelation of solutions—here acrylate-based monomer mixtures which form non-porous blocks and do not shrink upon polymerization—by string-like supramolecular assemblies of functional gelator molecules, and the subsequent fixation of these gels by an in situ polymerization followed by the removal of the gelator fibers thus finally yielding pore channels pre-determined by the size and shape of the template (here several nanometres diameter). The separation function of the membranes had been demonstrated because a selective transport of ions could be achieved. Pore-filling composite membranes had also been prepared using the same approach [291], cf. 4.5.2).

#### 4.5. Composite membranes

For established or novel polymers as selective non-porous barriers (cf. Table 2), the fabrication of thin-film composite (TFC) membranes is the main road to technical applications. For polymeric materials with more sophisticated (nanoporous) morphologies, the stabilization in a composite with a suited base membrane will also be the key to a successful evaluation (cf. 4.2.5). Other shapes of composite membranes have emerged in the last two decades, for both non-porous and porous polymeric barriers. For two-component membranes with no distinct layered morphology, the term ‘mixed matrix’ membrane is also increasingly used (cf. 2.2). Nevertheless, the final structure could be identical and the function of the composite or mixed matrix—organization of the components in space and stabilization of (at least) one of the components under separation conditions—would be the same. The preparation of mixed matrix membranes composed of organic polymers and inorganic fillers can add another dimension to improving membrane performance.<sup>12</sup> For example, zeoliths

have been added to polymer films to improve the selectivity in GS, silica-based particles or networks have been used to reduce excessive swelling and thus increase selectivity in PV and to control the water content in PEMs for fuel cells, and exfoliated minerals can considerably improve the performance of PEMs with respect to mechanical stability, proton conductivity and a reduced methanol permeability (cf. 4.2.1). However, in a polymer composite membrane, the (functional) polymer added to the base membrane will clearly control the separations performance (Fig. 21).

##### 4.5.1. Thin-film composite membranes

*Non-porous barrier.* According to the state-of-the-art, TFC membranes are made either by coating of a polymer on a support membrane or by an interfacial polymerization with help of the support membrane ([26–29,292,293] cf. Fig. 21(a)). In the latter process, the support membrane plays a crucial role, because it serves as reservoir for one of the precursors, and it defines the interface where the reaction takes place (cf. 2.2). It is very important for technical applications, that both processes are versatile for the fabrication of composite hollow-fiber membranes as well. Nevertheless, the trade-off between selectivity and permeability—typically observed in GS [51,52], but also in many liquid separations by RO or NF—is the main driving force for further membrane development. Overcoming that trade-off via a higher selectivity at same permeability could only be achieved by polymers with a different separation mechanism, based on a novel structure (cf. 4.2).

An obvious alternative would be increasing the flux at the same selectivity via further decreasing the barrier thickness. However, with above mentioned ‘conventional’ fabrication methods, the preparation of defect-free selective membrane ‘skin’ layers with thicknesses of less than 50 nm seems to be fundamentally difficult [259]. Earlier, several attempts had been made to use monolayers of functional amphiphilic molecules, e.g. prepared via the Langmuir–Blodgett (LB) technique, as ultra-thin selective barriers. However, those attempts had been essentially unsuccessful because stable and defect-free composite membranes for ‘macroscopic’ characterizations (not to speak about applications) could not be obtained reproducibly. Also, the fabrication of multilayers via repeated deposition of such monolayers did not yield the expected better membrane performance which would justify the very large efforts [294].

The ‘LBL’ technology (cf. 4.3.4) is based on the self-assembly of charged macromolecules in a vertical order with nanometre precision. Therefore, this approach has a significant advantage over the lateral order via self-assembly of small molecules in LB films (cf. above), because possible defects can be ‘healed’ within a few layers (i.e. a few nanometres). In fact, TFC membranes prepared by the coating of base UF membranes with pre-formed complexes of polyanion and polycation (e.g. cellulose sulfate and poly(diallyl dimethylammonium chloride) in solution had been reported before, and those ‘symplex’ membranes had very attractive separation properties [295,296]. Pioneering work towards composite membranes via the LBL deposition

<sup>12</sup> This special area of rapidly growing interest has not been included in this article.

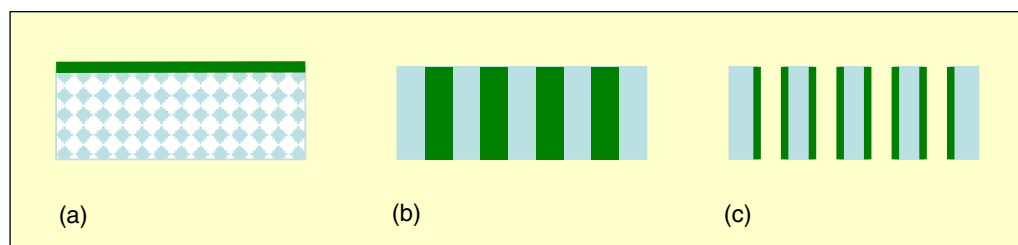


Fig. 21. Schematic depiction of three main composite membrane types: (a) thin-film, (b) pore-filling, (c) pore surface-functionalized (relative dimensions not to scale).

with separate polyelectrolytes had been done by Tieke et al. [261]. The identification of the critical number of bilayers to fully cover the porous substrate and of conditions where no penetration into the porous sub-structure occurred, had been crucial for the success of this approach [297]. Based on established combinations of base membranes and LBL coating conditions (cf. 4.3.4), wide variations of the internal layer structure had been performed by several groups; examples for polyelectrolytes used as building blocks for membrane barrier layers include the polyanions polystyrene sulfonate, polyvinyl sulfate or polyacrylic acid, and the polycations polyallylamine hydrochloride, polyvinylamine or polyethyleneimine. In particular, the type of fixed charge—including the option of reversible (de)protonation—and the charge density had been varied, and these parameters had been found to be critical for flux and salt rejection [259,298]. In addition, the charge density and spacing in the layers had been varied by using photo-cleavable protecting groups for the polyanion (a polyacrylic acid derivative) and their deprotection via photolysis after LBL assembly [299]. Furthermore, functional groups in the polyelectrolyte layers had been used for additional crosslinking reactions in order to stabilize the multilayers and tailor their permeabilities, for example by the formation of amide or imide bonds between the layers [300]. While most of the separations in earlier studies had been for small ions in water, i.e. in the range of NF, the extension to UF seems to be feasible as well (cf. below). Furthermore, applications for PV [257,261] and GS [301] with attractive selectivities at very high fluxes have also been reported.

The LBL technology has a great potential for the fabrication of technical TFC membranes, in particular because the number of layers required for separations which are fully controlled by the polymer film (and not by defects) had decreased in the last couple of years. Very much facilitated by the systematic work of Bruening et al. [259,260,297–301], it may be envisioned that selective skins from less than five bilayers (i.e. < 10 nm) on suited porous supports could indeed be used for practical highly selective separations. Recently, the possibility to prepare such ultrathin LBL skins not only on the inorganic Anopore<sup>®</sup> (the typical substrate used by Bruening et al.; cf. 4.1), but also on a polymeric base membrane, had been demonstrated [302]. Therefore, those membranes can have very high fluxes at similar selectivities as for conventional TFC membranes.

*Sieving hydrogels.* Several different approaches had indicated that TFC membranes can also be prepared for UF separations in water when a thin polymer hydrogel layer containing physical or chemical crosslinks is prepared on a porous support membrane. A successful commercial TFC composite membrane for UF has a separation layer of regenerated cellulose [303]. Of course, under aqueous separation conditions, such a membrane could also be considered having a porous barrier (cf. below). Examples for selective layers from synthetic polymers include poly(amide-imides) with PEG in the backbone [249], crosslinked polyvinylalcohol [250] or photo-grafted PEG methacrylates [227]. The separation based on sieving is due to the network (mesh) structure of the hydrogels, and it is analogous to the sieving selectivity of polyacrylamide-based hydrogels applied for electrophoretic separations [304] (cf. also 4.5.2). Recently, the first adaptation of the LBL technique to prepare TFC membranes for UF separations had been reported: The ultrathin selective barrier was based on ‘loose’ LBL layers based on the combination of the biogenic polyelectrolytes chitosan and hyaluronic acid, both having a relatively low charge density [305].

*Porous barrier.* The ‘S-layer’ membranes [162–164], which had already been discussed above, are still a reference for advanced UF membranes; unfortunately membrane manufacturing for technical separations had been too complicated (cf. 4.2.5).

Martin et al. [306] had prepared a MIP TFC membrane via UV-initiated crosslinking polymerization of a monomer mixture suited for the preparation of ‘bulk’ MIPs on an Anopore<sup>®</sup> membrane. Gas permeability measurements had indicated that the membranes were defect-free. Hence, the observed transport-selectivity for the MIP template in solution diffusion studies could be attributed to a facilitated transport through a ‘nanoporous’ separation layer on top of a porous support membrane.

