

Characteristics of main research directions investigated at the institute and the achievements 2010–2014

Institute	Institute of Macromolecular Chemistry of the CAS, v. v. i.
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Macromolecular science is an interdisciplinary science. The results are typically achieved by combining approaches from different scientific fields and using various complementary experimental methods. The Institute benefits from the wide range of expertise and experimental or theoretical methods gathered under one roof. Going from synthetic chemistry, through physical chemistry of macromolecular systems to polymer physics and material processing on one hand and biochemistry and biology in on the other, one can always find an expert in a particular field to get an advice or highly qualified collaboration on a project.

Research in the institute is focused on five main research directions according to which the formal structure of the institute is also organized:

Supramolecular Systems and Self-association Processes

The research within this direction is focused on the investigation of supramolecular and self-associated polymer systems both in the design and synthesis of polymers exhibiting self-association properties and in the physico-chemical expertise in self-association processes and know-how in the structural characterization of supramolecular systems. Supramolecular organization in polymers ranks among the key issues in modern polymer science, and here it forms a knowledge basis for other research programs of the institute, especially for those directed to nanostructured polymer materials on the one hand and biomacromolecular polymer systems for nanomedicine and diagnostics on the other.

The preparation of materials used for the construction of self-organized systems includes the synthesis of homopolymers, block and graft copolymers on the basis of styrene, 4-vinylpyridine, 2-alkyl-2-oxazoline, (meth)acrylate and (meth)acrylamide derivatives with narrow molar weight distributions and defined polymer chain lengths using anionic, cationic, radical and controlled radical polymerization; preparation of graft copolymers on the basis of glycogen and cellulose derivatives using controlled radical polymerization (reversible-deactivation radical polymerization); preparation of defined organic-inorganic copolymers (nanocomposites) containing polyhedral oligomeric silsesquioxane (POSS) units covalently bonded in a polymer chain; kinetic study of the anionic polymerization of (meth)acrylate esters and of the radical oligomerization of 1-alkenes; synthesis of copolymers with liquid-crystal (LC) blocks for the preparation of thermotropic and photosensitive polymeric materials.

A recently added facility in this area is a radiochemical laboratory for the synthesis and characterization of polymers and polymeric nanoparticles labelled with radioactive atoms. Such systems are used in particular in radiodiagnostics of tumours and are very promising in the associated radiotherapeutic techniques.

Physical and physico-chemical research in this area is oriented to supramolecular structures in systems containing homopolymers, block and statistical copolymers in bulk or in solutions as well as gels and dispersions of polymeric nanoparticles. Special attention is paid to the processes of phase separation, association, complexation and to the creation of micelles, nanoparticles, nanocapsules including self-organization processes on microscopic, mesoscopic and macroscopic levels. We investigate the structure and dynamic properties of various systems as well as the kinetics of structure creation or dissolution such as a) the kinetics and dynamics of polymer systems during phase-separation, intermolecular association,

micellization and complexation, b) processes of self-organization on the molecular level, c) polymers reacting to external stimuli, such as temperature or pH.

Phase-separation on the microscopic and macroscopic levels is important for many technical and medical applications. We study the kinetics of these processes which follow the route to the steady state of the system and the dynamics of these systems influenced by the microscopic motions of its individual components. This mobility often determines the macroscopic properties which are important for applications.

Polymer mixtures are investigated both in bulk and in solution, including solutions in mixed solvents, in dilute or concentrated conditions. The aim is mastering the process of self-organization in polymers and copolymers leading to nanostructured materials for nanotechnology and biomedical applications.

In the following, several examples of outstanding research results obtained in the evaluated period are described. A more comprehensive discussion with literature references is presented in the Appendix 3.5 devoted to the SUPRAMOL center.

Thanks to advances in polymer chemistry and polymer colloids, we succeeded in preparing supramolecular polymeric nanoparticles (NPs) exhibiting unique finely tuned properties for specific applications in nanomedicine. We synthesized new biocompatible pH-triggered block copolymers and biocompatible and biodegradable copolyesters by various techniques to prepare by physicochemical methods *surfactant free* NPs as drug delivery systems. We fully characterized the structural changes of the polymeric carriers resulting from loading and release of hydrophobic drugs. Selective protein fouling on NPs with well-known potential for tumor-targeting drug delivery was evidenced. On the other hand, preparation of NPs resistant to fouling from complex biological fluids is a challenging task in order to avoid protein adsorption and cell adhesion, and consequently the NPs uptake by the reticuloendothelial system. We modified the NP surface either physically by anchoring hydrophilic biocompatible polymers, such as, the multivalent *N*-(2-hydroxypropyl methacrylamide)-based copolymers or chemically by the incorporation of polymer brushes from oligo(ethyleneoxide) methacrylate using surface-initiated atom transfer radical polymerization technique.

In our newly established radionuclide laboratory we developed several unique products consisting of applicable polymers labeled with radioactive atoms. A) We prepared a system based on radiolabeled thermoresponsive polymers for injectable brachytherapy of solid tumors without the necessity of surgical implantation and with the possibility of splitting the dose as necessary into several locations. On a test ensemble of mice a dose-dependent tumor suppression was observed and even complete curing of 2 of 6 mice in the case of the higher radionuclide dose was achieved. B) A model polymer system for the radiotherapy with Auger electron emitters with multilevel targeting was developed. The system uses three steps where the previous step increases the selectivity of the following one: 1. Passive accumulation of the whole system in a tumor by the EPR effect; 2. Active intercalator with an Auger electron emitter is released due to pH drop in an endosome of the tumor cell; 3. The intercalator delivers the radionuclide into DNA in cell nucleus. The concept of the system is directed towards minimization of radiation burden of healthy tissues and allowing diagnostic and therapeutic approach for personalization of care. C) We also developed a ^{125}I -radiolabeled peptide with targeting sequence RGD, allowing binding to scaffolds for tissue engineering, superparamagnetic microparticles, nanodiamonds and water-soluble polymers by "click chemistry" with the possibility of exact radioanalytical determination of concentration in trace amounts.

We synthesized novel thermotropic liquid-crystalline polybutadiene-diols with azobenzene groups in side chains that exhibit a presence of nematic mesophase. Their dynamic mechanical and thermal behavior has proved that the absence of a semi-crystalline structure in the polymer phase behavior allows application of temperature-frequency superposition of elastic and viscous moduli.

Biomacromolecular and Bioanalogous Systems.

This field of research dealing with polymer systems for medicine, better quality of life and biotechnologies is very topical, due to its growing importance and it is attracting a great deal of attention in the professional community. The research is focused on the design and synthesis of highly

hydrophilic and water-soluble polymers, the study of the interaction between synthetic and natural macromolecules, and the study of possible uses of the synthetic polymers, copolymers and their conjugates with natural macromolecules as actively- or passively-targeted carriers of drugs enabling controlled release of the drugs and other biologically active molecules at the place of the required therapeutic effect. The results of the basic research are exploited for the development of polymer nanomedicines and diagnostics, namely in the field of anti-cancer drugs.

New materials are being developed based on the design of polymer biomaterials and functional bio/material interfaces that can be used as supporting structures (scaffolds) for regenerative medicine and tissue engineering, biosensors or devices for the controlled delivery of bioactive compounds. The multidisciplinary activity comprises organic chemistry, physical chemistry of polymers, chemical engineering, biophysics/biochemistry and physiology and it is based on well-balanced chemical/material and biochemical/biological approaches and understanding the mechanisms and events at biomaterial/cell interfaces.

New polymeric materials are tested using physical and chemical methods to determine swelling, mechanical, transport and optical properties, including their biocompatibility and interaction with living tissue. Innovative polymer materials are being developed that facilitate wound healing by removing reactive oxygen and nitrogen species through embedded physiologically bioactive substances with radical-scavenger properties.

Regular spherical polymer composite particles, combining a synthetic or a natural polymer and an inorganic component are developed, in particular magnetic particles, which are recently much in demand. Using a magnet, such particles are easily separated from media containing various heterogeneous components. They are used in biochemistry for isolation of enzymes, proteins and cells, as well as for removal of toxic inorganic ions from waste water. Magnetic components, such as iron oxides (magnetite, maghemite, ferrites), or perovskites, are completely encapsulated by polymers to avoid adverse interactions. Surface-modified magnetic nanoparticles for cell labeling and 3-D scaffold for cell cultures are being developed. For separation purposes, polymer composite particles containing chemical functional groups are produced.

In the following, several examples of outstanding research results obtained in the evaluated period are described. A more comprehensive discussion with literature references is presented in the Appendix 3.5 devoted to the BIOMOL center.

The interactions occurring at the interfaces between the biomaterial surfaces and biological environment, e.g., components of body fluids, cells and tissues, are of key importance in applications of polymer biomaterials in medicine and biotechnology. We developed several alternative approaches to control these interactions, either to minimize adverse reactions or to elicit a biologically specific response of the system. Specific properties of modified surfaces were obtained by binding to the surface a molecularly organized layer of hydrophilic polymer chains forming a polymer-brush. To prepare polymer brushes on the surfaces we investigated both grafting-to techniques, based on reactions of functional polymers with reactive groups on the surface, and grafting-from techniques, based on controlled polymerization of hydrophilic monomers initiated by growing centers created on the surface. By combining several physical methods, the kinetics of grafting polymerizations, the chain density and thickness of polymer brushes as well as resulting surface properties of biomaterials coated with molecular layers were characterized. Specific chemical reactions were investigated providing materials and surfaces with selective bio- interactions. In pilot experiments, applications of functional biomaterials in the design of selective biosensors as well as biomimetic scaffolds for regenerative medicine and/or tissue engineering were explored and confirmed.

We have shown that conjugates of *N*-(2-hydroxypropyl)methacrylamide (HPMA) copolymers with cancerostatics exhibit significant anti-cancer activity in vivo and their application for treatment of model tumours in mice often results in complete curing of the mice. Study of biodistribution of the polymer conjugates of drugs showed that selection of a proper size and structure of the polymer results in significant accumulation of the drug delivered by the polymer carrier into a solid tumour. This accumulation strongly depends on molar mass and architecture of the polymer carrier and, together with

dosing of the drug, has a crucial influence on the anti-tumour efficiency of these polymer drugs in vivo. We have also shown that molar mass of the polymer, its structure and architecture influence the process of elimination of the polymer carrier from organism by glomerular filtration. We have found thresholds for kidney elimination of the polymer HPMA-based carriers of a linear or star architecture which enabled us designing the structure of polymer cancerostatics fulfilling the most important requirements for efficient and safe treatment of tumours.

Superparamagnetic iron oxide nanoparticles have been prepared by the precipitation of ferrous and ferric salts by ammonium hydroxide and subsequent oxidation, which was followed by their coating with biocompatible polymers - poly(*N,N*-dimethylacrylamide) and poly(L-lysine) using a new original procedure. The nanoparticles were colloidally stable for a long time and can be applied as new contrast agents for cell labeling. The labeled cells can be transplanted in a damaged tissue of the organism and be noninvasively monitored as to their direction, migration, proliferation, differentiation and a long term fate using magnetic resonance imaging. At a cooperating institution the biocompatibility, utility, and high efficiency of cell labeling by the newly developed nanoparticles have been verified using human mesenchymal stem and spinal precursor cells.

Polymer Materials and Technologies.

Here main attention is paid to: (i) the study of polymer miscibility and interfacial tension in polymer systems, (ii) the study of the effect of reactive and copolymer-based compatibilization on the structure and properties of polymer blends, (iii) the study of the course of polymer crystallization, and (iv) the investigation of the degradation and stabilization of polymer materials. Phase structure of multiphase polymer systems is characterized, including image analysis, evaluation of filler dispersion, qualitative estimation of interfacial adhesion etc. We focus on searching the correlations between morphology and selected end-use properties (tensile properties, micromechanical properties, wear resistance...).

Polymer nanomaterials show excellent properties by comparison with homogeneous polymer systems or classical polymer composites. Nanostructured polymers and polymer nanocomposites are extensively investigated, in particular the organic-inorganic polymer systems. Polymer networks or thermoplastic polymers are used as organic matrices and an inorganic phase of the composites involves various types of nanofillers. Layered silicates, *in situ* formed nanostructures (mainly silica), nanotubes or well-defined nanobuilding blocks are the nanofillers applied in our nanocomposites. Moreover, responsive polymer hydrogels, semi-crystalline polymers, polymer foams and coatings, liquid-crystalline polymers, as well as biodegradable composites are investigated.

In the following, several examples of outstanding research results obtained in the evaluated period are described. A more comprehensive discussion with literature references is presented in the Appendix 3.5 devoted to the MATER center.

High demands on materials properties coming from application of new more efficient technologies result in increasing needs of development of new advanced materials. An important class of materials is represented by composite and nano-composite materials, based on polymer systems involving a nanofiller – a dispersed inorganic phase. We have developed polymer systems with different types of inorganic nanofillers; aggregates of nanosilica particles, defined nanoblocks of oxoclusters of silica (polyhedral oligomeric silsesquioxane, POSS) or tin, as well as layered silicates. Homogeneous dispersion of nanofiller in a polymer is key factor and, at the same time, the main problem in synthesis of nanocomposites. We have employed a new synthetic approach at the sol-gel preparation of epoxy-silica nanocomposites by using ionic liquids (IL). Application of the methylimidazolium IL makes it possible to control the silica structure and to modify the interfacial interaction. We prepared hybrids with different morphologies, well dispersed silica nanodomains and improved mechanical properties. The nanocomposite materials with well-balanced tensile properties were synthesized by combination of IL with the coupling agents to improve interfacial interaction. The system involving IL (1-triethylene glycol monomethyl ether-3-methylimidazolium methansulfonate) in the combination with the coupling agent glycidyoxypropyltrimethoxysilane (GTMS) shows a 6 times higher modulus and tensile strength as well as a 10 times higher toughness with respect to the reference epoxy-silica nanocomposite.