Ober and his group [307] had prepared a thin film composite of a blockcopolymer on an Anopore<sup>®</sup> membrane: Trans-membrane ‘nanopores’ had been obtained by the phase separation of block copolymers and selective removal of one block, and UF experiments had been performed which may indicate the feasibility of a protein separation based on size exclusion (and presumably additional charge interactions).

#### 4.5.2. Pore-filled composite membranes

Pore filling of stable support membranes [308], either via graft copolymerization from the base polymer (material) (cf. 4.3.3), via in situ polymerization (cf. 4.4.2) or via crosslinking of presynthesized polymers is a very promising approach towards high performance, functional separation membranes (cf. Fig. 21(b)). Selective or responsive polymers, which swell significantly in water or organic solvents can be mechanically stabilized by the fixation in the membrane pores (with or without anchoring to the wall). Especially for the function in organic solvents and/or in order to achieve a selectivity for small molecules, the prevention of excessive swelling by the pores will be an additional advantage.

Yamaguchi et al. [309–313] had investigated this concept with a variety of polymers and separation functions. Composite membrane preparation had been done via plasma activation of the base membrane—typically MF membranes from polyolefins—and a subsequent (graft)copolymerization of functional polyacrylate derivatives or other monomers. PV experiments had been used to study the permeability and selectivity as a function of the polymer structure [309–312]. Recently, the group had explored the application of these pore-filled MF membranes, for example in NF/RO or as ion-conducting membrane for fuel cell applications [314,315] (cf. 4.2.1). In all cases, the effective barrier thickness was determined by the used base membrane, i.e. not less than 20  $\mu\text{m}$ .

An alternative membrane type had been established using photo-initiated graft copolymerization onto a PAN UF membrane yielding a composite where the grafted polymer was immobilized in the pores of the very thin skin layer of the support membrane [316,317]. A high performance (selectivity and flux) in PV of organic/organic mixtures had been obtained and explained by the prevention of excessive swelling of the selective polymer (due to the filling of the pores) and the very low barrier thickness ( $< 1 \mu\text{m}$ , i.e. the skin of the UF support). It had also been shown that the selectivity can be tailored to various mixtures to be separated by using different functional monomers [316,318].

Childs et al. [319–322] had experimentally demonstrated and theoretically explained that the intrinsic properties of polymer hydrogels can be used very efficiently for the NF separation of ions and molecules when applying the pore-filling composite concept. First preparations had started with surface modifications of the support MF membrane [319] or/and in situ polymerizations towards polymeric ion-exchange polymer hydrogels in the pores [320]. Two examples are the in situ prepared poly(*N*-benzyl-4-vinylpyridinium chloride) and a polymer via crosslinking of polyvinylbenzyl chloride with piperazine and a subsequent quaternization—in both cases, the key parameters for membrane performance, the polymer volume fraction in the membrane pores and the charge density can be adjusted easily and reproducibly by the synthesis conditions.

Anderson et al. had prepared crosslinked polyacrylamide-based hydrogels in support MF membranes (called ‘gel in a shell’), and they had shown that the principle could also be

used for the separation of larger molecules, e.g. proteins [323–325]. A separation via pressure-driven filtration through the hydrogel, filling the pores of the membrane, is only possible for the composite membranes; without support the hydrogel would collapse under the separation conditions. The UF-selective polymer has no permanent pore structure, but in its swollen state selective separation is possible based on size exclusion (sieving) while the solvent flow is determined by friction with the polymer.

The pore-filling concept could—in principle—also be applied to permanently porous polymers as barrier. There are already examples for filling the pores of membranes or filters via in situ crosslinking polymerization towards porous monoliths (cf. 4.4.2). The specific aim was to produce MIP membranes by using established MIP synthesis protocols, which are not well suited for the preparation of free-standing films (cf. 4.4.2). Piletsky et al. used porous glass filters as base material to prepare ‘MIP membranes’ which were characterized in sensor configurations [326]. Dzgoev and Haupt performed the crosslinking polymerization of a functional monomer mixture to imprint a protected L-amino acid in the pores of a polypropylene MF membrane. Diffusion experiments indicated a faster transport of the L- vs. the D-derivative through the membranes; however, no real selectivities with mixtures had been measured [327]. Also, the very large fluxes indicated that those pore-filled composite membranes may have a considerable fraction of non-selective (i.e. large) pores. In order to better address these problems, the controlled pore-filling of track-etched PET membranes with pore diameters between 50 and 400 nm via pre-modification of the pore wall (cf. Fig. 17) and subsequent synthesis of MIP monoliths (having specific surface area  $> 100 \text{ m}^2/\text{g}$  and pore diameters  $< 100 \text{ nm}$ ) in these pores is currently under investigation. The cylindrical pores of the track-etched membranes serve as the ‘mold’ for the synthesis of molecularly imprinted monoliths; the resulting materials are ‘MIP nanomolith’ composite membranes [328].

An example for an even more sophisticated and controlled pore morphology in a non-porous crosslinked polymer were the ‘supramolecular channel’ membranes (cf. 4.4.2). In order to increase the mechanical stability and the permeability at the same time, the gelation had been performed in the pores of track-etched PET membranes. These composite membranes could be handled without problems, and the aligned pores of the matrix membrane contributed to an increased permeability [291]. Also for ‘nanoporous’ phase-separated block copolymers, the pores of the support membrane seemed to facilitate an orientation of the nanopores into a trans-membrane direction ([176], cf. 4.2.5).

#### 4.5.3. Surface functionalized porous composite membranes

Preparation methods for composite membranes with coated pore surfaces (cf. Fig. 21(c)) can be directly derived from surface modifications (cf. 4.3). Because the even functionalization of the interior surface of porous materials with macromolecules (via ‘grafting-to’) is complicated and often not efficient, the ‘grafting-from’ or ‘reactive coating’

approaches are much more suited. The main aims may be classified as follows:

- adjusting the pore size (by a controlled reduction of pore diameter);
- introduction of additional functional layers (for controlled interactions of permeands with the pore surface);
- introduction of responsiveness, either in terms of pore size or surface functionality (i.e. often in combination with one of the above mechanisms).

*Adjusting pore size (towards ‘nanoporous’ membranes).* Using commercial isoporous membranes as base material, some work towards ‘tailored’ isoporous membranes with pores in the size range between  $\sim 2$  and 20 nm had been performed.

The inorganic Anopore<sup>®</sup> membranes (cf. 4.1) had been used as substrates for various chemical functionalization and layer deposition techniques (cf. 4.5.1). Via a controlled step-wise CVD (cf. 4.3.4) the pore diameter had narrowed down to a few nanometres, so that selective separations of small molecules became possible [329].

Based on polycarbonate track-etched membranes (cf. 4.1), ‘nanotubule’ membranes with well-defined transmembrane pores having a diameter of a few nanometres had been developed by Martin et al. [37]. The preparation had been based on controlled deposition of gold layers on the pore walls of the base membranes with pore sizes between  $\sim 10$  and 30 nm (cf. 4.3.4). By this means, the pore size could step-wise, evenly and reproducibly be reduced. In combination with self-assembled monolayers (SAM) of functional thiols on the thus obtained nano-tubules, selective membrane separations could be achieved. With very narrow pores ( $< 2$  nm), even the separation of small molecules based on size or shape could be envisioned [330]. With somewhat larger pores, the separation of proteins based on their size could already be demonstrated, and the use of an electrical field as driving force was also possible [331,332]. Stroeve et al. had used the same technology with SAMs having terminal carboxyl groups, and the separation of proteins using combined effects of size exclusion and charge repulsion could be demonstrated [333,334]. Polyacrylic acid had also been grafted via thiol side groups to the gold pore walls, and a large switching of the effective pore size as a function of pH had been demonstrated [335]. The last examples illustrate that it would be also possible to combine all three aspects mentioned above by starting with a surface modification to adjust the membrane pore size. Irrespective the impressive and fundamentally interesting results with this special technique, the approach has its limitations. Especially, the gold plating step is a major complication for upscaling the process. Therefore, alternative approaches will be necessary.

*Functional layers on the pore surface for controlled (affinity) interactions.* Using typical porous membranes obtained from phase separation techniques, a surface functionalization is especially attractive if the resulting membrane could be used for an efficient (affinity) binding or a catalytic reaction on the pores during permeation through the membrane. Consequently, membranes with an isotropic cross-section had been mostly

considered (cf. below). However, for certain more specialized (novel) processes, anisotropic membranes with functionalized (internal) pore surface would also be very interesting (cf. 5.6).

Surface functionalized membranes adsorbers (with characteristic trans-membrane pore diameters between  $< 100$  nm to several micrometres) had been prepared via various grafting and reactive coating reactions, considering the respective reactivity and stability of the base membrane, and the resulting functionality and thickness of the grafted or coated layer.

In early work, several ‘grafting-to’ reactions to the base membrane (e.g. cellulose derivatives [189], chitosan [188], polyamide [206] or polysulfone [190]) had been explored.

Later, the large potential of tailored grafted layers via ‘grafting-from’ had been recognized; the group of Saito and Furusaki had done important pioneering work [336]. They had focused on hollow-fiber MF membranes made from polyolefine as base material, high energy irradiation initiation of graft copolymerization, and a large variety of functionalities had been prepared based on, (i) grafting poly(glycidyl methacrylate) layers, and (ii) derivatization of the epoxide groups to introduce strong and weak anion and cation exchange groups, chelating groups, hydrophobic groups or reactive groups for subsequent immobilization of more specific molecules [337]. Those functional polymer layers had either a two or three-dimensional structure and could be tailored for capturing and/or immobilization of various small or large molecules or particles based on affinity interactions. Examples from several other groups had demonstrated the versatility of this combination of suited bases membranes with various different functional layers ([189,232,336,337]; see also 5.5).

The surface functionalization of iso-porous track-etched membranes with a larger pore diameter (between 100 nm and 3  $\mu\text{m}$ ) had been performed via ‘grafting-from’ reactions in order to prepare enzyme-membranes as convective flow microreactors ([338,339], cf. Fig. 17 and 5.6). A further development of membranes for those and other applications had been accomplished by the immobilization of nanoparticles on the pore walls of surface functionalized track-etched membranes: Core-shell latices with epoxide groups on the their surface had been filtered through membranes with amino-functionalized pore surface, and after extensive washing, the pore surface had been covered evenly with the nanoparticles (Fig. 22, [340]). Variations had also been performed with respect to pore diameters and particle sizes, and the particle density could also be reduced by using a mixture of reactive with inert nanoparticles in the immobilization step. Such nanoparticle composite membranes are interesting because the laminar flow in the pores can be disturbed thus improving the mixing, and the nanoparticles with many unused reactive or functional groups on their surface can be used for the immobilization of enzymes or for affinity separations.

Thin molecularly imprinted polymer (MIP) layers are another promising alternative because substance-selective binding properties can be introduced. Piletsky et al. [234] had first demonstrated that macroporous membranes made from polypropylene could be functionalized via ‘grafting-from’ with MIP layers (cf. 4.3.3), and the resulting composite membranes

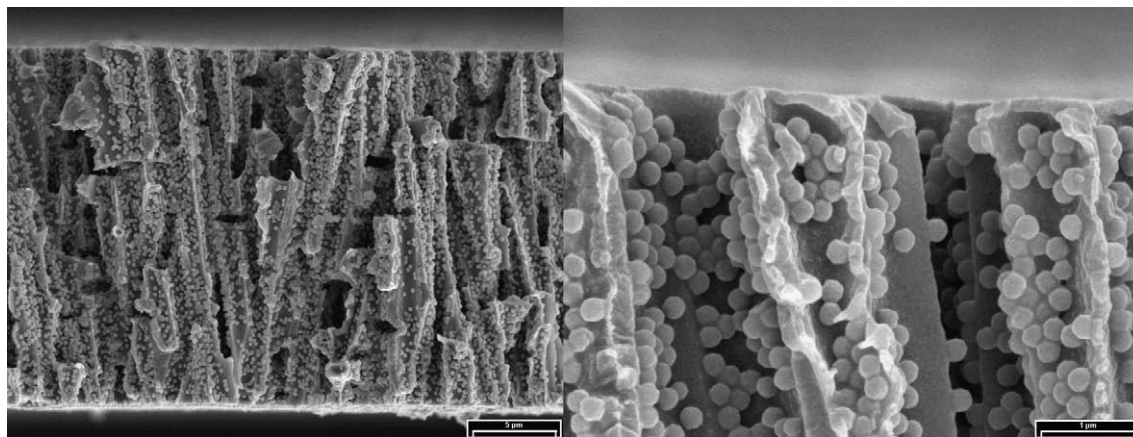


Fig. 22. SEM cross section images of a nanoparticle composite membrane—the base track-etched PET membrane (pore diameter 1  $\mu\text{m}$ ) had been functionalized via ‘grafting-from’ with an amino-functional polyacrylate, and then a mixture of monodisperse epoxide-reactive and inert core-shell nanoparticles (both with diameter 230 nm) had been filtered into the membrane, allowed sufficient time for coupling of epoxide to amino groups, and finally the membrane had been washed extensively (cf. [340]).

had been characterized as substance-specific membrane adsorbers. Two different types of photoinitiators had been used. With coated benzophenone (cf. Fig. 18(c)), a photo-initiated cross-linking graft copolymerization yielded very thin MIP films which were covalently anchored and covered the entire surface of the base membrane [234]. Using the  $\alpha$ -scission photoinitiator benzoin ether (cf. Fig. 18(b)), an imprinting effect could only be detected when this initiator had been coated to the surface, and not for the identical reaction mixtures containing the dissolved benzoin ether [341]. The main preconditions to obtain thin and imprinted layers are a surface-selective initiation (i.e. higher rates of crosslinking polymerization at the surface of the base material than in the bulk of the reaction mixture), and a relatively low overall monomer conversion (so that the thickness of the MIP layer is controlled by the interface reaction) [142,234,342–344]. Based on the results of surface and pore analyses, thicknesses of MIP layers with the highest affinity and selectivity were below 10 nm [142]. Moreover, it had been discovered that a previously prepared thin hydrophilic layer on the support membrane can have two functions [342], (i) matrix for the crosslinking polymerization and limiting monomer conversion to ‘filling’ the layer thus forming an interpenetrating polymer network, (ii) minimizing non-specific binding. A superior MIP composite membrane performance, especially a high template specificity, could be achieved using this advanced composite structure.

*Responsive or switchable membranes.* Using tailored grafted functional polymer layers on the pore walls of membranes, it is possible to reversibly change the permeability and/or selectivity. The most straightforward mechanism is the alteration of the effective pore diameter by changing the conformation of a grafted polymer via solution conditions as ‘stimulus’. The work on ‘smart (hydrogel) polymers’ had influenced these studies [345–349].<sup>13</sup> Later, the better

fundamental understanding of the properties of polymer brushes [183] had also contributed. With porous membranes as base material, reversible switching of permeability had been achieved using grafted pH responsive—(polyacrylic acid or polymethacrylic acid) [350,351]—temperature responsive—polyNIPAAm [352–355]—or other polymers. Combined stimuli, for example pH and temperature, to switch membrane permeability had also been investigated [356]. Stimuli-responsive membranes can also be obtained via membrane formation from copolymers which form phase separated and porous morphologies [100–103] (cf. 4.2.2). An overview on this topic can be found in a recent review [357].

For the function of such responsive membranes, the defined anchoring of grafted polymer chains or crosslinked polymer systems to the pore wall is most important. However, when using established membranes (with well-known pore structure), this may be complicated. For the polymerization, conventional radical methods have distinct advantages, but the control of the reaction in the pores may be difficult. With polypropylene (PP) membranes and benzophenone (BP) as photoinitiator, it had been demonstrated that a simple preadsorption of the BP on the PP surface can increase the surface selectivity of the ‘grafting-from’ reaction using the conventional radical method; the big advantage is that no special pre-modification of the base membrane is necessary ([229]; cf. 4.3.3). With acrylic acid (AA) as functional monomer, this had been directly correlated with the reversible change of permeability as a function of pH: PAA-grafted PP membranes via selective photoinitiation had the highest ‘switching ratio’ compared to other membranes reported before [229]. For similar membranes prepared via the ‘photoinitiator entrapping’—again using the combination of PP, BP and AA—a significantly higher ‘switching ratio’ than for the membranes prepared via photoinitiator adsorption only had been observed [232].

The results of a detailed investigation of ‘grafting-from’ reactions, initiated by BP derivatives, on track-etched membranes had further emphasized the large effect of the type

<sup>13</sup> Polymeric hydrogels, including stimuli-responsive materials, for applications in controlled release are also often designed as membrane systems; this work will not be included here.

of (reversible) photoinitiator immobilization in the pore wall: ion-exchange between photoinitiator and surface functional groups had been more efficient than simple adsorption ([194], cf. 4.3.3-Fig. 17). This had been mainly deduced from permeability measurements as function of pH. These investigations had been extended to other grafted polymers, and by applying trans-membrane streaming potential measurements as additional characterization method: The interplay of base membrane surface charge, functional group density in the polymer layer and thickness of this polymer layer—all as function of pH, ionic strength and temperature—had been elucidated [358]. In conclusion, the effects of grafted polymer and solution conditions onto membrane permeability and streaming potential can be used for a detailed investigation of grafted polymer layers. With isoporous base membranes the effective layer thickness and the zeta potential can be estimated. On the other hand, preparations of grafted layers on porous membranes, with the aim to introduce additional functionalities (e.g. affinity in three-dimensional layers) can be evaluated by using stimuli-responsive membrane permeability—depending on the context, such an environment-responsivity may be a detrimental or beneficial effect (cf. 5.5).