We have prepared also the O-I nanocomposites with controlled molecular architecture, containing well-defined building nanoblocks POSS or tinoxoclusters as nanofillers incorporated into the organic matrix - the epoxy network. The covalently bonded or physically dispersed POSS aggregates reinforce the epoxy matrix. Based on the acquired knowledge of structure-properties relationships we have synthesized the hybrids with improved thermomechanical, antioxidation and electro-dielectric properties. These systems serve as prospective materials for insulators in electrotechnical applications.

We have developed a new recycling process based on chemolysis (chemical recycling) of waste polyurethane (PUR) foams combining suitable high-boiling alcohols (glycols) with microwave heating. During the chemolytic - glycolytic degradation, waste PUR is decomposed into liquid product, recyclate, with functional hydroxyl groups. The product can be used as a raw material for preparation of new PUR materials. The process is suitable for recycling of waste flexible PUR foams from seats of cars, aircrafts, etc., which are collected in authorized centers. Currently known processes of chemical recycling of PUR waste are not economically convenient due to high energy consumption and long reaction time (long product cycle). We found that reaction mixture can be efficiently heated using the low-energy microwave radiation, which enables ca 4 times reduction of the product cycle and ca 6 times reduction of energy cost of the process. Another our technology can adopt waste products of plant oils as chemolytic agents, thus making the technology more economically feasible and environmentally effective. The prepared product can be mainly applied as a raw material in the production of thermo-insulating rigid PUR foams for building industry. The recycling technologies developed in the MATER center have been protected by patents and are already licensed to industrial partners.

Structure and Dynamics of Macromolecules

Here the activity is oriented to various approaches of the analysis of polymer structure and the development of methodology for structural studies, using physical methods as well as mass spectroscopic and chromatographic methods. The focus is on general and fundamental relations between the structures of macromolecular systems and their properties.

Liquid-state and solid-state NMR spectroscopy is devoted to probing the structure and dynamics of a variety of polymer systems. Advanced research is performed in the area of investigation of self- organization of macromolecules: cooperative inter-polymer H-bonds, investigation of self-organization of amphiphilic molecules in water: considerable role of cooperative hydration, NMR investigations of phase transitions in aqueous polymer solutions and gels, development of NMR crystallography for pharmaceutical applications, solid-state NMR study of structure and dynamics of polymer nanocomposites, investigation of structure and stability of aluminosilicate inorganic polymers.

Raman and infrared spectroscopy is applied to the structural analysis of molecules. A knowledge of the molecular structure is correlated with that of the macroscopic properties of the materials thus enabling their better understanding and their prediction. Instrumental equipment of vibrational spectroscopy provides the possibility to analyze a wide range of samples by the modern methods of FTIR and Raman spectroscopy – solutions, polymer blends, solid materials (foils, gels, layers, powders) and composites. In this area activity is mostly focused at molecular modelling, quantum chemical methods, aggregation behaviour of thermoresponsive block co-polymers, cooperative interactions, mobility and interactions in polymer blends, crystallization behaviour and partial order in semi-crystalline polymers, intercalated clays, modified magnetic nanoparticles for medicinal purposes, degradation of polyolefins for medicinal and construction purposes.

Polymer systems often need to be simplified by using separation techniques to allow detailed characterization using chromatographic techniques and mass spectrometry. In this area both the theoretical development of these methods is pursued and their application to practical problems. The objects studied include not only synthetic polymers but also their conjugates with biologically-active agents and various assemblies, if these are stable under the conditions of separation such as nano particles based on polyelectrolyte complexes of DNA, conjugates of poly(ethylene glycol) with special peptides, comb copolymers of polystyrene-poly(*tert*-butyl(meth)acrylate), pseudopolyrotaxane of synthetic polymers and cyclodextrins.

In the field of structural analysis of biomacromolecules protein X-ray crystallography is performed to conduct detailed studies of proteins or protein complexes and ligands and their function as well as in other crystallisable macromolecules. Protein samples are mostly prepared in collaboration with other laboratories. This leads to systematic analysis of interactions between proteins and synthetic polymers utilized in biomedical applications.

In the following, several examples of outstanding research results obtained in the evaluated period are described, a more comprehensive discussion with literature references is presented in the Appendix 3.5 devoted to the STRUCTURE center.

Ethylene oxide–propylene oxide triblock copolymers commercially known as Pluronic or Poloxamers have been of scientific interest in the last two decades for their practical use as nonionic surfactants and potential carriers of less soluble substances but also, from the theoretical point of view, for their remarkable self-association and self-ordering behavior at higher temperatures and/or higher concentrations in water. In this context we have made a considerable breakthrough in understanding of self-aggregation processes of these systems. Formation of a complex hydration shell in vicinity of amphiphilic molecules was confirmed by using NMR and FTIR spectroscopy and ab initio DFT calculation. The central position of the proposed hydration shell is occupied by a single H₂O molecule that forms two hydrogen bonds with the organic molecule in *tg*t conformation. Other molecules are involved in the formation of a large cluster that stabilizes the resulting conformation. The compact structure of the hydrate is warranted by O...H hydrogen bonds, some of them perceptibly tighter than those in the primary hydrate. A significant proportion of unconventional hydrogen bonds in which methyl groups are involved was also confirmed.

Amorphous aluminosilicate inorganic polymers (AIPs) have attracted considerable interest in material engineering and building industry. Undesired crystallization accompanied by the loss of mechanical properties, however, has limited the widespread application of these systems. To clarify this phenomenon, we synthesized two types of chemically identical AIPs that differ in durability under hydrothermal conditions. Whereas phase-stable AIP systems remain amorphous, phase-unstable AIP systems undergo extensive crystallization. The application of ²⁷Al MQ/MAS and {¹H}-REDOR-²⁷Al MQ/MAS NMR spectroscopies, combined with the recently developed biaxial shearing transformations, revealed a two-component character of the prepared AIPs. The prevailing fraction of [AlO₄]⁻ species (amorphous phase) is charge-balanced by Na⁺ counter-ions. In contrast, the minor fraction of [AlO₄]⁻ tetrahedral, which can be attributed to the partially ordered domains of aluminosilicate networks, shows extensive variability in the chemical nature of the counter-ions. A comparison of the prepared AIPs revealed that the partially ordered domains of the phase-unstable AIPs contained a considerably larger amount of [AlO₄]⁻ species charge-balanced by H⁺. The destabilization of AIPs is thus associated with the presence of bridging hydroxyl groups that induce breaking of Si-O-Al bonds. The resulting decrease in network density can induce a temporal release of SiO₄ monomer units, their subsequent rearrangement and the formation of a crystalline phase.

Polymers for Optoelectronic and Energy Applications

Here the research is oriented to optical and/or electrical phenomena in polymers and to advanced materials for energy storage or conversion, relying on the close cooperation of chemists, materials scientists and physicists. Preparation of conducting polymers is investigated, along with optically-active polymers, and utilized in solar cells. Materials for flexible electronics and conducting inks are developed. A creative activity exists in the field of inorganic–organic hybrid materials for energy conversion. Solid- state ionically conductive materials and materials with mixed electronic–ionic conductivity are new classes of conducting materials. Application of conducting polymers in gas separation is investigated and in particular the polymer membrane technology contributes to the construction of fuel cells and to hydrogen chemistry.

Conducting polymers are investigated alone, or as components of composite materials. Oxidative chemical polymerization is the main synthetic tool. Conducting polymers are prepared as powders, which

can have granular or nanotubular morphology. Thin polymer films are deposited on virtually any surface immersed in the reaction mixture. Colloidal dispersions are obtained if a water-soluble polymer stabilizer is present. Hybrid composite particles are produced by the coating of various inorganic materials with conducting polymers. Carbon nanotubes, montmorillonite, silica, or ferrites can serve as examples of the inorganic component.

The morphology-retaining carbonization of conducting polymers, composites of conducting polymers with noble metals, e.g. silver, and the combination of conducting polymers with ionic liquids represent current interests of the team. The produced materials are currently tested in cooperating institutions as semiconductors, analytical electrodes, sensors, flame retardants, catalyst supports in heterogeneous catalysis, in the corrosion protection of metals, in fuel cells, electro-rheology, and gas separation.

In the area of photonics we develop novel polymers and polymer systems for potential applications in photodiodes, solar cells and light-emitting devices (LEDs), further also in memory components, optical storage, sensors etc. Novel conjugated polymers and copolymers with targeted properties are synthesized. Synthetic procedures, such as Suzuki, Yamamoto or Stille coupling, are used; in some cases their modification has been developed. Monomers for polymer syntheses are usually prepared in multistep procedures using common organic synthesis methods.

The polymers are studied in both solutions and thin films using whole series of optical, electrical, photoelectrical, electrochemical and spectro-electrochemical methods. Absorption, reflectivity, photoinduced changes, stationary and time-resolved photo- and electro-luminescence, photoconductivity, charge photogeneration and transport are investigated. The results are exploited to design new polymers or for polymer modification, and also in the study of polymer devices (solar cells, LED). Polymer blends and ordered nano-arrays are studied to modify photophysical and electrical properties of thin films with the aim of increasing device efficiency and performance improvement

In the area of optoelectronics, the research activities are focused on studies of photo- and electro-active polymers and their low-molecular-weight analogues. Physical phenomena, such as electrical conductivity, photoconductivity, photochromism, photorefractivity, electro-luminescence, as well as the injection, generation, recombination, and transport of charge carriers are investigated with respect to their dependence on the chemical structure of the materials. Both p- and s- conjugated polymers are studied. Understanding the processes associated with photon absorption and emission, like photoexcitation, excited state dynamics, photoinduced electron transfer, changes in molecular conformations, dissociation and recombination of ion-pairs enabled us to determine the basic principles of designing organic solar cells. The transport of free charge carriers and polarons are studied on polymer photoconductors and structures of organic FET transistors.

The electronic structure and conformation of molecules are studied also theoretically by *ab initio* and semi-empirical quantum chemical methods. Photostabilization studies are focused on various polymer systems with photoactive impurities like the transformation products of stabilizers or sensitizing dopands and/or photoactive built-in functional moieties. Details of photochemical and photophysical activity mechanisms for various classes of light stabilizers were elucidated to minimize the depleting effects of the photoactive polymeric matrix. Experimental work is supported by theoretical studies and quantum chemical calculations of exciton-phonon coupling and vibrationally-induced energy dissipation.

Innovative membranes are developed for separation techniques and applications in energetics. New polymers, designed for the membrane preparation, are synthesized, new membranes are fabricated and their physicochemical properties are investigated including determination of permeability and diffusivity (in dry or swollen state), kinetics and extent of sorption in membranes, gas pycnometry and membrane ion conductivity. Non-flammable gel electrolytes based on polymerizable ionic liquids are elaborated as our participation in the development of new generation of lithium batteries for automotive industry.

In the following, several examples of outstanding research results obtained in the evaluated period are described. A more comprehensive discussion with literature references is presented in the Appendix 3.5 devoted to the OPTOEL center.

Proton exchange membrane fuel cells with polymer membranes containing sulfonic acid groups are routinely used on a commercial basis. However such fuel cells can only work in the presence of water when the sulfonic acid groups are dissociated and proton-conductive. The automotive industry demands fuel cells operating at temperatures above 150 °C allowing the use of hydrogen produced by reforming alcohol. We developed membranes with ion conductive component that is an ionic liquid. It is well-known that ionic liquids are ion conductive even at elevated temperatures above 100 °C. The membranes conductivities depend on the ionic liquid and polymer type and mainly on the affinity between the ionic liquid and polymer. Only well miscible components showed good properties. Membranes with a high conductivity were tested in a fuel cell at 160 °C. Though the output did not meet yet the requirements for commercial applications, the use of an ionic liquid as the membrane conductive component represents a new principle in the construction of fuel cells.

Based on the studies of the preparation and characterization of conducting polymers, polyaniline in particular, the principles of the formation of nanostructures produced by these polymers have been elucidated. The nanostructures are generated in the course of preparation, i. e. during the oxidation of aniline, and include nanotubes, nanofibers, microspheres, thin film, colloidal particles and various hierarchical structures. All of them have a common origin: aniline oligomers self-organize to various objects, and polyaniline chains grow from them and produce the polymer nanostructure. Nanostructures of conducting polymers are increasingly used for the surface modification of materials, such as supports for noble-metal catalysts as well as in catalysts without metal component. The knowledge and understanding of nanostructures produced by conducting polymers has a fundamental importance in the design of new materials.

New polymers based on the poly(3-hexylthiophene) derivative with cationic imidazolium- side groups were developed that exhibit sensitivity of optical absorption and electrical conductivity to various gases, particularly to the methanol and ethanol vapours and humidity. Moreover, this polymer exhibits mixed electronic (resp. hole) and ionic conductivity and it is soluble in water and other water miscible environmental friendly solvents. The new material was combined with Au and Ag nanoparticles, which led to the increase of gas-sensing properties. This increase was assigned to the strong local electric field developed in the composites due to the plasmonic effects in the metal nanoparticles.

Research Report of the team in the period 2010–2014

Institute	Institute of Macromolecular Chemistry of the CAS, v. v. i.
Scientific team	1 SUPRAMOL

*In references, the names of authors from this Centre are **bold and underlined**, names of other authors from this institute are **bold**.*

Some results listed in this section appear also in the section describing selected results of the Institute.

Result 1

Radionuclide-labeled polymer systems

Radionuclide delivery systems were prepared thanks to a unique facility of the SUPRAMOL Centre, the authorized Laboratory for synthesis of polymers carrying radioactive atoms. These polymers, either in dissolved state or in the form of well-defined micelles or nanoparticles, can transport radioactive atoms in a controlled way to specific sites in living organisms for diagnostic and therapeutic purposes [S27, A28, [ASEP \(ID 359030\)](#), [ASEP \(ID 346570\)](#), [ASEP \(ID 365874\)](#)], which is especially useful especially for tumor-related diseases. We developed a triple targeting approach

allowing tumor-selective delivery of Auger electron emitter-based theranostics into solid tumors. [S20, [ASEP \(ID 360736\)](#), [ASEP \(ID 394937\)](#)] These systems were always fully characterized by physico-chemical methods and their successful biological applications were established by *in vitro* and *in vivo* testing at cooperating institutions.

Another part of work with radionuclides in connection with polymers is the use of radiolabels to track the fate of the polymer system in living organism, e.g., of chelating polymer beads for the treatment of Wilson's disease [A123, [ASEP \(ID 395188\)](#), [ASEP \(ID 431233\)](#)].

Extreme concentration sensitivity of radionuclide techniques allows to determine ultratrace amounts of components even in very complex mixtures, which we find useful for, e.g., determination of content of bioactive peptides on tissue engineering scaffolds [A161, [ASEP \(ID 429250\)](#)] or on modified nanodiamond probes [[ASEP \(ID 429976\)](#)].

Members of the Centre have performed purification of the polymers, radioisotopic labeling of the polymers and all static and dynamic light scattering experiments. Cooperating members from other Centres of the Institute have synthesized the starting monomers. Biological tests have been done with the help of external partners.

S27. **Hrubý, M.**; Poučková, P.; Zadinová, M.; **Kučka, J.**; Lebeda, O. Thermoresponsive polymeric radionuclide delivery system - an injectable brachytherapy. *European Journal of Pharmaceutical Sciences* 2011, 42, 5, p. 484-488. [ASEP \(ID 359030\)](#)

A28. **Hrubý, M.**; **Filippov, S.**; **Pánek, J.**; **Nováková, M.**; **Macková, H.**; **Kučka, J.**; **Ulbrich, K.** Thermoresponsive micelles for radionuclide delivery. *Journal of Controlled Release* 2010, 148, 1, p. e60-e62. [ASEP \(ID 365874\)](#)

S20. **Sedláček, O.**; **Hrubý, M.**; **Studenovský, M.**; **Kučka, J.**; Větvička, D.; Kovář, L.; Říhová, B.; **Ulbrich, K.** Ellipticine-aimed polymer-conjugated Auger electron emitter: multistage organelle targeting approach. *Bioconjugate Chemistry* 2011, 22, 6, p. 1194-1201. [ASEP \(ID 360736\)](#)

A123. **Škodová, M.**; **Kučka, J.**; **Vetrík, M.**; **Skopal, J.**; **Walterová, Z.**; **Sedláček, O.**; **Štěpánek, P.**; **Mattová, J.**; **Poučková, P.**; **Urbánek, P.**; **Hrubý, M.** Chelating polymeric particles intended for the therapy of Wilson's disease. *Reactive and Functional Polymers* 2013, 73, 11, p. 1426-1431. [ASEP \(ID 395188\)](#)

A161. **Popelka, Š.**; **Houska, M.**; **Havlíková, J.**; **Proks, V.**; **Kučka, J.**; **Štuncová, A.**; **Bačáková, L.**; **Rypáček, F.** Poly(ethylene oxide) brushes prepared by the "grafting to" method as a platform for the assessment of cell receptor-ligand binding. *European Polymer Journal* 2014, 58, p. 11-22. [ASEP \(ID 429250\)](#)

Result 2

Thermoresponsive nanoparticles

Several types of novel nanoparticles were prepared using the thermoresponsive properties of certain poly(2-alkyl-2-oxazolines). A new group of nanostructured hybrid dendrimeric stimuli-responsive polymers was designed and synthesized that connects the body's own biodegradable polysaccharidic dendrimer glycogen with the widely tuneable thermoresponsive behavior of polypeptide-analogic poly(2-alkyl-2-oxazolines), which are known to be biocompatible. Glycogen-graft-poly(2-alkyl-2-oxazolines) were prepared by a simple one-pot two-step procedure. As confirmed by light and X-ray scattering, as well as cryo-transmission electron microscopy, the grafted dendrimer structure allows easy adjustment of the cloud point temperature and nanostructure of the self-assembled phase separated polymer [A180, [ASEP \(ID 435100\)](#)]. Thermoresponsive nanoparticles based on statistical poly(2-isopropyl-2-oxazoline-co-2-butyl-2-oxazolines) and the biocompatible surfactant Pluronic F127 were prepared, modified for labelling [S14, [ASEP \(ID 381219\)](#)] and fully characterized by scattering techniques [S11, [ASEP \(ID 399157\)](#)]. Relation of the structural parameters to the properties of the constituting polymers was described, in particular the molar mass

and hydrophobicity of the polymer do not influence the final particle structure

A180. **Pospíšilová, A.; Filippov, S.; Bogomolova, A.; Turner, S.; Sedláček, O.; Matushkin, N.; Černochová, Z.; Štěpánek, P.; Hrubý, M.** Glycogen-graft-poly(2-alkyl-2-oxazolines) - the new versatile biopolymer-based thermoresponsive macromolecular toolbox. *RSC Advances* 2014, 4, 106, p. 61580-61588 [ASEP \(ID 435100\)](#)

S11. **Bogomolova, A.; Hrubý, M.; Pánek, J.; Rabyk, M.; Turner, S.; Bals, S.; Steinhart, M.; Zhigunov, A.; Sedláček, O.; Štěpánek, P.; Filippov, S.** Small-angle X-ray scattering and light scattering study of hybrid nanoparticles composed of thermoresponsive triblock copolymer F127 and thermoresponsive statistical polyoxazolines with hydrophobic moieties. *Journal of Applied Crystallography* 2013, 46, 6, p. 1690-1698 [ASEP \(ID 399157\)](#)

S14. **Pánek, J.; Filippov, S.; Hrubý, M.; Rabyk, M.; Bogomolova, A.; Kučka, J.; Štěpánek, P.** Thermoresponsive nanoparticles based on poly(2-alkyl-2-oxazolines) and pluronic F127. *Macromolecular Rapid Communications* 2012, 33, 19, p. 1683-1689 [ASEP \(ID 381219\)](#)

Result 3

pH sensitive drug delivery systems

Members of the Centre have performed kinetic studies of the pH sensitive polymers after pH jump by SAXS and SANS experiments on a system of amphiphilic N-(2-hydroxypropyl) methacrylamide (HPMA)-based copolymers bearing the anticancer drug doxorubicin. Hydrophobicity was varied by a variable content of cholesterol. We found the important result that doxorubicin is not impregnated inside a cholesterol core but are instead uniformly distributed across the whole nanoparticle, including the hydrophilic HPMA shell surface.

Cooperating members from other Centers of the Institute have synthesized the polymers. Experiments have been done on external large-scale facilities – synchrotrons and reactors. We developed 3D structure of a nanoparticles before and after pH jump and traced its fate in time [S9, S13, [ASEP \(ID 398411\)](#), [ASEP \(ID 379698\)](#)1,2]. The distribution of all entities – doxorubicin and cholesterol in the nanoparticles was established.

The behavior of pH-responsive polymers poly(N-methacryloyl-L-valine), poly(N-methacryloyl-L-phenylalanine), and poly(N-methacryloylglycine-L-leucine) has been studied in the presence of the nonionic surfactants. The pure polymers phase-separate in an acidic medium. The addition of the surfactant prevents phase separation and promotes reorganization of polymer molecules. The nature of the interaction between polymer and surfactant depends on the amino acid structure in the side chain of the polymer. These results may help in the design of new pH-responsive site-specific micellar drug delivery systems or pH-responsive membrane-disrupting agents. [A175, [ASEP \(ID 432165\)](#)]

S9. **Filippov, S.; Franklin, J. M.; Konarev, P. V.; Chytil, P.; Etrych, T.; Bogomolova, A.; Dyakonova, M.; Papadakis, C. M.; Radulescu, A.; Ulbrich, K.; Štěpánek, P.; Svergun, D. I.** Hydrolytically degradable polymer micelles for drug delivery: a SAXS/SANS kinetic study. *Biomacromolecules* 2013, 14, 11, p. 4061-4070 [ASEP \(ID 398411\)](#)

S13. **Filippov, S.; Chytil, P.; Konarev, P. V.; Dyakonova, M.; Papadakis, C. M.; Zhigunov, A.; Pleštil, J.; Štěpánek, P.; Etrych, T.; Ulbrich, K.; Svergun, D. I.** Macromolecular HPMA-based nanoparticles with cholesterol for solid-tumor targeting: detailed study of the inner structure of a highly efficient drug delivery system. *Biomacromolecules* 2012, 13, 8, p. 2594-2604 [ASEP \(ID 379698\)](#)

A175. **Bogomolova, A.; Keller, S.; Klingler, J.; Sedlak, M.; Rak, D.; Štuncová, A.; Hrubý, M.; Štěpánek, P.; Filippov, S.** Self-assembly thermodynamics of pH-responsive amino-acid-based polymers with a nonionic surfactant. *Langmuir* 2014, 30, 38, p. 11307-11318 [ASEP \(ID 432165\)](#)

Result 4

External stimuli sensitive triblock copolymers with complex structure and their interactions with surfactants.

External stimuli sensitive triblock copolymers with complex structure based on poly(2-alkyl-2-oxazoline)s were synthesized in the SUPRAMOL Centre. Such copolymers are more complex than conventional copolymers, they are sensitive to multiple stimuli since they bear hydrophobic and thermosensitive moieties [[ASEP \(ID 427980\)](#), [ASEP \(ID 399157\)](#), 2-3]. These systems were fully characterized by a variety of physico-chemical methods – DLS, SAXS, SANS, ITC. Additional control over self-assembly of such copolymers was tested. It was proven that the presence of low-molecular or polymeric surfactant can additionally bring a new way to create hybrid nanoparticles with required properties [S5, S11, [ASEP \(ID 427980\)](#), [ASEP \(ID 399157\)](#)]. Such systems were characterized in great details from thermodynamic point of view [S5, [ASEP \(ID 432165\)](#), [ASEP \(ID 427980\)](#)].

S5. **Bogomolova, A.; Filippov, S.; Starovoytova, L.; Angelov, B.;** Konarev, P.; **Sedláček, O.; Hrubý, M.; Štěpánek, P.** Study of complex thermosensitive amphiphilic polyoxazolines and their interaction with ionic surfactants. Are hydrophobic, thermosensitive, and hydrophilic moieties equally important? *Journal of Physical Chemistry B* 2014, 118, 18, p. 4940-4950 [ASEP \(ID 427980\)](#)

S11. **Bogomolova, A.; Hrubý, M.; Pánek, J.; Rabyk, M.;** Turner, S.; Bals, S.; **Steinhart, M.; Zhigunov, A.; Sedláček, O.; Štěpánek, P.; Filippov, S.** Small-angle X-ray scattering and light scattering study of hybrid nanoparticles composed of thermoresponsive triblock copolymer F127 and thermoresponsive statistical polyoxazolines with hydrophobic moieties. *Journal of Applied Crystallography* 2013, 46, 6, p. 1690-1698 [ASEP \(ID 399157\)](#)

Result 5

Stealth responsive polymer nanoparticles as drug-delivery systems

Stealth (non-specific protein adsorption from complex biological medium) responsive polymers to temperature (thermo-responsive) or pH (pH-responsive) were prepared as biodegradable/biocompatible drug-delivery systems targeting respectively, the elevated temperature (~ 39 – 42 °C) or the slightly lower pH (~ 6.5 – 7.2) of solid tumors. Through the synthesized polymers core-shell nanoparticles (NPs) systems were obtained by the self-assembly of the novel tri-block or diblock copolymers [S3, [ASEP \(ID 428455\)](#), [ASEP \(ID 364286\)](#)]. The NPs full characterization through refined scattering techniques as static (SLS), dynamic (DLS) and electrophoretic (ELS) light scattering, as well as, small angle X-ray scattering (SAXS) techniques were reported [S3 [ASEP \(ID 428455\)](#), [ASEP \(ID 364286\)](#)]. The assembly under simulated physiological conditions (phosphate buffer pH 7.4) and the disassembly under pH simulated cytosolic or extracellular (pH-responsive polymers) tumor conditions (pH 6.5- 7.2), as well as, a temperature-induced aggregation driven by hydrogen bonding (~ 56 - 60 °C) (thermo-responsive polymer) were documented.

Following the studies aiming the preparation of drug-delivery systems, non-specific protein adsorption from complex biological media, especially from blood plasma, is an urgent challenge for the application of the NPs. Thus, the evaluation of the interaction of the NPs systems after contact with complex biological media is of extreme importance. Several techniques were employed, such as, DLS, SLS and ELS, as well as, isothermal titration calorimetry (ITC), circular dichroism (CD) spectroscopy and surface plasmon resonance (SPR). Their successful biological interaction was followed by these techniques [A78, A31, [ASEP \(ID 378727\)](#), [ASEP \(ID 431000\)](#), [ASEP \(ID 357473\)](#)].

The members of our research team were responsible for the synthesis and the full characterization of the polymers utilized to the self-assembled systems, the full characterization of the NPs and all the tests realized in the paper with the unique exception of the in vitro cell

experiments. Cooperating members from other institutions have performed the ITC and CD experiments.