More sophisticated response mechanisms are based on triggering the effects of molecular recognition via tailored macromolecular structures in porous membranes. Early work had been performed mainly by Japanese groups (cf., e.g. [359–362]). Yamaguchi et al. had developed an ‘ion gating’ membrane, based on the surface modification of a polyethylene MF membrane with a grafted copolymer of NIPAAm and crownether-functionalized acrylamide ([363,364], Fig. 23). The response mechanism of this membrane had been clarified based on the understanding of the phase transitions and lower critical solution temperature of the functional copolymer in the presence or absence of ions with high affinity for the crownether ‘receptors’ [365].

A molecule-responsive ‘gate’ membrane had been prepared via surface functionalization of the skin layer pores of a commercial cellulosic dialysis (UF) membrane with a hydrophilic molecularly imprinted polymer (MIP); the diffusion permeability of this membrane increased significantly when the template (theophyllin) had been added while other similar molecules gave no or less effects [366,367]. However, the mechanism of this reversible ‘gating’ effect is not fully clear yet.

## 5. Performance of advanced functional polymer membranes

The performance criteria for advanced membranes will obviously depend on the state of development and technical implementation of the respective membrane process. For established membrane processes (cf. 5.1 and 5.2) one must distinguish between requirements for improved performance of an already established separation—e.g. in terms of the flux/selectivity relationship or the fouling problem (cf. 5.3)—and the need for a really novel solution because current membranes will not be suited for a certain separation. Here, an

advanced membrane which should be interesting not only for the scientific community, must immediately compete with existing materials, especially in terms of the manufacturing technology (fit to established processes) and the separation-related performance criteria (especially stability). For emerging or completely novel membrane processes, the potential of membrane technology—including the ‘tool box’ by combining various barrier types with different driving forces (cf. Table 1)—will be explored in order to solve problems which may not be solved with other technologies (cf. 5.4–5.8). Here, there are more opportunities for a wide range of research activities.

### 5.1. Improved selectivity and permeability for nonporous barriers

Membrane separations based on non-porous or microporous barriers are the largest and most promising area for material’s development by the synthesis of novel polymers. Irrespective the enormous development of microporous inorganic membranes (for a review cf. [368]), the subtle fine tuning of barrier properties which is required for a wide range of molecule-selective separations seems to be possible only with organic (polymeric) structures.

#### 5.1.1. Gas separation

GS with membranes is established in large scale for selected processes such as the separation of oxygen and nitrogen, hydrogen and nitrogen, or carbon dioxide and methane. Nevertheless, GS had not yet been implemented in the large scales envisioned a decade ago. Active research and development is still devoted to the removal of carbon dioxide from various streams. Other important separations are the conditioning of natural gas or the purification of process gases. The separation of (organic) vapors, for the recovery for valuable material or for the removal of undesired components, is another opportunity.

Both anisotropic and composite membranes are used (cf. Table 2), and the key problems are related to the selectivity/permeability ratio and the stability under process conditions (plastification, swelling, temperature). For improving the selectivity for permanent gases at competitive fluxes (with the pair oxygen/nitrogen as a standard), the development of rigid polymers with barrier properties similar to molecular sieves is in progress (cf. 4.2.1). For such special polymers, which may have high cost, the manufacturing of thin film composite membranes, i.e. processing of the polymer from solutions, should be possible (cf. 4.5.1). Another strategy is the crosslinking of the selective polymer, which could also be implemented into existing manufacturing processes via an efficient post-treatment step, e.g. by UV-irradiation. This latter strategy would also provide options for the separation of gases which strongly interact with the polymer (e.g. carbon dioxide) or of organic vapours.

#### 5.1.2. Reverse osmosis

RO is well established for various kinds of water purification; the largest current applications are desalination for drinking and process water, and fine purification, especially



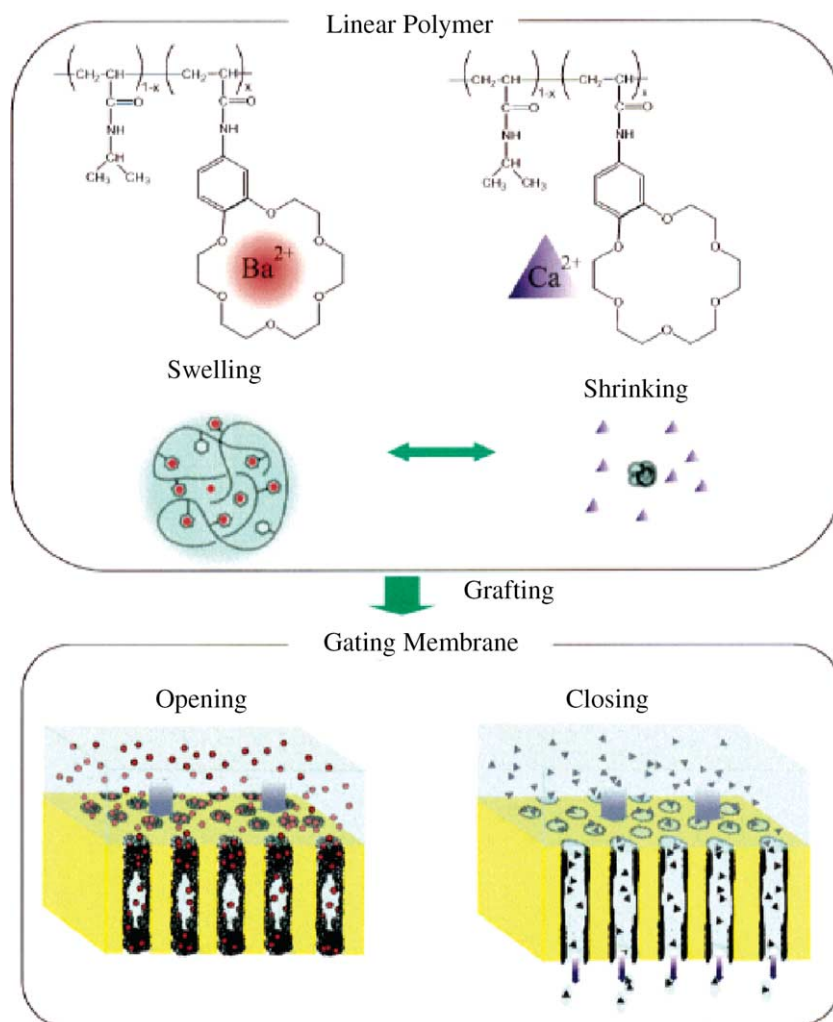


Fig. 23. A molecular recognition ion gating membrane, based on the surface modification of a polyethylene microfiltration membrane with a grafted copolymer of NIPAAm and crownether-functionalized acrylamide (reprinted, with a slight modification, with permission from [365]. Copyright (2004) American Chemical Society).

for the microelectronics and medical industries. Potential novel applications range from the fine purification of more complex aqueous streams (e.g. the removal of toxins from drinking water) to a fractionation of molecules with relatively low molecular weight. For future applications with non-aqueous media the material requirements are similar to the ones for NF and PV membranes (cf. 5.1.3 and 5.1.4).

Both anisotropic and composite membranes are used (cf. Table 2). Currently, the price for RO membranes is so low that completely novel polymers (for integrally anisotropic membranes) would only be attractive if they could be cheaper (as compared to cellulose acetate), and if they would fit without major adaptations into existing manufacturing technologies. The latter would also be true for alternative in situ polymerized polymers as barriers in TFC membranes. If novel membrane separations (e.g. in non-aqueous media) would be technically and economical feasible (e.g. due to the value of the product), membranes based on novel membranes or manufacturing technologies could be acceptable. One straightforward approach towards non-aqueous separations is to explore the resistance and performance of established RO membranes, and

the necessary increase of stability may be achieved by a chemical crosslinking.

### 5.1.3. Nanofiltration

NF had become a well accepted individual membrane separation process between RO and UF. In the last decade, some very successful large-scale processes had been technically established, mainly in the water treatment. The currently largest installation of a NF system is successfully used for the purification of drinking water for Paris, in particular for removing pesticides and other harmful substances [369]. Applications in other industries are devoted to the cleaning of process water. The development of solvent-resistant NF membranes for the treatment of organic streams is a very attractive objective. One of the pioneering large scale SRNF applications is the MAX-DEWAX<sup>®</sup> process for the recovery of the solvent (a mixture of methyl ethyl ketone and toluene) from lube oil filtrates, using special polyimide membranes ([70]; cf. Fig. 6—4.2.1). The success of this process had largely facilitated research activities. Other important applications of

such size-based ‘filtration’ separations include the retention or recycling of valuable homogenous catalysts ([66,370]; cf. 5.6).