S3. **Petrova, S.; Jäger, E.; Konefal, R.; Jäger, A.; Venturini, C. G.; Spěváček, J.; Pavlova, E.; Štěpánek, P.** Novel poly(ethylene oxide monomethyl ether)-*b*-poly(ε-caprolactone) diblock copolymers containing a pH-acid labile ketal group as a block linkage. *Polymer Chemistry* 2014, 5, 12, p. 3884-3893 [ASEP \(ID 428455\)](#)

A78. Giacomelli, F. C.; **Štěpánek, P.**; Schmidt, V.; **Jäger, E.; Jäger, A.**; Giacomelli, C. Light scattering evidence of selective protein fouling on biocompatible block copolymer micelles. *Nanoscale* 2012, 4, 15, p. 4504-4514 [ASEP \(ID 378727\)](#)

A31. **Rodriguez-Emmenegger, C.; Jäger, A.; Jäger, E.; Štěpánek, P.**; Alles, A. B.; Guterres, S. S.; Pohlmann, A. R.; **Brynda, E.** Polymeric nanocapsules ultra stable in complex biological media, *Colloids and Surfaces B: Biointerfaces* 2011, 83, 2, p. 376-381 [ASEP \(ID 357473\)](#)

Result 6

Biocompatible and biodegradable polymer nanoparticles for biomedical applications

Novel biocompatible and biodegradable copolyester nanoparticles based on monomers derived from renewable sources were successfully prepared and fully characterized [S17, [ASEP \(ID 376067\)](#)]. The NPs were able to encapsulate between 3 to 5 times more the hydrophobic chemotherapeutic drug (Paclitaxel) in comparison to their FDA-approved counterparts PLA and PLGA. It was found that the NPs are water swollen and their inner structure changes under effect of the drug encapsulation. The degradability (about 8 weeks) and the absence of cell toxicity make this new polyester NPs a promising tool for biomedical applications. In order to control the polyester NPs size and size distribution, fundamental physicochemical studies were done allowing fine-tuning the particles sizes from 20 to 200 nm [[ASEP \(ID 399466\)](#)] targeting the tumor microenvironment and their leaky and fenestrated characteristics allowing the accumulation of macromolecules (EPR phenomena). Latter one, the NPs were cover with a biocompatible hydrophilic polymer with the aim of the preparation of long circulating drug-delivery systems with stealth properties. The influence of the hydrophilic polymer coverage on particles inner structure, fouling properties and *in vitro* cytotoxicity were accessed by several techniques [S17, [ASEP \(ID 379960\)](#), [ASEP \(ID 357473\)](#)]. Optimal stealth properties and drug encapsulation efficiency were achieved after optimization of the NPs surface coverage with the hydrophilic polymer [S18, [ASEP \(ID 379960\)](#)]. The optimized system was, by a simple way, simultaneously loaded with docetaxel and doxorubicin chemotherapeutics providing a more efficient suppression of tumor-cell growth and animal survivor as proved *in vivo* by using mice bearing EL-4 T cell lymphoma when compared to the effect of nanoparticles loaded with single drugs [S7 [ASEP \(ID 385103\)](#)].

Members of the SUPRAMOL team have performed synthesis and purification of the polymers and all static and dynamic light scattering and small angle x-ray experiments. Biological tests have been done with the help of external partners.

S17. **Jäger, E.; Jäger, A.; Etrych, T.**; Giacomelli, F. C.; **Chytil, P.; Jigounov, A.**; Putaux, J.-L.; Říhová, B.; **Ulbrich, K.; Štěpánek, P.** Self-assembly of biodegradable copolyester and reactive HPMA-based polymers into nanoparticles as an alternative stealth drug delivery system. *Soft Matter* 2012, 8, 37, p. 9563-9575. [ASEP \(ID 379960\)](#)

S7. **Jäger, E.; Jäger, A.; Chytil, P.; Etrych, T.**; Říhová, B.; Giacomelli, F.; **Štěpánek, P.; Ulbrich, K.** Combination chemotherapy using core-shell nanoparticles through the self-assembly of HPMA-based copolymers and degradable polyester. *Journal of Controlled Release* 2013, 165, p. 153-161. [ASEP \(ID 385103\)](#)

Result 7

Biocompatible and biodegradable acid-labile block copolymers.

A new class of biocompatible and biodegradable acid-labile PEO-*b*-PCL diblock copolymers containing ketal groups as block linkers was obtained with a view to their potential application as pH-triggered release and drug-delivery systems. The synthesis was carried out using different techniques such as DCC method, “click” chemistry and ROP. The nanoparticles were found to be degraded into non-toxic compounds under buffer-simulated acidic cytosolic or endosomal conditions in tumour cells (pH~5.0). [ASEP \(ID 428455\)](#)

The SUPRAMOL team performed all the synthesis, characterization of the obtained compounds such as precursors, macromer, macroinitiator and final diblock copolymers, in particular by dynamic light scattering (DLS), nanoparticle tracking analysis (NTA) (everything, except the transmission electron microscopy (TEM) images).

S3. **Petrova, S.; Jäger, E.; Konefal, R.; Jäger, A.; Venturini, C. G.; Spěváček, J.; Pavlova, E.; Štěpánek, P.** Novel poly(ethylene oxide monomethyl ether)-*b*-poly(epsilon-caprolactone) diblock copolymers containing a pH-acid labile ketal group as a block linkage. *Polymer Chemistry* 2014, 5, 12, p. 3884-3893. [ASEP \(ID 428455\)](#)

Result 8

Novel phospholipid nanoparticles

We prepared novel type nanoparticles that consist of several phases or compartments. The kinetic pathway of their nonequilibrium self-assembly and protein loading was determined by millisecond time-resolved small-angle X-ray scattering (SAXS) at high resolution. The obtained three-phase liquid-crystalline nanoparticles put forward important advancements in drug delivery nanoarchitecture. [S1, [ASEP \(ID 428446\)](#)]. We also monitored the formation of PEGylated nanoparticles with nonlamellar inner-membrane organization and open nanochannels between nonlamellar forming lipids and plasmid DNA. The rate constant of the pDNA/lipid nanoparticles complexation and the evolution of corresponding structural intermediates were determined. The results contribute to the development of novel gene carriers and elucidation of assembly pathways in biomolecular systems. [S8, [ASEP \(ID 392998\)](#)]. The formation of the smallest cubosome from individual PEGylated phospholipid nanovesicles was studied by Cryo transmission electron microscopy, light scattering and small angle X-ray scattering. The structure was elucidated using complex models of SAXS data analysis. The reported structural findings are anticipated to advance the engineering of small lipid nanoparticles with controllable channels for biomolecular loading and release.[S16, [ASEP \(ID 384663\)](#)]. Model studies on interaction of plasmid DNA and PEGylated large unilamellar lipid vesicles revealed the formation of pear type elongated multilamellar vesicles that are important in the context of nanomedicine gene therapy towards treatment of neurodegenerative disorders. [S21, [ASEP \(ID 364996\)](#)]

The team contributed in all parts of the work. In particular the sophisticated X-ray millisecond measurements and extensive data analysis were done by the IMC team. Cryo-TEM images were realized by the cooperating partner. The DNA material was obtained from the cooperating institution.

S1. **Angelov, B.;** Angelova, A.; **Filippov, S.;** Drechsler, M.; **Štěpánek, P.;** Lesieur, S. Multicompartment lipid cubic nanoparticles with high protein upload: millisecond dynamics of formation. *ACS Nano* 2014, 8, 5, p. 5216-5226. [ASEP \(ID 428446\)](#)

S8. **Angelov, B.;** Angelova, A.; **Filippov, S.;** Narayanan, T.; Drechsler, M.; **Štěpánek, P.;** Couvreur, P.; Lesieur, S. DNA/Fusogenic lipid nanocarrier assembly: millisecond structural dynamics. *Journal of Physical Chemistry Letters* 2013, 4, 11, p. 1959-1964. [ASEP \(ID 392998\)](#)

S16. **Angelov, B.;** Angelova, A.; Garamus, V. M.; Drechsler, M.; Willumeit, R.; Mutafchieva, R.;

Štěpánek, P.; Lesieur, S. Earliest stage of the tetrahedral nanochannel formation in cubosome particles from unilamellar nanovesicles. *Langmuir* 2012, 28, 48, p. 16647-16655. [ASEP \(ID 384663\)](#)
S21. **Angelov, B.**; Angelova, A.; **Filippov, S.**; Karlsson, G.; Terrill, N.; Lesieur, S.; **Štěpánek, P.** Topology and internal structure of PEGylated lipid nanocarriers for neuronal transfection: synchrotron radiation SAXS and cryo-TEM studies. *Soft Matter* 2011, 7, 20, p. 9714-9720. [ASEP \(ID 364996\)](#)

Result 9

POSS-containing (co)polymers

For the first time, a commercial methacrylate monomer containing polyhedral oligomeric silsesquioxane (POSS) moiety was polymerized to high molecular weights by ATRP [S2, [ASEP \(ID 434548\)](#)]. The key role of low ceiling temperature of the POSS monomer was revealed. Under optimized conditions (low reaction temperature, high monomer concentrations), methacrylate POSS homopolymers having low dispersity and high molecular weights (up to 500 000) were obtained. Our original findings were then used for the preparation of new types of hybrid organic-inorganic materials, including various diblock and triblock copolymers with low [A110, [ASEP \(ID 391497\)](#)] or high [[ASEP \(ID 434548\)](#) S2] content of the POSS monomer. Self-assembly of POSS copolymers in selective solvents was studied, and the formed ordered micellar-like structures were characterized [[ASEP \(ID 422335\)](#)]. The above research resulted in 3 publications in impacted journals.

Members of the Centre have performed the synthesis of POSS homopolymers and POSS-containing copolymers, their isolation, basic SEC and NMR polymer characterization, and determination of ceiling temperature as well as polymerization enthalpy and entropy values. Cooperating members from other Centres of the Institute have studied self-assembly and micellar properties of the synthesized copolymers by SAXS, TEM and DSC methods.

S2. **Raus, V.**; **Čadová, E.**; **Starovoytova, L.**; **Janata, M.** ATRP of POSS monomers revisited: toward high-molecular weight methacrylate–POSS (co)polymers. *Macromolecules* 2014, 47, 21, p. 7311-7320. [ASEP \(ID 434548\)](#)

A110. **Janata, M.**; **Sikora, A.**; **Látalová, P.**; **Čadová, E.**; **Raus, V.**; **Matějka, L.**; **Vlček, P.** Synthesis of defined polyhedral oligosilsesquioxane-containing diblock and triblock methacrylate copolymers by atom transfer radical polymerization. *Journal of Applied Polymer Science* 2013, 128, 6, p. 4294-4301. [ASEP \(ID 391497\)](#)

Result 10

Polymeric liquid-crystalline materials

Liquid-crystalline (LC) polymers containing mesogenic groups in side chains have been prepared via radical addition of the in advance synthesized nematic thiols onto double bonds of poly(butadiene)diol. Thermal behavior of these comblike polymers has been characterized by differential scanning calorimetry, X-ray scattering and polarizing optical microscopy [S12, [ASEP \(ID 339561\)](#), [ASEP \(ID 342072\)](#)]. Using the rheological testing, we have proved that the absence of a semi-crystalline structure in the polymer phase behavior allows application of temperature-frequency superposition of elastic and viscous moduli. [A118, [ASEP \(ID 394297\)](#)]. The low-molecular-weight LC thiols and corresponding polymers containing azobenzene derivatives are promising materials for potential applications in optical switching, digital and holographic data storage and optical modulators. The influence of the grafting degree of the azobenzene-containing side groups and the length of terminal oxyaliphatic spacer in the side groups on the dynamics of the laser holographic volume and surface gratings recording was measured [[ASEP \(ID 360625\)](#)].

Members of the Centre performed syntheses of the mesogenic diol, preparation of the comblike LC polymers and their characterization using polarizing optical microscopy.

S12. **Poláková, L.; Sedláková, Z.; Látalová, P.** Synthesis and thermal behavior of telechelic poly(butadiene)diols with azobenzene-based liquid-crystalline units in side chains. *Polymer Bulletin* 2010, 4, 4, p. 315-326. [ASEP \(ID 339561\)](#)

A118. **Poláková, L.; Sedláková, Z.; Beneš, H.; Valentová, H.; Krakovský, I.; Rabie, F.** Dynamic mechanical and thermal behavior of novel liquid-crystalline polybutadiene-diols with azobenzene groups in side chains. *Journal of Rheology* 2013, 57, 5, p. 1297-1310. [ASEP \(ID 394297\)](#)

Result 11

Radical polymerization of 1-alkenes revisited

Radical polymerization of selected 1-alkenes (1-hexene, 1-octene and 2-methyl-1-heptene), initiated with classical radical initiators and catalyzed by lithium salts of selected carboranes was studied. In accordance with previously published results, it was found that the use of radical initiators under catalysis by “naked” lithium cation of carboranes promotes the radical polymerization of 1-alkenes, otherwise nonpolymerizable by the radical mechanism. However, although relatively high monomers conversions were reached for some of the thermal initiators used, only low-molecular-weight 1-alkene oligomers with $M_n < 1000$ were formed, regardless of the initiator and carborane anion used [S22, [ASEP \(ID 359127\)](#)]. This finding was in a strong contrast with published results about the polymerizability of simple 1-alkenes to high- molecular-weight polymers under the same conditions. The above research resulted in 1 publication in an impacted journal.

Members of the Centre have performed all polymerization experiments and SEC analysis of prepared polymers. Cooperating members from other Centres of the Institute have made GC analyses to determine monomer conversions. Carborane synthesis has been performed by external partners.