Trends in membrane development are the adaptation of existing RO TFC membranes to NF for aqueous applications. In particular, charged membranes with a ‘loose’ polymer structure will enable separations of ions enhanced by Donnan exclusion [371]. Existing RO and NF membranes are also evaluated in selected processes with organic streams [372]. For more aggressive solvents, the material’s requirements are very critical, and the research along the guidelines discussed earlier (cf. 4.2.1 and 4.5) will ultimately lead to suited novel membranes. For example, the NF pore-filled composite membranes ([321,322]; cf. 4.5.2) may be commercialized soon. TFC membranes prepared via the LBL technology ([259,302]; cf. 4.5.1) will most probably also find attractive applications in the near future.

#### 5.1.4. Pervaporation

Until now, the technical implementation of PV had been below the expectations. Established in relatively small scale is the selective removal of water from organic streams or of relatively unpolar organic components from aqueous solutions [373]. In those cases, a sufficient selectivity can be assured irrespective the polymer swelling by the preferentially sorbed component. Commercial hydrophilic and organophilic TFC membranes are available for those applications. PV had also been successfully tested for the facilitation of (bio)chemical reactions by the removal of a byproduct, e.g. water [374].

Much more complicated is the situation when the separation of different organic substances by PV is concerned [67,373]. This, however, would be required for applications in the petrochemical industry—for example the replacement of or the combination with rectification, especially for the separation of azeotropic mixtures—or in the fine chemicals or biotech industries. The stability problem had been solved quite well with inorganic membranes (cf., e.g. [368]), but the broader application is hindered by the limited range of selectivities and the very high price of these materials. Therefore, polymer development is still a major goal in PV (cf. 4.2.1). Mainly composite membranes, via pore-filling of solvent and temperature stable porous membranes (with a thickness <50  $\mu\text{m}$ ) or as TFC membranes (cf. 4.5), can be envisioned to be implemented into technical processes.

A very promising composite membrane with an extremely thin effective barrier is based on the photo-initiated ‘grafting-from’ functionalization of solvent-stable UF membranes made from polyacrylonitrile, and the reasons for their high performance had been discussed before ([316,318]; cf. 4.5.2). Manufacturing of this membrane had been implemented by a start-up company, and a stable performance of this membrane had been demonstrated in a long-term pilot study for the removal of aromatics from aliphatics: In 18 months of continuous operation in the by-pass of an industrial rectification, flux and selectivity had been fully stable and the benzene content of the product stream had been below 1% [375]. Recently, it had been announced that the desulfurization of benzene could become the first large scale PV process in the petrochemical industry—currently,

a demonstration plant with a capacity of 300 barrel per day is operating successfully, and large scale installations (greater than 10,000 barrels per day) are under consideration [376].

#### 5.1.5. Membranes for fuel-cell systems

Enormous research activities have been devoted in the last decade to the improvement of membranes for fuel-cell systems, with a focus on low-temperature applications (cf. 4.2.1). Various strong consortia steered or lead by industrial partners are developing advanced polymer electrolyte membranes (PEMs). The most successful activities are those focused onto the integration of all essential components of a membrane electrode assembly (MEA), i.e. the separation and the catalytic functions ([377], cf. 5.6). Both, homogeneous and composite membranes are applied in small scale units. Besides the standard PSFA materials such as Nafion, improved PFSA polymer membranes, e.g. from 3M [91], PBI-based membranes, e.g. from Celanese [97], and the Japanese pore-filled polyolefine membranes [314,315] seem to be most the promising advanced materials.

#### 5.2. Improved selectivity and permeability by controlled pore size and porosity

##### 5.2.1. Dialysis and ultrafiltration

D and UF membranes have analogous porous barrier structures. For established materials prepared via the NIPS process, the pore size distribution with diameters in the lowest nanometre range is rather broad (cf. 2.2). Due to the different driving forces for separation in D and UF (cf. Table 1), and much influenced by the early commercialization of hollow-fiber membrane dialyzers, D as now a separate field.

D is mainly applied as hemodialysis for the treatment of patients, what lead to very strict requirements with respect to material’s safety (cf. [3]). For the same reason, significant efforts are devoted to the improvement of biocompatibility of the membranes (cf. 5.4). A more precise filtration is also still a target for membrane improvement; however, the ‘ideal’ selectivity curve of a hemodialysis membrane is still not known based on a fundamental understanding of all critical components to be removed or retained [378]. Recently, the combination of D with selective adsorption had been actively developed, and the integration of useful adsorber functionalities in the membrane can also be achieved [379] (cf. 5.5). Finally, the well-developed D membranes and modules are a comfortable basis for the development of other (novel) membrane technologies, e.g. membrane contactors [380] or enzyme-membrane reactors (5.6).

UF has many very diverse applications, from ‘simple’ concentrations and fractionations to much more refined separations of very complex mixtures in many different industries (food and beverage, chemical and pharmaceutical, biotechnology, medical; for reviews cf. [381,382]). However, in the last few years the commercialization of UF-based separations had been very much facilitated by the large scale applications for process and potable water purification. The growth in the latter market is partially also due to the ongoing ‘redefinition’ of the requirements for pathogen removal or sterile filtration (cf. 5.2.2). In those large

scale water treatment systems, capillary membranes are increasingly used—however, the module design is different from D, the most successful new configurations are submerged fibers where the driving force is generated by creating a lower pressure on the permeate side [383].

One of the remarkable recent achievements with respect to fine separations with UF had been the invention of the high performance tangential flow UF [384]. Based on well-controlled hydrodynamic conditions and transmembrane driving forces, a high selectivity for macromolecules with very similar size could be achieved. Separation selectivity could be further increased by using additional (repulsive) interactions of (at least one of) the solute(s) with the membrane; for this purpose, a surface modification of a commercial cellulose TFC membrane had been developed [385,386] (cf. 4.3).

A more precise sieving would be expected from novel membranes based on different macromolecular architectures, e.g. phase separated block copolymers (cf. 4.2.5). Even when UF membranes with a very narrow pore size distribution seem to be very attractive as the basis for a very sharp separation based on size, more often the selectivity of a membrane under process conditions is changed or even eliminated by membrane fouling (cf. 5.3). On the other hand, fouling is much less critical for UF processes at relatively low driving force, such as D (cf. above).

In addition—similar to the trends in RO and NF (cf. 5.1)—UF membranes which are stable in organic or other aggressive media would be very attractive. Some interesting novel technical membranes based on novel polymer chemistry can be expected (cf. 4.2.1). It should be considered that for UF (and MF), meso- and macroporous inorganic membranes are already a viable (and not too expensive) alternative (cf. [1]). However, stable synthetic polymers should be superior in terms of controlled porosity and more flexible processability (e.g. in the capillary or hollow-fiber format).

### 5.2.2. Towards precise microfiltration

MF is—with the exception of hemodialysis—the largest segment for applications of membrane technologies. Similar to UF, the range of industries is wide (cf. 5.2.1), and the particular requirements of the separation are very diverse (cf. [381,382]). However, with a separation principle similar to filtration, the ‘precision’ is mainly related to the retention or a very high (‘safe’) reduction of certain particles. Once this criterion is fulfilled, the processes will be optimized with respect to flux or throughput/filter service time as performance criteria. Developing special (tailored) pore size distributions over the membrane cross-section by modifications within established manufacturing processes is an option for the development of improved membranes (cf. Fig. 2).

The ‘classical’ application of MF is sterile filtration, and in this context the main criterion is minimizing the risk of a hazardous biological contamination [387]. Hence, typical specifications of MF membranes are based on bacteria retention (‘log reduction’), and typically a cut-off pore diameter of 0.2  $\mu\text{m}$  (determined using *Brevibacterium* dim.) had been considered to be sufficient. However, with the increasing knowledge about the risks related to smaller virus particles, a ‘redefinition’ of these

criteria is underway [388–390].<sup>14</sup> One consequence would be replacing MF by UF in certain applications (cf. 5.2.1). In order to optimize retention properties at the highest possible flux, the differences between traditional MF (isotropic cross-section) and UF membranes (anisotropic cross-section) will vanish when such critical separations will be addressed.

On the other hand, in modern biotechnologies larger bioparticles, e.g. viral vectors or vaccines, become also valuable targets for a separation and purification. Membrane adsorbers had already been recognized to be well suited for these purposes (cf. 5.5). However, it had been shown recently, that a fractionation of different viruses based on their size may also be possible using established commercial MF membranes [391].

For most of the above applications, MF membranes with a regular pore shape and porosity, very narrow pore size distribution and low membrane thickness seem to be very attractive. While inorganic microsieves are already commercially available (cf. 4.1), radically novel polymer membranes could be obtained by advanced manufacturing, e.g. thin isoporous polymeric microfilters by ‘PS $\mu$ M’ ([44,45]; cf. 4.1) or by nanoparticle templated pore formation in thin crosslinked barrier layers ([272–274]; cf. 4.4.1).