S22. **Janata, M.; Vlček, P.; Látalová, P.; Svitáková, R.; Kaleta, J.; Valášek, M.; Volkis, V.; Michl, J.** Radical polymerization of 1-alkenes catalyzed by lithium salts of carboranes. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 49, 9, p. 2018-2023. [ASEP \(ID 359127\)](#)

Result 12

Branched polymers

Various branched copolymers of defined structure (i.e., with defined backbone/grafts lengths and number of grafts) were synthesized using grafting-from and grafting-onto strategies. Backbones and grafts of selected branched copolymers were constructed from styrene or methacrylate monomeric units by the method of anionic polymerization. Thus, polystyrene-g-polystyrene and poly(4-methylstyrene)-g-poly(methacrylic acid) were prepared [S29, A147, [ASEP \(ID 424807\)](#), [ASEP \(ID 345549\)](#)]. Some of the copolymers were utilized as models for verifying the newly developed method for decomposition of non-baseline-resolved multimodal SEC elution curves of polymers [A147, [ASEP \(ID 424807\)](#)]. Self-assembly and micelles properties of other synthesized copolymers were studied in backbone/grafts-selective and non-selective solvents using static and dynamic light scattering methods [S29, [ASEP \(ID 345549\)](#)]. Further, hybrid natural-synthetic copolymers, based on cellulose esters grafted with various (meth)acrylate polymers, were prepared by a novel method exploiting SET-LRP process for the first time for such a purpose [S24, [ASEP \(ID 350691\)](#)].

Members of the Centre have performed the synthesis of all polymers, their isolation, and their basic SEC and NMR characterization. Cooperating members from other Centres of the Institute have made detailed SEC study of the synthesized copolymers. Self-assembly and micellar properties of the prepared copolymers have been studied by external partners.

- S24. **Vlček, P.; Raus, V.; Janata, M.; Kříž, J.; Sikora, A.** Controlled grafting of cellulose esters using SET-LRP process. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 1, p. 164-173. ISSN 0887-624X. [ASEP \(ID 350691\)](#)
- S29. Štěpánek, M.; Košovan, P.; Procházka, K.; **Janata, M.; Netopilík, M.; Pleštil, J.**; Šlouf, M. Self-assembly of poly(4-methylstyrene)-g-poly(methacrylic acid) graft copolymer in selective solvents for grafts: scattering and molecular dynamics simulation study. *Langmuir* 2010, 26, 12, p. 9289-9296. [ASEP \(ID 345549\)](#)
- A147. **Netopilík, M.; Janata, M.** Decomposition of size-exclusion chromatography elution curves of complex branched polymers. *Journal of Chromatography A* 2014, 1330, p. 14-19. [ASEP \(ID 424807\)](#)
- A144. **Matějka, L.; Janata, M.; Pleštil, J.; Zhigunov, A.; Šlouf, M.** Self-assembly of POSS-containing block copolymers: fixing the hierarchical structure in networks. *Polymer* 2014, 55, 1, p. 126-136. [ASEP \(ID 422335\)](#)

Result 13

Modification of cellulose by synthetic polymer grafting

Novel natural-synthetic hybrid graft copolymers having cellulose-based backbone and styrenic or (meth)acrylate grafts were prepared via controlled radical polymerization methods. Besides atom transfer radical polymerization (ATRP), a new method, single electron transfer living radical polymerization (SET-LRP), was used for the first time for such a purpose [S23, S24, [ASEP \(ID 364282\)](#), [ASEP \(ID 350691\)](#)]. Copolymer backbone was formed either by a cellulose derivative (e.g., cellulose diacetate), or by native cellulose. Unprecedented level of architecture control was achieved for native cellulose by carrying out its modification under homogeneous reaction conditions. Remarkable influence of cellulose activation method, used for bringing cellulose into solution, on the subsequent modification efficiency was revealed. In this context, a new cellulose activation method based on solvent-exchange to 1,4-dioxane was introduced and studied in detail [A96, [ASEP \(ID 382476\)](#)].

Members of the Centre have performed the synthesis/modification of all materials, their isolation, and their basic characterization by SEC and NMR. Cooperating members from other Centres of the Institute have performed further NMR, DSC, FTIR, porosimetry, SEM and TEM analyses. Solution behavior was studied and AFM analysis was carried out by external partners.

S23. **Raus, V.; Štěpánek, M.; Uchman, M.; Šlouf, M.; Látalová, P.; Čadová, E.; Netopilík, M.; Kříž, J.; Dybal, J.; Vlček, P.** Cellulose-based graft copolymers with controlled architecture prepared in a homogeneous phase. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 49, 20, p. 4353-4367. [ASEP \(ID 364282\)](#)

S24. **Vlček, P.; Raus, V.; Janata, M.; Kříž, J.; Sikora, A.** Controlled grafting of cellulose esters using SET-LRP process. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 49, 1, p. 164-173. [ASEP \(ID 350691\)](#)

A96. **Raus, V.; Štuncová, A.; Dybal, J.; Šlouf, M.; Vacková, T.; Šálek, P.; Kobera, L.; Vlček, P.** Activation of cellulose by 1,4-dioxane for dissolution in N,N-dimethylacetamide/LiCl. *Cellulose* 2012, 19, 6, p. 1893-1906. [ASEP \(ID 382476\)](#)

Result 14

Polymer-clay nanocomposites

A novel polymer nanocomposites containing organomodified montmorillonites [S30, A2, [ASEP \(ID 348578\)](#), [ASEP \(ID 338835\)](#)], layered double hydroxides [[ASEP \(ID 349656\)](#)] and carbon nanotubes [[ASEP \(ID 388106\)](#) A104] were prepared via in-situ polymerization technique by two-stage process which allowed control over the extent of intercalation, most likely leading to exfoliated nanostructures. The first stage of the process consisted of the organic modification of nanofiller. This process anchored chemically reactive species on the surface of nanofiller and improved the mixing between the clay and the monomer. The second stage of the process comprised of the in situ

emulsion polymerization and solution polymerization of vinyl type of monomer and the unsaturated acryloxy groups anchored on the surface of the nanofiller. Resulting nanocomposites were characterized in terms of their microstructure and diffraction (XRD), their thermal properties (TGA and DSC), and gas permeation properties. The resulting exfoliated morphology led to a decrease in gas permeabilities [[ASEP \(ID 348578\)](#) S30, [ASEP \(ID 338835\)](#) A2, [ASEP \(ID 349656\)](#)].

Members of SUPRAMOL have performed modification of nanofillers with organic modifiers, purification and characterization of organonanofillers and in-situ polymerization. Gas permeabilities measurements have been done with the help of external partners.

S30. **Herrera-Alonso, J. M.; Sedláková, Z.**; Marand, E. Gas transport properties of polyacrylate/clay nanocomposites prepared via emulsion polymerization. *Journal of Membrane Science* 2010, 363, 1-2, p. 48-56. [ASEP \(ID 348578\)](#)

A2. **Herrera-Alonso, J. M.; Sedláková, Z.**; Marand, E. Gas barrier properties of nanocomposites based on in situ polymerized poly(n-butyl methacrylate) in the presence of surface modified montmorillonite. *Journal of Membrane Science* 2010, 1-2, p. 251-257. [ASEP \(ID 338835\)](#)

A104. Surapathi, A.; Chen, H.-Y.; Marand, E.; Johnson, J. K.; **Sedláková, Z.** Gas sorption properties of zwitterion-functionalized carbon nanotubes. *Journal of Membrane Science* 2013, 429, p. 88-94. [ASEP \(ID 388106\)](#)

Result 15

Self-stabilized elastomeric polyurethanes

Two approaches to the self-stabilization of elastomeric polyurethanes have been studied:

First, three new low-molecular-weight stabilizers, bearing in their molecules a tri(dimethylsiloxane) chain, end-capped with primary OH groups, have been synthesized and characterized. One is based on a sterically hindered phenolic antioxidant, the others on sterically hindered piperidines (HALS-type). When added to the reaction mixture for the preparation of model soluble elastomeric polyurethanes (containing a polybutadiene α,ω -diol, a diisocyanate and a catalyst), each of these stabilizers, due to the presence of the OH group, is joined by a covalent bond at one or both chain ends of the polyurethane formed, and acts simultaneously as a molecular-weight regulator [A7. [ASEP \(ID 341596\)](#)]

Second, sterically hindered phenolic antioxidants bearing two aliphatic hydroxyl groups were incorporated by covalent bonds into the polyurethane chain based on α,ω -dihydroxypolybutadiene (OH-telechelic liquid rubber) and a diisocyanate. Two such antioxidant diols were used to prepare these self-stabilized polyurethanes, namely *N*-{6-[bis(2-hydroxypropyl)amino]hexyl}-3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)-propanamide and 4-[[bis(2-hydroxypropyl)amino]methyl]-2,6-di-*tert*-butylphenol. It was found out that the length of the spacer (a short chain between the phenolic structure and the polyurethane main chain) plays an important role: a longer spacer, which is the case of the former antioxidant diol, gives the phenolic moiety more degree of freedom and less steric hindrance which results in a better antioxidant performance [[ASEP \(ID 0428424\)](#)].

Members of our Centre have performed synthesis of low molecular stabilizers and polyurethanes preparation. Cooperating members from other Centres have performed characterization by physico-chemical methods and stability tests.

A7. Hetflejš, J.; Šabata, S.; **Podešva, J.**; **Kovářová, J.**; Prokůpek, L.; **Netopilík, M.**; **Spěváček, J.**; Sýkora, J. Novel stabilisers acting simultaneously as molecular-weight regulators in soluble elastomeric polyurethanes. *Polymer Degradation and Stability* 2010, 95, 4, p. 579-586. [ASEP \(ID 341596\)](#)

Podešva, J.; **Hrubý, M.**; **Kovářová, J.**; **Spěváček, J.** Antioxidants for autostabilized elastomeric polyurethanes, patent CZ 304302 (19.2.2014). [ASEP \(ID 0428424\)](#)

Research Report of the team in the period 2010–2014

Institute	Institute of Macromolecular Chemistry of the CAS, v. v. i.
Scientific team	2 BIOMOL

The following listing of the main results is organized in chapters representing the long term tasks followed in the BIOMOL center and identified here by headings in capital letters. References to publications of results are given by ASEP number, which links directly to full information on-line.

WATER-SOLUBLE AND MICELLAR POLYMER-DRUG CONJUGATES FOR TUMOR-TARGETED THERAPY

Result 1

High-molecular-weight HPMA copolymers as tumor-specific carriers of drugs

New polymer drug carriers based on *N*-(2-hydroxypropyl)methacrylamide (HPMA) copolymers and their conjugates with a broad spectrum of cancerostatics (taxols, pirarubicin, doxorubicin, mitomycin

C) were designed, synthesized and their anti-tumor activity and biological properties were evaluated *in vitro* on model cell cultures and *in vivo* in mice. In the conjugates the drugs were attached to the carrier by linkages stable during transport in blood circulation and undergoing hydrolysis and enabling the drug release (drug activation) in mild acidic tumor tissue and tumor cells environment. Relation between the conjugates structure, architecture, mechanism of action [ASEP (ID 422315); ASEP (ID 427397)], biodistribution [ASEP (ID 397906); ASEP (ID 383776); ASEP (ID 376255)] and other biological properties were studied on linear polymer conjugates [ASEP (ID 376255); ASEP (ID 338308); ASEP (ID 346325)], diblock polymers [ASEP (ID 427397)] and dendrimer-derived star [ASEP (ID 363631); ASEP (ID 359227); ASEP (ID 438606)] conjugates. We have shown, that with increasing molecular weight of the carrier above renal threshold it is possible significantly prolong blood circulation, increase drug accumulation in solid tumors due to EPR effect (solid tumor targeting) and in consequence with this considerably improve efficiency of treatment and prolong survival of animals, up to complete cure of tumor-bearing mice [ASEP (ID 383776)]. In the synthesis of high-molecular-weight (HMW) polymer carrier systems semitelechelic polymers with M_w below renal threshold were used for preparation of the diblock carrier with M_w exceeding renal threshold or for grafting onto polyamido amine dendrimer to form star HMW structure [ASEP (ID 363631); ASEP (ID 427397)]. In all cases the spacers interconnecting polymer chains or polymer grafts with the dendrimer core were designed as reductively or enzymatically degradable thus forming biodegradable structure of the carriers excretable from organism after their biodegradation by glomerular filtration in a form of short polymer chains [ASEP (ID 359227)]. In detailed elimination studies we have shown, that linear HPMA copolymers up to $M_w \sim 70\,000$ g/mol are safely eliminated in urine while the elimination limit for branched or grafted copolymers is lower (50 000 g/mol) [ASEP (ID 383776)].

Synthesis of well-defined polymer carriers with narrow distribution of molecular weight was achieved by controlled radical (RAFT) polymerization [ASEP (ID 347842); ASEP (ID 391498)]. This technique enabled synthesis of polymer precursors with various polymer chain-terminating functional groups well-suited for the synthesis of HMW polymer-drug conjugates with more complex and well-characterized architecture and narrow molecular weight distribution.

Result 2

Linear HPMA copolymer-drug conjugates and polymer systems for active targeting of drugs

Multivalent HPMA copolymer drug carriers enable specific delivery of a one drug, combination of two drugs or combination of a drug with targeting moiety to achieve specific drug delivery to various tumors or tumor cells. Polymer conjugates bearing DOX and dexamethasone [ASEP (ID 359969)] and DOX and mitomycin C [ASEP (ID 421776)] bound to the HPMA copolymer carrier were synthesized and their potential in treatment of B-cell lymphoma 38C13 or EL4 T-cell lymphoma in mice was evaluated. In both cases synergistic effect of both drugs used in combination was significant and predominated the antitumor effect obtained with single drug bearing conjugates. Advantages of polymer drug conjugates in combination therapy were confirmed also for other HPMA copolymer-based systems [ASEP (ID 343927); ASEP (ID 354076)].

Conjugation of HPMA copolymer carrier with anticancer drug doxorubicin DOX and various derivatives of ABC transporters was used with the aim of overcoming multidrug resistance in treatment of cancer [ASEP (ID 431003)]. This strategy was used to block the ATP-driven P-gp efflux pump of drug resistant cells. It was shown that cytostatic activity of the conjugates with Dox and P-gp inhibitor reversin both bound via pH-sensitive bond to the same carrier was 30 times higher than that of the conjugate without the inhibitor. It demonstrates that this strategy can be used for overcoming multidrug resistance.

Linear HPMA copolymer conjugates with pirarubicin were developed as highly effective anticancer drugs [ASEP (ID 422315)] exhibiting excellent anti-tumor activity in treatment of S-180 sarcoma in mice, without signs of any side effects. If used in treatment of terminal human patients (Prof. Maeda,

Sojo University, Japan, ~ 30 patients)), no side effects were observed and significant remission of the disease and elimination of numerous metastatic nodules was documented [paper in preparation].

Specific targeting of polymer drug conjugates to tumor tissue and tumor cells is a prerequisite for successful treatment of metastases, non-vascularized tumors and leukemias. Linear HPMA copolymers were also used for the study of methods of conjugation of the carrier with targeting moiety. Comparison of biodistribution and EPR effect-mediated passive and receptor-specific oligopeptide-based (RGD, NGR) active tumor targeting of polymer conjugates in mice [ASEP (ID 425232)] contributed to understanding of mechanism and efficiency of drug delivery to solid tumors which is important for further design and synthesis of new highly potent anti-tumor drugs. Improvement of binding reactions of targeting moieties to the carrier was studied by using methods of click chemistry [ASEP (ID 424588)], using both metal catalysis and catalysis-free conjugation, which is more suitable for biomedical applications.

Attachment of targeting moieties to a polymer drug carrier without losing their binding activity to cell membrane antigens was realized by non-covalent interactions of coiled coil peptides (forming heterodimers in solution), one of the peptides being attached to the polymer carrier and second to a scFv fragment of targeting monoclonal antibody [ASEP (ID 388063); ASEP (ID 429827); ASEP (ID 364976); ASEP (ID 390945)]. Cancer cells-specific targeted conjugate can be formed shortly before application by simple mixing of a solution of the peptide-modified scFv fragment with a solution of the anticancer drug and peptide-bearing HPMA copolymer carrier, both most suited for the required treatment. Feasibility of this strategy was verified by targeting carbonic anhydrase IX cancer cells membrane antigen *in vitro* (antibody M75 scFv) or by treatment of BCL1 leukemia in mice (anti-B1 scFv).

Result 3

HPMA copolymer micelles for drug delivery

Novel micellar drug delivery systems were synthesized with the aim of improving passive targeting of anti-cancer drugs to solid tumors due to EPR effect. Poly(HPMA)-bound Zn protoporphyrin self-assembled in aqueous solutions forming stable polymer micelles with a hydrodynamic diameter of ~ 83 nm [ASEP (ID 388150)]. This conjugate was tested as an efficient anti-cancer drug suitable for photodynamic therapy combined with tumor detection with fluorescence imaging (polymer theranostic) in model S-180 mouse sarcoma. Effective and tumor selective accumulation and high *in vivo* therapeutic effect was achieved by inducing singlet oxygen formation by endoscopic light-irradiation thus confirming our idea to use the micelles for simultaneous solid tumor imaging and therapy.

Different micellar drug delivery system was used for delivery of doxorubicin (DOX) covalently incorporated in crosslinked hydrophobic core of PEO-HPMA copolymer-lactic acid micelles via hydrazone bond-containing spacer [ASEP (ID 346588)]. The micelles of 80 nm in diameter were stable at pH 7.4, released DOX in mild acidic environment and showed much better anti-tumor activity than free DOX in mice bearing B16F10 melanoma. In the next study we synthesized the EGa1 nanobody-modified similar core-crosslinked polymeric micelles containing DOX and the micelles were found to inhibit tumor growth even in the absence of a drug. The nanobody-modified micelles containing DOX were significantly more effective than nanobody-free micelles containing doxorubicin [ASEP (ID 384103)]. These results suggest that the combination of two therapeutic strategies (DOX-containing micelle, nanobody) within one nanomedicine formulation is a highly promising approach for improving the efficacy of tumor-targeted combination therapy.

HPMA COPOLYMERS FOR GENE DELIVERY

Result 4

HPMA copolymer-coated viral gene delivery vectors

Surface modification of oncolytic adenoviruses (Ad) as gene delivery vectors with reactive HPMA copolymers resulted in “stealth” of the viruses thus avoiding phagocytic capture, reduction of their hepatic sequestration, general infection and toxicity [ASEP (ID 384590)] and improvement of their circulation kinetics. Use of the polymer-coated Ad in combination with microbubbles and ultrasound enhanced the *in vivo* delivery to tumors, improved extravasation and tumor accumulation and cancer cells killing [ASEP (ID 399052)]. Attachment of targeting moieties to the polymer-coated viruses improves specificity and efficiency of gene delivery as demonstrated on E-selectin targeted Ad vectors [ASEP (ID 358495); ASEP (ID 362894)] or vectors targeted by scFv fragment of anti-PSMA antibody bound to the polymer coat via non-covalent linkage formed by the complex of bungarotoxin and ungarotoxin binding peptide [ASEP (ID 349126)].

Chemical aspects of emerging field of development of polymer-coated gene delivery vectors as a basis for design and synthesis of advanced nucleic acid therapeutics discriminating between cell types and responding to target-associated conditions to trigger gene expression in target cells has been reviewed [ASEP (ID 378755)].

MAGNETIC PARTICLES

Result 5

Surface-modified magnetic nanoparticles

New types of surface-modified magnetic nanoparticles were developed by the team of the BIOMOL Center [ASEP (ID 348526)]. The particles proved to be highly efficient labeling agents for magnetic resonance imaging (MRI) of implanted cells. In order to design dual cell detection involving simultaneous imaging by fluorescent microscopy and MRI, nanoparticles with two reporters, a fluorescent dye and a superparamagnetic core included in one particle, were also synthesized and characterized [ASEP (ID 359777)]. The γ -Fe₂O₃ nanoparticles were obtained by coprecipitation of Fe(II) and Fe(III) salts and oxidation and coated with poly(2-hydroxyethyl methacrylate) [ASEP (ID 359776)], poly(L-lysine) [ASEP (ID 348526)] or carboxymethyl chitosan (CMCS) [ASEP (ID 359777)]. As a fluorescent label, fluorescein isothiocyanate (FITC) was covalently bound to the CMCS-coated nanoparticles. The nanoparticles successfully labeled rat and human mesenchymal stem cells, or macrophages *in vitro*. Tracking of macrophages using the developed particles is useful for monitoring of inflammations and cell migration in cell therapy. Large amounts of iron were found inside the cells labeled with FITC-modified nanoparticles according to the relaxation time measurements [ASEP (ID 359777)]. When used at moderate concentrations, the particles were not cytotoxic.

Members of the BIOMOL Centre synthesized and characterized the particles, cooperating researchers of the Institute participated on physical characterization. Biological tests were performed with the help of external partners

Result 6

Monodispersed magnetic polymer microspheres

Several types of magnetic polymer microspheres of very narrow particle size distribution and containing reactive functional groups were developed in the BIOMOL Center by employing different polymerization techniques and monomers, such as glycidyl methacrylate [ASEP (ID 383717)], 2-hydroxyethyl methacrylate [ASEP (ID 391867)], styrene [ASEP (ID 364363)], or *N*-propargylacrylamide [ASEP (ID 365161)]. Particles possessing a wide range of diameters and surfaces properties were then used as attractive materials for separation of biomolecules from complex biological mixtures, in microchips for diagnostics of tumors and neurodegenerative diseases, etc. Magnetic polymer microspheres offered easy handling and quick manipulation in magnetic field, which made them

suitable for applications in immunoassays, immunomagnetic metal affinity chromatography, detection of pathogens in food, blood, etc. Porous monodispersed microspheres were typically prepared by swelling method [[ASEP \(ID 383717\)](#)], optionally by hypercrosslinking of polystyrene microspheres [[ASEP \(ID 364363\)](#)]. Iron oxide was then precipitated in the microsphere pores to render the particles magnetic. Repeated precipitation made possible to increase the iron oxide content to more than 30 wt.%. Other preparation methods included precipitation/dispersion polymerization in the presence of iron oxides [[ASEP \(ID 365161\)](#)]. Though this was easy and quick technique, the encapsulation efficiency was inferior to the swelling method. Non-specific protein adsorption on the particles was reduced by covering their surface with albumin [[ASEP \(ID 383717\)](#)] or poly(ethylene glycol) [[ASEP \(ID 434370\)](#), [ASEP \(ID 391867\)](#)]. The microspheres were successfully used for detection of *Francisella tularensis* [[ASEP \(ID 373792\)](#)], glycoproteins, epithelial cancer cells [[ASEP \(ID 383717\)](#)], and β -amyloid peptides [[ASEP \(ID 434370\)](#)].

Members of the BIOMOL Centre synthesized and characterized the microspheres, cooperating colleagues from this Institute participated on physical characterization and radiochemistry measurements. Biological tests were performed with the help of external partners.

POLYMER HYDROGELS AND NETWORKS

Result 7

Methacrylate hydrogels for biomedical application

Group of polymer gels synthesized various hydrogels for biomedical use, especially for tissue engineering, following general aims as biodegradability, controlled porosity and enhanced mechanical properties. All mentioned parameters are significantly influencing interaction of polymer materials with living tissue, therefore their control and adjustability is needed. Biodegradability of three-dimensional hydrogel systems could be solved by using degradable cross-linker for their synthesis. The new type of irreversibly reductively biodegradable hydrogel was prepared. Its degradation is based on natural presence of –SH groups in mammalian body. Therefore the hydrogel is stable during its storage in phosphate buffered saline and relatively quickly start to degrade in the presence of L-cysteine. Moreover, another type of hydrazone bond-containing cross-linker was synthesized and, consequently, radically cross-linked poly-HPMA hydrogels possessing good stability in basic and neutral pH environment were prepared. Stability in neutral pH condition provide further manipulation advantage and the hydrogels can be prepared in advance [[ASEP \(ID 359453\)](#); [ASEP \(ID 359454\)](#)].

The novel macroporous hydrogels based on chitosan with porous structure tailored by ice-templating and porogen leaching were developed and prepared as a scaffold for tissue engineering. Combining both of techniques, the double porous structure was reached. The result is described in the paper [[ASEP \(ID 391893\)](#)].

One of the serious problems of hydrogel applications in general represents their interaction with proteins, fouling or moulds contamination etc. One contribution to „antifouling systems“ was done by copolymerization of carboxybetaine monomers with 2- hydroxyethyl methacrylate (HEMA). Small addition of carboxybetaine monomers led to a very high increase in the water content without impairing their mechanical properties and an unprecedented reduction of fouling from blood plasma. The results are described in paper [[ASEP \(ID 384769\)](#)].

Improvement of swelling or mechanical properties mentioned above is very often task of research of hydrogel materials. We prepared new composite of bacterial cellulose (BC) with several types of methacrylate based hydrogels. Used BC was produced by fermentation by the bacterium *Acetobacter xylinum*, as three-dimensional network consisting of nano-sized fibrils. The double network structure of these composites caused the significant improvement in mechanical properties compared to neat BC or methacrylate hydrogels. Received results, especially from the viewpoint of Young modulus, present our composite as good candidate for using in regeneration of tissues of skeletal system, joints or cartilages. The result was published in paper [[ASEP \(ID 377479\)](#)].

Result 8

Study of hydrogel formation and characterization methods

The characterization of hydrogels (or gels in general) using various methods of measurements of their mechanical properties is one of possibilities to describe behaviour of polymer networks. Therefore, significant part of our papers concerned this problematic, in both of, theoretical and experimental level. The dependence of the polymer network properties on their formation and structure was observed.

The frequency dependent rheological responses of swollen macroporous covalently crosslinked hydrogels were used to characterize the porous structure properties such as pore connectivity and as a method to determine the crosslink density of the swollen hydrogel matrix.

The crosslinking of preformed star-like precursors with polyfunctional cross-linker was described by a model based on theory of branching processes taking into account the distribution of number and length of precursors arms, differences in functional group reactivity, and the substitution effect. Relations for molecular weight averages, gel point conversion and concentration of elastically active network chains in the postgel state were derived and verified with experimental model systems.

The model of non-uniform swelling degree in an adhering cross-linked polymer film has been formulated including reformulation of the thermodynamic mixing term of the well-established swelling model. The model of polymer chain behavior is formulated for non-Gaussian polymer chains and includes the effect of finite chain extensibility on the deformation response and in the swelling experiment.

The OH-functional preformed precursors of compact molecular structure were used to study experimentally and theoretically the formation-structure-properties relation of polyurethane networks designed as models related to coating applications. The work puts forward a semi-empirical model of cyclization extent that predicts relation between pre-gel behavior with the postgel crosslink density as well as the effect of bonds lost in elastically inactive cycles on final network properties.

To keep non-uniformities of grafted (co)polymers within a certain range is crucial for success of their application in biomedical and supramolecular science. Factors affecting non-uniformities - molecular weights of backbone polymer and grafts and their distributions, and other structural factors - were examined and a formalism of their description by generating functions was proposed.

Results mentioned above are documented by following papers: [ASEP \(ID 429952\)](#); [ASEP \(ID 391832\)](#); [ASEP \(ID 388196\)](#); [ASEP \(ID 376314\)](#); [ASEP \(ID 346545\)](#).