### 5.3. Minimized membrane fouling

Membrane fouling is caused by undesired interactions—typically of colloids, e.g. proteins or oil droplets in water—with the membrane material [392–394]. Depending on the process, many substances are potential foulants; and the related mechanisms are still an important research field [395–397]. The consequence is a reduction of membrane performance, either due to the build-up of an additional barrier layer or due to a failure of the barrier, e.g. because the wettability of a porous membrane in a membrane contactor had been increased. Other process conditions have also influence on the extent of fouling. However, the main approach towards minimizing membrane fouling is the prevention of the undesired adsorption or adhesion processes on the surface of the membrane, because this will prevent or, at least, slow down the subsequent accumulation of colloids, e.g. by denaturation and aggregation of proteins. Also, membrane cleaning will be easier. For membranes where the consequences of fouling occur only in the interphase in front of the membrane (RO, NF, UF, PV or membrane contactor), a modification of the outer (frontal) membranes surface will be sufficient. However, MF and partially also UF membranes are often modified on the entire surface because fouling can occur also inside the pore structure (cf. Fig. 16).

Commercial TFC UF membranes with a separation layer made from regenerated cellulose should nowadays be

<sup>14</sup> With the enormous growth of membrane technologies and the resulting need for a refined and complete economical analysis of the performance, novel problems such as the ‘aging’ of membranes (typical life-times for RO, UF or MF membranes in water or other process technologies are 3–5 years) and the related risks which had not yet been addressed in detail become more important as well.

considered the state-of-the-art for low fouling UF membranes; those membranes are widely used in UF steps during the downstream processing of recombinant proteins [303,385]. The need for improvement originates mainly from the limited stability of these membranes under other process conditions.

Mechanically stable polymers as materials for porous membranes (cf. Table 2) are often rather hydrophobic. Therefore, often an effective hydrophilization of the membrane surface will be the primary goal. Grafting reactions of hydrophilic macromolecules can provide an additional sterical shielding of the surface. For several applications, the introduction of charged functional groups may be the first choice. A negative surface charge of the membrane will have a beneficial effect on separations of biological media around neutral pH, because most proteins and cellular components have also a negative charge. ‘Grafting-from’, e.g. via graft copolymerization of acrylic acid [213,224,226], polymer-analogous reactions [190–192] or the surface treatment with plasma [200] can also yield membranes with charged groups on the surface. Nevertheless, in most cases neutral and hydrophilic layers (e.g. similar to cellulose) will be best suited. ‘Grafting-to’ of polyethylene glycol (PEG) to polysulfone yields membrane surfaces, where significant amounts of protein still adsorbed, but the fouling tendency was effectively reduced [209,210]. A more effective strategy is ‘grafting-from’, e.g. of vinyl pyrrolidone, hydroxyethyl methacrylate, acrylamide (cf. Fig. 18), or PEG (meth)acrylates [213,218,227]. Biomimetic polymer layers can also be obtained, e.g. from the zwitterionic monomer methacryloxyethylphosphorylcholin (MPC) having functional side groups derived from the head groups of essential lipids of the cell membrane [398–400]. Further guidelines for the ‘design’ of ‘fouling-resistant’ surface functionalities could be retrieved from model studies using functional self-assembled monolayers on surface plasmon resonance sensors [401,402]. In addition, the internal structure of a functional (and three-dimensional!) polymer layer is also important, because the accessibility for proteins should be minimized. Therefore, an adjusted crosslinking of hydrophilic polymer layers can further reduce the protein fouling tendency [403]. The shielding of the membrane surface towards larger colloidal particles (e.g. oil droplets in water) is also effective with uncrosslinked, hydrophilic and flexible polymer brush layers [225].

Ultimately, a suited combination of grafted layer and membrane barrier structure will be essential. The entire surface of MF membranes is often modified with crosslinked hydrophilic polymer layers (cf. 4.3.4). For UF and RO membranes, however, uncrosslinked grafted polymer layers are better suited, because the additional barrier resistance of the ‘anti-fouling’ layer should be as low as possible. Alternatively, with TFC UF membranes, prepared via coating with a hydrophilic polymer [249,250], via an interfacial reaction [252] or via photo-initiated ‘grafting-from’ of PEG methacrylates [227], a simultaneous adjusting of cut-off and minimizing of fouling could be realized. For example, after the functionalization with a grafted poly (PEG methacrylate), a separation of

proteins according to their size was possible, what had not been the case with the respective unmodified UF membrane [227].

#### 5.4. Optimized biocompatibility

The main biomedical applications of membrane technology are hemodialysis, plasmapheresis and oxygenation (membrane oxygenators are used during open heart surgery) [404,405]. Further membrane processes for blood and plasma fractionation as well as membrane-based cell and tissue culture reactors gain also increasing importance [33,405]. The most general definition for ‘biocompatibility’ of materials—supporting the function of living systems—would consider the complexity of the applications, with the membranes being only one (often, however, an indispensable) component. For the majority of the currently relevant processes the behavior of the membrane in contact with blood is crucial.

Minimizing the nonspecific adsorption of proteins is important in order to preserve the performance of the membrane. Hence, modification strategies, which yield ‘fouling-resistant’ membranes (cf. 5.3) could also serve as the basis for biocompatible membranes. However, additional biological responses to the contact with the membrane system must be considered in many cases [107,404,405]. A surface modification in order to improve the biocompatibility should at least suppress the pathophysiological defense mechanisms, e.g. immuno response and/or complement activation, and at the same time show a minimum cell toxicity.

Advanced modifications enable, therefore, the combination of several functions, ideally via the creation of biomimetic layer structures on the membrane surface:

- shielding (in order to avoid the adsorption and denaturation of proteins via hydrophobic or ionic interactions);
- selective adsorption and stabilization of the conformation of adsorbed proteins;
- covalent immobilization of biomolecules or induction of biomimetic effects via synthetic structures.

‘Grafting-to’ and ‘grafting-from’ syntheses of multifunctional polymer layers are especially suited for those purposes [405]. For membranes in contact with blood, the focus had been onto various variants for the immobilization of heparin, which are also applied technically, especially for membrane oxygenators [404]. Also special ionic structures with an action similar to heparin, or biomimetic phosphorylcholin-functional polymers (e.g. based on MPC) had been applied to improve the blood compatibility of membranes [398,399,404].

The specific capturing or the controlled release of substances are increasingly integrated into biomedical applications. Therefore, strategies for the preparation of membrane adsorbers (cf. 5.5) will be applied also to membranes for (hemo)dialysis or for cell and tissue culture reactors.

An example for an even more advanced biomaterial are membranes for the culture of adherent cells, which

selectively remove dead cells [406]—this function is based on the specific capturing of potassium ions (released upon cell death) changing the conformation of a grafted LCST-copolymer with crownether receptors what had already been used to prepare ion-gating membranes ([365], cf. 4.5.3).

### 5.5. Membrane adsorbers

Separations with membrane adsorbers (membrane chromatography, solid phase extraction) are a very attractive and rapidly growing application field for functional macroporous membranes. Several reviews had dealt with membrane adsorbers; some authors had tried to cover all important aspects from the materials to the process engineering [10,189], others had focused on special membranes [188,337] or on the various applications [407–410]. It should be mentioned that polymeric monoliths—made by a different manufacturing technology but having similar pore morphology (cf. 4.4.2)—compete with macroporous membrane adsorbers in some applications, especially for ultra-fast high-resolution separations [280,281,284].

The key advantages in comparison with conventional porous adsorbers (particles, typically having a diameter of  $\geq 50 \mu\text{m}$  [411,412]) result from the pore structure of the membrane which allows a directional (convective) flow through the majority of the pores. Thus, the characteristic distances (i.e. times) for pore diffusion are drastically reduced. The separation of substances is based on their reversible binding on the functionalized pore walls. Therefore, the internal surface area of the membrane and its accessibility is most important for the (dynamic) binding capacity. Typical specific surface areas of microfiltration membranes are only moderate (for a nominal pore diameter of  $0.2 \mu\text{m}$  between 5 and  $50 \text{m}^2/\text{g}$ ; for larger pore diameters even much smaller). Consequently, the development of high-performance membrane adsorbers should proceed via an independent optimization of pore structure and surface layer functionality, providing a maximum number of binding sites with optimum accessibility. Surface functionalizations of suited porous membranes, mostly MF membranes or macroporous filter media, via ‘grafting-to’ (e.g. [206]) or via ‘grafting-from’ (e.g. [413]) can be efficient approaches. A ‘tentacle’ or ‘brush’ structure of the functional layer can be used for a significant increase of the binding capacity in comparison with binding on the plain pore wall. Finally, the chemistry of the functional layer determines the selectivity of the separation (e.g. metal chelate [414], chiral recognition [126,415] or immunoaffinity [206,413,416]).

It had been emphasized that the particular advantage of the membrane adsorbers as compared with conventional beads is the speed of separation along with relatively low amount of buffer making it especially suited for separation of sensitive biomolecules [412]. These benefits will become critical for separations of large molecules and particles, because the effects of pore diffusion will be much larger than for small molecules. Therefore, novel fast and tailored

separations using macroporous adsorber membranes will mainly focus onto nucleic acids, proteins and other biomacromolecules as well as larger particles such as viruses [417,418]. An typical example for the decontamination of large liquid volumes from very dilute harmful or toxic substances which is already applied in the biotech industry is the ‘polishing’ of products such as recombinant proteins by the removal of contaminants, e.g. DNA or endotoxins.