POLYMER BIOMATERIALS AND BIOMIMETIC SYSTEMS

Result 9

Biomaterials based on biodegradable synthetic poly(amino acid)s

Synthetic poly(amino acids), (polyAA), both statistical and block copolymers of amino acid derivatives, are being studied as enzymatically biodegradable, fully synthetic candidates for functional polymer biomaterials. Synthesis of raw materials through polymerization of AA *N*-carboxyanhydrides, post-synthetic hydrophilic modification and introduction of functional groups for further binding of biomimetic structures has been explored and documented. The efficiency of modification reactions was thoroughly quantified. [\[ASEP \(ID 369730\)\]](#) Two types of 3D-architectures as potential tissue-engineering scaffolds have been developed:

a) *Fibrous scaffolds* prepared either by compression of polyAA fibers spun from a solution, or nanofibers obtained through electrospinning process.

b) *Poly AA hydrogels* composed of crosslinked synthetic poly(amino acid)s. The highly swollen gels with a macroporous structure and controlled pore size and morphology were formed through radical copolymerization of poly(AA)-based hydrophilic prepolymers. The 3D-structure of hydrogels have been created either through phase-separation of gel phase, or porogen leaching. [3D-constructs

with a precise architecture has been created through direct laser writing by two-photon polymerization technique. [[ASEP \(ID 433911\)](#)]

Through adjusting the poly(amino acid) structure by copolymerization, the degradation of hydrogels specifically by enzymes present in the regenerating tissues can be achieved. The enzymatic degradation of AA-based prepolymers as well as resulting 3D-gels was documented and proved. [[ASEP \(ID 359220\)](#)] The modification of inner surfaces of the pores in both types of polyAA 3D-scaffolds with biomimetic cell-adhesion peptides was explored and the effect of biomimetics on cell adhesion and migration of cells into the 3D-structure was evaluated.[[ASEP \(ID 345865\)](#)].

The results are important for further development of a novel class of biomaterials responsive to the changes of environment in the regenerating tissues.

Result 10

Surface-initiated controlled polymerization approaches to creation of biofunctional surfaces

The anti-fouling properties of polymer brushes depend on the structure, surface density and the length of tethered polymer chains. Various techniques have been explored to produce stable surface brushes of end-tethered hydrophilic polymer chains as a key step in creation of non-fouling surfaces, which than could serve as a neutral inert background for attachment of bio-recognizable structures. In particular we focused on development of surface-initiated controlled polymerization techniques which would make it possible to form brushes of polymers with controlled the chain length and to carry out the polymerization in aqueous media and complex buffers, that would enable us to form brushes not only of poly(ethylene oxide,) but also from polymers with a range of different side chains. We investigated the interaction with human blood serum and plasma of various “anti-fouling” surfaces capable of preventing non-specific protein adsorption, such as surfaces of oligoethylene glycol, terminated self-assembling monolayers (SAMs), poly(ethylene glycol) (PEG) grafted onto the SAMs, and zwitterionic polymer brushes prepared by surface initiated atom transfer radical polymerization.

We achieved and described the first successful living/controlled reversible addition fragmentation transfer polymerization (RAFT) of carboxybetaine methacrylamide in buffer at 70 and 37 °C. [[ASEP \(ID 360784\)](#)], [[ASEP \(ID 384769\)](#)] Antifouling poly(MeOEGMA) block copolymer brushes were prepared by controlled surface initiated ATRP in buffer at room temperature. The growth of the second block of MeOEGMA was performed in 10% fetal bovine serum.[[ASEP \(ID 376434\)](#)] Ultra-low-fouling poly[N-(2-hydroxypropyl) methacrylamide] (poly(HPMA)) brushes were prepared for the first time, exhibiting the level of blood plasma fouling below the detection limit of the most sensitive techniques. [[ASEP \(ID 360787\)](#)] Contradicting the generally accepted idea of protein adsorption, there was no direct relationship between the surface and the ability to prevent adsorption of main plasma proteins (albumin, IgG and fibrinogen) either from solutions or full blood plasma. Also, the observations indicated that only some specific proteins are responsible for deposition from plasma. [[ASEP \(ID 391894\)](#)].

The antifouling surfaces were functionalized with selectively recognizable bioactive structures either to be used in the design of biosensors or biomimetic surfaces for cell adhesion and tissue engineering studies.

For this purpose a new strategy of the end-group functionalization of antifouling polymer brushes via a Diels-Alder “click” reaction was developed. The mild conditions utilized for the transformation of the polymer end-groups to cyclopentadiene ensured the preservation of the antifouling properties. [[ASEP \(ID 428662\)](#)] The adsorption of poly(dopamine) was studied as a surface-independent method for creating an anchoring layer on the surface, to which the PEO chains can be grafted (grafting-to) or the initiating groups bound, affording the growth of polymer chains (grafting-from approach). [[ASEP \(ID 359207\)](#)] Thus, poly(dopamine) functionalized with tetrazole. Antifouling polymer brushes were grown from the photo-patterned initiator which allowed gaining spatial control of the adhesion of fibroblasts on surfaces. This confirms the feasibility of creating a surface pattern of areas selectively promoting cell adhesion and growth.[[ASEP \(ID 398406\)](#)], [[ASEP \(ID 429251\)](#)]

Result 11

Polymer biomaterials with biomimetic surfaces for tissue engineering

To create biomimetic surfaces of biomaterials studied as scaffolds for tissue engineering, the cell-adhesion peptides derived from the primary structure of ECM proteins have been synthesized and the effect of their exposure on the biomaterial surface was investigated. To recognize the specific effect of the surface-bound peptides on the promotion of cell-biomaterial interactions, a nonspecific protein adsorption has to be first prevented by coating the biomaterial surface with non-fouling polymer brush. Several avenues to creation of biomimetic surfaces on polymer biomaterials designed to be used as scaffolds for tissue engineering/regeneration has been explored and applicability of the concepts evaluated.

A new „colloidal printing“ concept has been developed based on creation a molecular brush layer on the biomaterial surface through deposition of amphiphilic block copolymers through their adsorption from selective solvents [[ASEP \(ID 335741\)](#)]. The copolymer may carry either neutral hydrophilic or functional end-groups, through which the adhesion and differentiation of interacting cells can be controlled. Through self-assembly of amphiphilic block copolymers a nanopattern of biomimetic structures on the biomaterial surface can be created, which is of key importance in providing solid-phase signals to cells at biomaterial/cell interfaces [[ASEP \(ID 391642\)](#)]. The results open new possibilities for the design of biomimetic biomaterials as well as for studies of fundamental processes of cell/biomaterial interactions.

A simple, substrate-independent method of biomimetic surface modification was elaborated, based on the creation of a PEO brush on a poly(dopamine) anchoring layer. [[ASEP \(ID 381352\)](#)] The chain density, thickness, swelling, and conformation of PEO layers were determined using various physical techniques. [[ASEP \(ID 389382\)](#)]The effect of PEO chain length on prevention of non-specific protein adsorption was documented. [[ASEP \(ID 364383\)](#)]

Click-chemistry reactions, such as alkyne-azide cycloaddition, have been used for selective modifications of non-fouling brushes with various biomimetic peptides. Facile control of peptide concentration through radioactive labeling was introduced and its suitability for studies of cell-biomaterial interactions was confirmed.[[ASEP \(ID 380130\)](#)] Additional alternative method for bio-functionalization of materials was developed, affording a surface brush of tethered PEO chains with terminal alkyne groups through grafting of amino- PEO to a poly(glycidyl methacrylate) anchoring layer on the surface. The composition, stability and binding capacity of the PEO brush for biomimetic peptides was documented and the applicability of the brush as a platform for cell-biomimetic ligand studies has been confirmed. [[ASEP \(ID 429250\)](#)]

Result 12

Functional biomaterials through fibrin coating

The mechanisms participating in blood coagulation cascade were utilized for a controlled preparation of artificial fibrin (Fb) nanostructures on the surfaces of solid supports. Fb networks were formed on the surface through catalytic action of surface-immobilized thrombin in the ambient Fbg solution. The morphology of surface-bound Fb gel layer and its thickness can be varied on a scale ranging from 10 to 100 nm, by using specific inhibitors of blood coagulation and appropriate reaction conditions. [[ASEP \(ID 356629\)](#)]The coating of polymer materials with Fb gels supported significantly the adhesion and growth of vascular endothelial cells on polymer surfaces. Unlike other usage of fibrin gel, e.g. fibrin glue known from the literature, the newly developed techniques make it possible to coat the inner surface of porous scaffolds designed for tissue engineering with a surface-attached thin fibrin film, while preserving the volume of pores free for cell migration and vascularization.[[ASEP \(ID 425258\)](#)], [[ASEP \(ID 357917\)](#)]

FUNCTIONAL POLYMERS FOR BIOSENSORS

Result 13

Through nonfouling polymer brushes towards high-specificity biosensors

Any material coming into contact with complex environments of living body is prone to adsorb components of body fluids, namely proteins. Unless surface of the material are specifically treated, the protein adsorption, representing the first event of the body reaction upon the contact, proceeds almost immediately and results in a complete coverage of the material surface. For the interactions with the body fluids, such as blood plasma or lymph, or cells and tissues, such biomaterials thus expose the surfaces, the structure of which has already been modified by adsorbed protein molecules. Therefore, the fouling of surfaces with proteins represents a key issue in developing biomaterials designed to elicit specific reaction with cells or tissues, in prevention of immune reaction or targeting the drug delivery systems. Controlling the surface fouling is of primary importance in design of biosensors, as the any unspecific protein adsorption undermines the sensor sensitivity and its applicability in vivo. Formation of surface brushes of end-tethered hydrophilic polymer chains is the most efficient and widely accepted method for prevention the protein fouling. The anti-fouling properties of polymer brushes depend on the structure, surface density and the length of tethered polymer chains. While poly(ethylene glycol)-based surface modifications are the most widely used to reduce surface fouling, so far known theories about fouling process are not sufficient to explain the interaction of blood plasma and serum with low-fouling surfaces. [\[ASEP \(ID 360787\)\]](#). Ultra-low-fouling poly[N-(2-hydroxypropyl) methacrylamide] (poly(HPMA)) brushes were prepared for the first time. The level of blood plasma fouling was below the detection limit of the most sensitive techniques despite being a hydrogen bond donor and displaying a moderate wettability, thus challenging the currently accepted views for the design of antifouling properties. We developed and mastered several techniques for creation of surface polymer brushes and analyzed in detail the dependence of fouling on the brush structure and properties, as well as with respect to the selectivity for the adsorbed proteins. [\[ASEP \(ID 391894\)\]](#), [\[ASEP \(ID 420875\)\]](#). For the first time the potential of three low-fouling surface chemistry platforms for biosensing in complex real-world media important for food safety and medical diagnostics was thoroughly investigated and compared. The results on fouling resistance, functionalization capacity, and biorecognition activity suggest that pCBAA brushes are promising candidates for biosensing in complex biological fluids including blood plasma and food samples. [\[ASEP \(ID 396975\)\]](#) Taking advantage of these techniques a surface plasmon resonance biosensor for the detection of Cronobacter, a foodborne pathogen, in milk was developed. The introduction of antifouling polymer brushes prevented false positive and the bacteria could be identified. [\[ASEP \(ID 362960\)\]](#) The application of non-fouling polymer brushes allowed us to detect a disease marker in clinical serum sample by an optical affinity biosensor. The assay was developed able to differentiate various stages of the Epstein-Barr virus infection. The approach is promising for replacing currently used methods that require highly trained personnel restricted to specialized laboratories. In particular, it is attractive for "in-field" and point-of-care detection of biomarkers in complex medium. [\[ASEP \(ID 427702\)\]](#) Hierarchically structured diblock copolymer brushes are shown here as an effective way to limit the increase in fouling caused by the activation of functional groups for the attachment of biorecognition elements. The growth of antifouling diblock copolymer brushes was enabled by the utilization of surface-initiated atom transfer radical polymerization. As a proof of concept, a biosensor able to detect a targeted protein spiked in undiluted blood plasma has been presented. [\[ASEP \(ID 429950\)\]](#)

Research Report of the team in the period 2010–2014

Institute	Institute of Macromolecular Chemistry AS CR, v.v.i.
Scientific team	3 MATER

Result 1

Tin-based nanobuilding blocks in epoxy nanocomposites

Hybrid organic-inorganic epoxies with the tin polyhedral clusters, *n*-butylstannoxane dodecamer, were prepared. The tin cages were incorporated in the epoxy network as an inert block [S1], as a linear unit [S1, S4] or as a network junction [S1, S15]. The “Sn cages” are especially attractive due to their anti-oxidizing effect in organic matrices, besides “classical” mechanical reinforcement. The latter effect was assigned to physical interactions among the polymer bonded Sn cages, while the anti-oxidizing effect was shown to be a result of oxidation-induced crosslinking reactions between Sn atoms of the Sn cage and suitable sites on the matrix [S15]. At elevated temperatures, the Sn cages can oligomerize to larger nano-domains [S15, S4], thus generating additional chemical crosslinks. The highest anti-oxidizing activity was found for linearly bonding cages [S4], which is marked already at

contents as low as 0.05 wt.%, and very strong near 1 wt%. A slightly smaller activity was found in the case of the non-bonding cages [S1], while the effect is weakest if the cages are incorporated in network junctions [S1]. An interesting feature is the short-range mobility of Sn cages in the matrix, observed at elevated temperatures under anaerobic conditions. The effect of Sn cage on thermo-mechanical properties and on oxidation resistance of reinforced epoxy matrices was found to strongly depend on their network mesh sizes [S6]. The strongest mechanical reinforcement was observed in the hybrids with a network mesh width close to the size of Sn cage. In a narrow-mesh-matrix, a sterically induced plasticization of the epoxy network was observed. On the other hand, the strongest anti-oxidative effect of the Sn cage was observed in the matrix with the widest mesh.

Syntheses of the hybrids, and a part of their characterization (DMTA, TEM and TGA) was performed in MATER. SAXS/WAXS, IR and NMR characterization were carried out in other Centres. The development of a synthesis path to the nano-building block was carried out by external partners.