The first generation of membrane adsorbers, macroporous membranes (cellulose-based—Sartobind<sup>®</sup>, Sartorius [419]; polyethersulfone-based—Mustang<sup>®</sup>, Pall [420]) with functional polymer layers on the pore surface, is commercially available since a decade, and several technical separations in large as well as in analytical scale had been implemented.

Recently, the immobilization of functional polymeric adsorber particles in a porous polymer structure (mixed matrix adsorber membrane), obtained via phase separation of the respective dispersions, had also been explored [421].

An overview on different surface functionalizations—with ion-exchange groups [232], immobilized biomolecule for affinity binding [413] or thin-layer MIP [341,344], all based on an even surface coverage of the entire pore surface of stable macroporous membranes achieved by selective photo-initiation—along with the different modes of separation, determined by the layer functionality—is given in Fig. 24. The ‘tool-box’ for membrane design involves systematic and rational variations of components (base membrane, monomers), compositions (wrt monomer, solvents, etc.) and conditions (photoinitiator, UV time, etc.). Such investigations, supported by detailed studies of the surface chemistry and the related interactions using plane film model systems [403] or of the distribution of binding sites in membranes using confocal fluorescence microscopy [418], will pave the road to the next generation of functional membrane adsorbers.

### 5.6. Catalytically active membranes

The concept of the catalytic membrane reactor (CMR) is focused onto one of the most stimulating visions in reaction engineering, i.e. the integration of reaction and separation [422]. Excellent overviews on this rapidly developing field are available, either covering all types and configurations of CMR [423], or with a particular attention onto biocatalytic membrane reactors [424].

In the simplest type of a CMR, the membrane should only retain the catalyst in the reactor—the membrane is exclusively a barrier. An analysis of continuous reactor operation reveals that the retention of the catalyst should be very close to 100% in order to be economical [424–426]. Here, the true precision of size-based separation using commercially available UF or NF membranes can be a problem (cf. 5.2). One of the commercially most successful examples of such a CMR is the enzyme membrane-reactor (EMR) for the synthesis of chiral amino compounds; the key function of the EMR is the

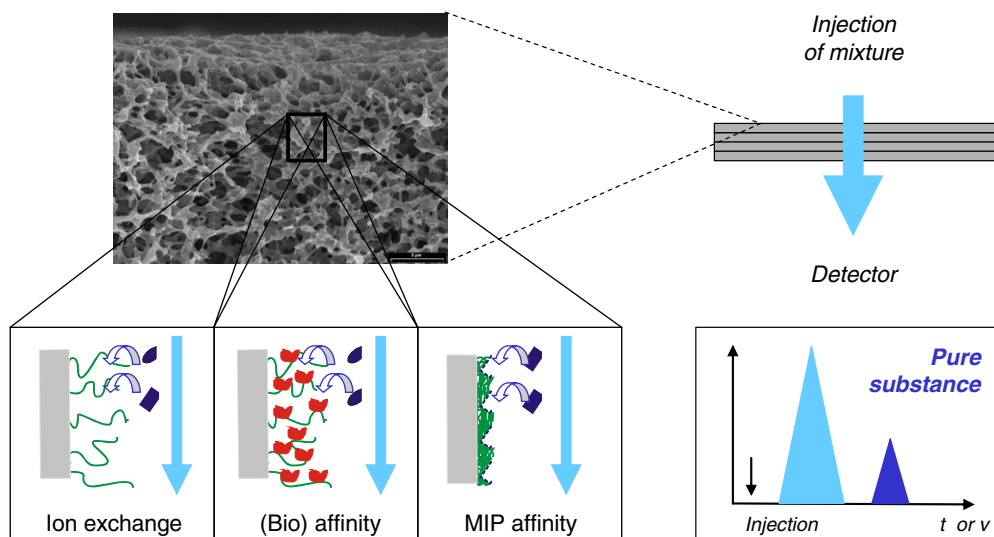


Fig. 24. Different types of membrane adsorbers—the affinity and dynamic binding capacities for certain substances can be ‘tailored’ by surface functionalization of a suited porous base membrane.

continuous regeneration of the cofactor [427]. As outlined above (cf. 5.1.3 and 5.2) membrane separations in organic solvents are even more demanding. In fact, attractive CMR applications have become a main driving force towards the development of novel solvent-resistant and highly selective NF membranes, and some promising examples how to achieve this goal have been reported recently [66,372,428].

Membranes which directly combine catalytic activity with a special barrier structure are of even larger scientific interest. This may be achieved by embedding a catalyst in the membrane or immobilizing it on the surface or in the volume of the membrane pores. In addition, the location relative to the barrier—only ‘upstream’ or ‘downstream’ or evenly distributed through the thickness of the membrane—may facilitate completely different types of reactions [422,423]. In chemical catalysis, reactions in the gas phase require temperature-stable membranes, while for reactions in solution, the solvent stability of the membranes is critical (cf. above). Therefore, today mostly inorganic membranes are used as support for the catalyst for such reactions (cf. [423]). Occasionally polymeric membranes have been used for the immobilization of a catalyst, e.g. for redox reactions of organic substrates. For example, in a partial hydrogenation (the control of the reaction would focus on preventing full conversion), an influence of the residence time—adjusted by the flow rate through the membrane—onto the reaction selectivity and hence product yield could be observed [429]. The catalytic detoxification of aqueous streams is another example [430]. Membranes for fuel cells (cf. 5.1.5) should also be treated as integrated systems, i.e. the combined development of the selective membrane with the catalyst integrated in the membrane reactor system [377,431] is the most promising approach in this very promising, challenging and competitive area.

Much more flexibility with respect to the membrane materials exists for biocatalysis in aqueous media. The

immobilization of biocatalysts on or in membranes can be performed using techniques, which had been established for enzyme immobilization, i.e. enzyme adsorption to the polymer surface, enzyme crosslinking or entrapping, or covalent binding of the enzyme on the polymer surface. With UF membranes based on polyacrylonitrile and the enzyme amyloglucosidase the different possibilities had directly compared [192,432]. For continuous operation, a stronger binding at sufficient activity and accessibility should be preferred. Various other kinds of membrane functionalization had been explored, either via preparation from special polymers [388,433] or via heterogeneous surface modification [192], both in order to introduce reactive groups for covalent coupling of an enzyme. Also, biomimetic functional polymer layers for enzyme immobilization while preserving high bioactivity had also been proposed, examples include a synthetic glycopolymer [434,435] or grafted polyacrylate layers with coimmobilized dextran [436].

Nowadays, UF or D membranes or macroporous membrane adsorbers (cf. 5.5) are available or can be tailored for the immobilization, and the resulting enzyme-membranes can be adapted to the requirements of the particular biotransformation. Nevertheless, this technology is still in its infancy and only a few technical applications have been indicated yet [437–439]. The development of the first larger technical process for a biocatalytic transformation—a two-phase lipase-mediated enantio-selective cleavage of an ester in a hollow-fiber enzyme-membrane reactor—had been well described in detail [440]. In this latter case, the function of the membranes was to stabilize the phase boundary between organic and aqueous phase, and to immobilize the enzyme in the vicinity of this phase boundary. In general, the potential of an enzyme-membrane to influence the course of the reaction also by its barrier selectivity had not often been used until now.

Continuous (bio)catalytic reactions of low-molecular weight substrates leading to macromolecular products are a

particular challenge. The separation of the product from the enzyme (both high-molecular weight) is complicated, and the immobilization of the enzyme in a porous support will very quickly lead to the blocking of the pores by the product. An enzyme-membrane reactor based on surface functionalized track-etched membranes (cf. 4.3.3), with the enzyme covalently immobilized on the pore walls and the option to run the reaction at very high transmembrane flow rates has been demonstrated to lead to significant improvements as compared to all other options for reaction engineering of a continuous enzymatic process (Fig. 25). The synthesis of oligosaccharides of the 1,4- $\alpha$ -glucan type or of the polysaccharide inulin with an exceptionally high molecular weight ( $> 1 \times 10^7$  g/mol), respectively, from the disaccharide sucrose as substrate, had been performed using the covalently immobilized enzymes amylosucrase or fructosyl transferase, respectively, in membranes with pore diameters between 200 and 1000 nm [338,339]. Further improvements of enzyme-membrane reactor productivity had been achieved using nanoparticle composite membranes for enzyme immobilization ([340], cf. Fig. 22—4.5.3).

### 5.7. Membranes in sensor systems

A chemo- or biosensor is a system consisting of a receptor coupled with a transducer to a detector, thus enabling the conversion of a chemical signal—binding to the receptor—into a physical signal. Many technically established sensor systems or sensors in the research lab involve membranes, their structure may be rather diverse but they should fulfill at least one of the following main functions (often, synthetic membranes will combine all these functions):

- barrier between the sensor system and its environment, allowing selective access (e.g. of the analyte only) to the receptor or/and protecting the receptor from disturbing influences of the environment;
- matrix for the immobilization of the receptor or/and tool for bringing it into proximity to the detector—if the transducer

is a separate chemical species, the membrane is also the means to integrate the entire sensing system.

Hence, it becomes clear, that many different membrane principles, barrier structures, transport mechanisms, and hence materials and their processing can be used to develop sensors systems. Special reviews can provide comprehensive insights into this diverse and dynamic field [441]. Several types of advanced functional polymer membranes have already been characterized in sensor set-ups or/and could be considered prototypes for novel sensors, for example molecularly imprinted membranes (cf. 4.4.2) or ion- or molecule-specific stimuli-responsive membranes (cf. 4.5.3).

### 5.8. Membranes in 'lab-on-a-chip' systems

Besides the typical separation functions known from the large scale applications, membranes can have additional features. In the 'micro- or nanoworld', the characteristic dimensions such as membrane thickness or pore size can be similar to the dimensions of the entire (still complex) system. For example, porous membranes can be used as mixers, or an array of pores may be used as flow-through reactor (cf., e.g. Fig. 25) or for separations via differential mobility.

First attempts in that direction had been done by introducing established (commercial) membranes, which are porous, flexible, robust and compatible with plastic microfluidic networks into miniaturized systems. In a recent review by Lee et al. [442], the relevant applications under investigation—microdialysis (cf. 5.2.1), protein digestion with membrane-immobilized proteases (cf. 5.6), and membrane chromatography (cf. 5.5)—were outlined. For example, 'nanoscale' proteolytic enzyme-membrane reactors enabled a significant improvement of protein digestion, peptide separation and protein identification using mass spectrometry at very small sample volumes [443].

Even more sophisticated functions rely on the special structure of commercial track-etched membranes, having nanometre sized pores with a very narrow size distribution and a

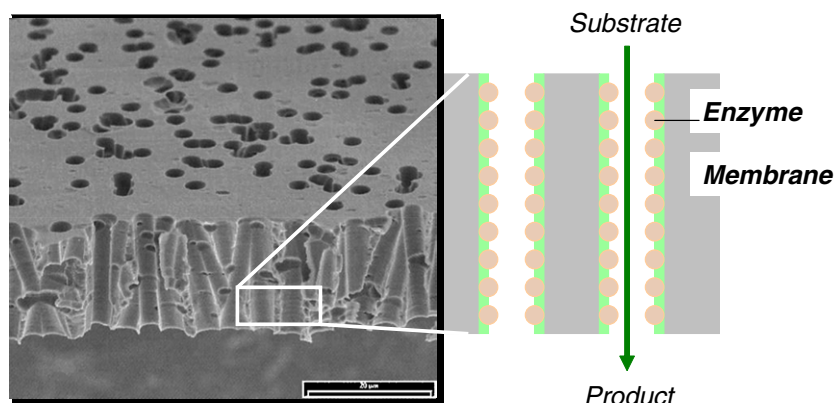


Fig. 25. Flow-through enzyme-membrane reactor (EMR)—the capillary pores of track-etched membranes are especially suited for facilitating enzymatic polymerization reactions.

significant surface charge due to polymer (carboxyl) end-groups. Such membranes have been proposed as gateable nanofluidic interconnects or fraction collectors; the (selective) flow of analytes through the pores can be switched by an electrical potential across the membrane [444,445]. However, a recent study involving time-resolved experiments and a theoretical analysis had emphasized that for such a membrane having a pore diameter around 25 nm, the current densities had been two orders of magnitude lower than usually encountered in micro-fluidic systems with electro-osmotic fluid delivery. That finding may, unfortunately, point to a considerable handicap in the application of nano-fluidic elements in ‘nano-systems’ with electro-osmotic fluid delivery [446].

Lee et al. had already emphasized that the in situ synthesis of tailored membranes in micro-systems will be the logical next step [442]. In fact, both main strategies for the in situ preparation of barrier membranes, interfacial (cf. 4.4.1) and bulk polymerizations (cf. 4.4.2) have been reported in first examples. Hisamoto et al. [447] produced ultrathin nylon membranes in microchips by using interfacial polycondensation at the phase boundary of a bi- or multilayer flow. The function of the membranes was evaluated by measuring the permeation of ammonia and by monitoring substrate conversion after immobilization of the enzyme peroxidase. Song et al. [448] prepared ‘microdialysis’ membranes by in situ UV initiated polymerization—using a focussed 355 nm laser beam—of a zwitterionic monomer with a bisacrylamide. The molecular weight cut-off could be adjusted by the phase separation of the polymer hydrogel via the ratio between solvent (water) vs. non-solvent (2-methoxyethanol) in the reaction mixture. Those membranes could also be used for electrophoretic concentration of proteins in microchips [449].

## 6. Conclusions

From its beginning, the field of membranes had been very interdisciplinary. It involves the inspiration by biology, modeling of membrane transport, chemical synthesis and structure characterization for membrane materials, membrane materials sciences and engineering, membrane formation and modification, membrane characterization, module design, process engineering, integration of membrane processes into industrial processes as well as economical, ecological and safety issues. This ‘cross-fertilization’ had been most fruitful, and a world-wide community of ‘membranologists’ had been established over the last decades. Today, a sound basis for the growth of membrane technology is based on the impressive technical achievements, the acceptance in various industries, and the integration of courses and programs on membranes into the university education. Most important, the membrane industry itself has a profound perspective as it is illustrated by the growth rates, the steadily increasing diversity of applications, and the growing number of technically feasible membrane processes.

With the selective membrane as key element, the contribution of polymer chemistry, physics and engineering to this success had been very important, and the potential

contributions to the further progress of the field are diverse and significant. One important conclusion from the analysis of the activities in different areas outlined in this article is that advanced polymer membranes will often be based on tailored functional macromolecular architectures instead of just ‘bulk polymer’ properties.<sup>15</sup> Examples include the designed packing of chain segments in the solid state creating selectivity by interconnected free volume (cf. 4.2.1), the predetermined regular ‘nanoporous’ morphologies from phase separated block or graft copolymers (cf. 4.2.5), polymeric hydrogels with controlled mesh structure (cf. 4.5.3), micro- or macropore structures created by using templates during membrane synthesis or formation (cf. 4.2.3 or 4.4), functional grafted macromolecular layers to facilitate binding to pore walls or to protect the membrane barrier from unwanted interactions (cf. 4.3 or 5.3), and affinity binding sites in membranes by immobilization through macromolecular linkers or by in situ synthesis via molecular imprinting of polymers (cf. 4.3, 4.5.3 or 5.5).

For membranes which are ultimately intended for large scale applications, it must be kept in mind that the current membrane formation processes via phase separation have already been optimized at large expenses so that one cannot easily deviate very significantly from it without significant economic penalty. On the other hand, the existing processes are quite flexible and still offer considerable room for innovative adaptation. Important roads for that will be blending of polymers with different functions or the design of polymers for an easy and efficient post-treatment [27]. On the other hand, it had been shown, that composite membranes can provide very efficient alternatives because much less of a special polymer will be required and/or the polymer can be protected from the stress imposed by the process conditions (cf. 4.5). The preparation of mixed matrix membranes (cf. 2.2 and 4.5), composed of organic polymers and inorganic fillers, can add another dimension to improving membrane performance.

Advanced membranes of the next generation will have more functions than just being selective barriers with high performance (flux, stability, etc.). The combination of membranes with catalysis is intensively studied and, occasionally, already used in technical scale (cf. 5.6). ‘Smart’ membranes with changing selectivities or adaptive surfaces can be created using approaches currently investigated in research labs. Examples for such stimuli-responsive membranes (cf. 4.5.3) show that a synergistic interplay of pore structure and tailored functional macromolecular systems can be used to create ‘biomimetic’ membranes. When this is realized as a composite membrane, based on an already established (technical) membrane, the novel materials have a strong potential for future applications because they are already partly ‘adapted’ to a technical environment.

<sup>15</sup> Some interesting polymeric materials which can be used for the preparation of membranes with special electrical, magnetic or optical properties had not been covered here.



Ultrathin biomimetic membranes (mimicking cell membranes), such as for example proposed in the early and visionary work of Ringsdorf et al. [450], have not been covered in this article (at least not directly). For example, systems for active transport through the membrane had already been studied—a concept which is far from any technical feasibility. Those scientific activities had in the last decade not been in the focus of the ‘membranologist’s’ community anymore; and the main reason was presumably the success in implementing the state-of-the-art membrane technology in so many industrial processes (cf. above). However, a ‘revival’ of this research, i.e. the development of more sophisticated biomimetic macromolecular membrane systems, is presumably already underway (cf. [451]). This work will also largely facilitate the development of novel advanced and technically viable membranes.

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