S1. **Strachota, A.; Rodzen, K.;** Ribot, F.; **Trchová, M.; Steinhart, M.; Starovoytova, L.; Pavlova, E.** Behavior of tin-based "super-POSS" incorporated in different bonding situations in hybrid epoxy resins. *Macromolecules* 2014, 47, 13, p. 4266-4287. [ASEP \(ID 0431040\)](#)

S4. **Strachota, A.; Rodzen, K.;** Ribot, F.; **Perchacz, M.; Trchová, M.; Steinhart, M.; Starovoytova, L.; Šlouf, M.; Strachota, B.** Tin-based "super-POSS" building blocks in epoxy nanocomposites with highly improved oxidation resistance. *Polymer* 2014, 55, 16, p. 3498-3515. [ASEP \(ID 0431055\)](#)

S6. **Rodzen, K.; Strachota, A.;** Ribot, F.; **Šlouf, M.** Effect of network mesh size on the thermo-mechanical properties of epoxy nanocomposites with the heavier homologue of POSS, the inorganic butylstannoxane cages. *European Polymer Journal* 2014, 57, August, p. 169-181. [ASEP \(ID 0431048\)](#)

S15. **Strachota, A.;** Ribot, F.; **Matějka, L.;** Whelan, P.; **Starovoytova, L.; Pleštil, J.; Steinhart, M.; Šlouf, M.; Hromádková, J.; Kovářová, J.; Špírková, M.; Strachota, B.** Preparation of novel, nanocomposite stannoxane-based organic-inorganic epoxy polymers containing ionic bonds. *Macromolecules* 2012, 45, 1, p. 221-237. [ASEP \(ID 0372985\)](#)

Result 2

Effect of ionic liquids on synthesis and properties of epoxy-silica nanocomposites

The ionic liquids (ILs) were used as additives at formation of epoxy-silica nanocomposites, via the generation of silica by sol-gel process within the epoxy network. The application of different ILs allows controlling the silica structure and modifying interphase interaction, thus producing hybrids with diverse morphologies and improved mechanical properties [S22]. Both anion and cation of the imidazolium based ILs affected the hybrid formation and final properties. The research proved the effect of ILs on enhancement of tensile properties in rubbery epoxy-silica nanocomposites. The use of ILs together with the coupling agent created a synergy between physical and chemical interfacial bonding, enabling an increase in toughness without loss of stiffness. The nanocomposites were remarkably both stiffer and tougher, the best one displaying 6 times higher modulus and tensile strength as well as more than 10 times higher energy to break [S14].

The concept of the research, synthesis of the nanocomposites and the investigation of their thermomechanical and tensile properties as well as morphology are contributions of MATER Center. The first author R. K. Donato and K. Z. Donato were UNESCO students of MATER.

S22. **Donato, R. K.; Matějka, L.;** Schrekker, H. S.; **Pleštil, J.; Jigounov, A.; Brus, J.; Šlouf, M.** The multifunctional role of ionic liquids in the formation of epoxy-silica nanocomposites. *Journal of Materials Chemistry* 2011, 21, 36, p. 13801-13810. [ASEP \(ID 363254\)](#)

S14. **Donato, R. K.; Donato, K. Z.;** Schrekker, H. S.; **Matějka, L.** Tunable reinforcement of epoxy-silica

nanocomposites with ionic liquids. *Journal of Materials Chemistry* 2012, 22, 19, p. 9939-9948. [ASEP \(ID 376690\)](#)

Result 3

Self-assembly in POSS containing organic-inorganic hybrids

Two types of organic-inorganic (O-I) hybrids containing POSS (polyhedral oligomeric silsesquioxanes) were prepared and characterized. (a) The O-I block copolymers (BCP) were synthesized by ATRP. The BCPs involve POSS (polyhedral oligomeric silsesquioxane) as a pendant unit along the particular polymer block chain. In the selective solvents the BCPs undergo a self-assembly arrangement to form ordered micellar-like structures. Crosslinking of the BCP through the micelle shells results in a long-range structure ordering and fixing the unique hierarchical ordered structure of the POSS containing O-I hybrids [S3]. (b) The Epoxy-POSS hybrid networks have been prepared by incorporating the novel diepoxy-POSS monomer in an epoxy network. During the hybrid formation the POSS self-assemble to form ordered crystalline lamellae and cylinders in the matrix. The organic-inorganic hybrid shows the temperature induced order-disorder transitions. The well-arranged POSS domains provide the hybrid with a significant reinforcement. The effect of POSS-POSS interactions on the hybrid ordering and reinforcement was determined [S5].

The concept of the research, synthesis of the hybrids, crosslinking of BCPs as well as rheology, thermomechanical and microscopic characterization were performed in MATER. The BCPs were synthesized in SUPRAMOL and the POSS monomer was supplied by coworkers from Hybrid Plastics.

S3. **Matějka, L.; Janata, M.; Pleštil, J.; Zhigunov, A.; Šlouf, M.** Self-assembly of POSS-containing block copolymers: fixing the hierarchical structure in networks. *Polymer* 2014, 55, 1, p. 126-136. [ASEP \(ID 422335\)](#)

S5. **Matějka, L.; Amici Kroutilová, I.; Lichtenhan, J. D.; Haddad, T. S.** Structure ordering and reinforcement in POSS containing hybrids. *European Polymer Journal* 2014, 52, March, p. 117-126. [ASEP \(ID 424806\)](#)

Result 4

Coalescence in quiescent and flowing polymer blends

Coalescence in immiscible polymer blends during their annealing, cooling or flow was studied. Theory of coalescence in molten quiescent polymer blends containing anisometric droplets was derived [A63]. It was shown that the effect of the droplet anisometry affects their coalescence only in blends with a high content of the dispersed phase. The effect of various approximations, used for calculation of the average time of coalescence, on the rate of van der Waals forces induced coalescence was analyzed [S18]. Fair semiquantitative agreement between the theory and experiment was found [A37]. It was shown that rejection of dispersed particles from growing spherulites of crystallizing matrix contributes remarkably to their coalescence [A114]. New equation for matrix drainage between strongly deformed droplets, applicable for any ratio of viscosities of droplets and matrix in contrast to previous theories, was proposed [A138]. Theory of flow-induced coalescence based on the switch between expressions for matrix drainage between spherical and strongly deformed droplets was derived [S16]. The theory was utilized for analysis of the effects of matrix elasticity and droplet size distribution on the course of coalescence. It was found that the effect of the matrix elasticity is quite weak for shear-flow-induced coalescence but it is pronounced for extensional-flow-induced coalescence [S16]. Dependence of the probability of coalescence on the

average droplet radius for blends with broad droplet size distribution differs strongly from that for monodisperse systems, commonly used for evaluation of experimental data [S8]. The research covers 8 papers.

All authors are from MATER Center.

S8. **Fortelný, I.; Jůza, J.** Flow-induced coalescence in polydisperse systems. *Macromolecular Materials and Engineering* 2014, 299, 10, p. 1213-1219. [ASEP \(ID 432205\)](#)

S16. **Fortelný, I.; Jůza, J.** Modeling of the influence of matrix elasticity on coalescence probability of colliding droplets in shear flow. *Journal of Rheology* 2012, 56, 6, p. 1393-1411. [ASEP \(ID 379765\)](#)

S18. **Fortelný, I.; Jůza, J.; Dimzowski, B.** Coalescence in quiescent polymer blends with a high content of the dispersed phase. *European Polymer Journal* 2012, 48, 7, p. 1230-1240. [ASEP \(ID 377756\)](#)

A63. **Fortelný, I.; Jůza, J.; Vacková, T.; Šlouf, M.** The effect of anisometry of dispersed droplets on their coalescence during annealing of polymer blends. *Colloid and Polymer Science* 2011, 289, 17/18, p. 1895-1903. [ASEP \(ID 367514\)](#)

Result 5

Polycarbonate-based polyurethane (PU) elastomers and PU nanocomposites

All-aliphatic polycarbonate (PC)-based PU systems and PU nanocomposites were synthesized from polycarbonate macrodiols (Asahi Kasei Chem. Co., Japan). The detailed study was pointed on the systems made from macrodiols of molecular weight ca 1000 or 2000, butane-1,4-diol and 1,6-diisocyanatohexane. The nanocomposites with two types of layered silicates, Cloisite 30B and bentonite, for organic systems and two kinds of nanosilica (hydrophobic, hydrophilic) were prepared and characterized. It was found that PC-based PUs have excellent end-use (especially mechanical) properties, compared to polyether- or polybutadiene-based analogues. The products filled with bentonite feature excellent mechanical properties [S25,A112]: elongation-at-break are mostly over 700%, and some energy-to-break quantities exceed the value 200 mJ.mm⁻³. Temperature-modulated DSC revealed the filler affinity both to soft and hard segments [S25,A91]. The multiscale characterization covering segmental up to macroscopic levels was realized. This topic covers 10 papers (published between years 2010 and 2014) and 1 book chapter.

The programme (i.e. topic, components and the synthesis) was fully prepared and realized in MATER. Most of techniques used for PU and nanocomposite characterization were carried out in MATER, e.g. TEM, AFM, DMTA and tensile characterization. Most of papers were issued from the cooperation between IMC and University of Novi Sad within the framework 7th RP DEMATEN.

S25. **Špírková, M.;** Pavličević, J.; **Strachota, A.; Poreba, R.;** Bera, O.; **Kaprálková, L.; Baldrian, J.; Šlouf, M.;** Lazić, N.; Budinski-Simendic, J. Novel polycarbonate-based polyurethane elastomers: composition–property relationship. *European Polymer Journal* 2011, 47, 5, p. 959-972. [ASEP \(ID 359231\)](#)

A91. **Špírková, M.; Poreba, R.; Pavličević, J.; Kobera, L.; Baldrian, J.; Pekárek, M.** Aliphatic polycarbonate-based polyurethane elastomers and nanocomposites. I. The influence of hard-segment content and macrodiol-constitution on bottom-up self-assembly. *Journal of Applied Polymer Science* 2012, 126, 3, p. 1016-1030. [ASEP \(ID 379085\)](#)

A112. **Poreba, R.; Špírková, M.; Brožová, L.; Lazić, N.; Pavličević, J.; Strachota, A.** Aliphatic polycarbonate-based polyurethane elastomers and nanocomposites. II. Mechanical, thermal, and gas transport properties. *Journal of Applied Polymer Science* 2013, 127, 1, p. 329-341. [ASEP \(ID 381339\)](#)

Result 6

Rheological study of chitosan acetate solutions containing chitin nanofibrils

The rheological study revealed the chitin nanofibrils as an effective “gelling agent” of chitosan acetic solutions. The phenomenon was explained by a chitosan-like surface of chitin nanofibrils and by the interactions inducing orientational cooperativity of chitosan molecules dissolved in close neighborhood of the anisotropic nanofibrils. The addition of bioplasticizers (glycerol or poly(ethylene glycol)), improving mechanical properties of chitosan films, delayed significantly the onset of gelation of the chitosan solutions containing nanofibrils [S2].

The rheology was performed in MATER. The investigation was carried out in cooperation with the Center STRUCTURE. Prof. Morganti, R&D director of the company MAVI SUD S.R.L., was the coordinator of the European project. MAVI is an Italian company producing chitin nanofibrils.

S2. **Mikešová, J.; Hašek, J.; Tishchenko, G.;** Morganti, P. Rheological study of chitosan acetate solutions containing chitin nanofibrils. *Carbohydrate Polymers* 2014, 112, 4 November, p. 753-757. [ASEP \(ID 430054\)](#)

Result 7

Epoxy-POSS nanocomposites

The epoxy-POSS nanocomposite networks with POSS bound or with untethered POSS dispersed in the matrix were prepared and their thermomechanical and electrical properties were determined. The hybrid shows an enhanced thermomechanical behavior and improved thermo-oxidative stability. The POSS effect on mechanical properties includes reinforcement due to POSS aggregates, diminishing of the epoxy network crosslinking density by tethered POSS and physical crosslinking via POSS domains [S19]. Theories of network formation and rubber elasticity as well as the model for particulate composites were applied to interpret the mechanical properties of the hybrids. The homogeneous nanocomposites containing POSS well dispersed as junctions of the network display improved electrical properties, i.e. high resistivity and low dielectric loss factor, in the range of 1-10 wt.% POSS [S26].

The synthesis of nanocomposites as well as determination of their thermomechanical properties and morphology were carried out in MATER Center. Electrical properties were measured in University of West Bohemia, Plzeň. P. Murias was UNESCO student of MATER Center. Both papers were written by the member of MATER Center.

S19. **Matějka, L.; Murias, P.; Pleštil, J.** Effect of POSS on thermomechanical properties of epoxy-POSS nanocomposites. *European Polymer Journal* 2012, 48, 2, p. 260-274. [ASEP \(ID 371537\)](#)

S26. Boček, J.; **Matějka, L.;** Mentlík, V.; Trnka, P.; **Šlouf, M.** Electrical and thermomechanical properties of epoxy-POSS nanocomposites. *European Polymer Journal* 2011, 47, 5, p. 861-872. [ASEP \(ID 359192\)](#)

Result 8

Super-porous thermoresponsive hydrogels

Fast thermo-responsive super-porous hydrogels based on the PNIPAM /SiO₂ nanocomposite were optimized to obtain an increased force (pressure) response to temperature jumps [S17], which is useful for the potential application as mechanical actuators. The aim was achieved by increasing pore wall thickness via changing the monomers' concentration during the hydrogels' cryogenic synthesis.

A 3-fold increase in the force response and a 4-fold increase in modulus were achieved, while the swelling amplitude and the very fast swelling kinetics only slightly deteriorated. As a further development, the super-porous PNIPAM gels were reinforced by acid- and base-resistant TiO₂ nanoparticles (instead of SiO₂) [S30]. The reinforcing effect of TiO₂ was strongly enhanced through the incorporation of small amounts of sodium methacrylate (SMA) as comonomer. A significant pH-responsivity was found in gels with high amounts of chemical crosslinker, in addition to SMA comonomer.

All the work consisted in synthesis and characterization of the nanocomposite porous hydrogels was carried out in MATER. Depa and Huerta-Angeles were UNESCO students in the MATER Center.

S17. **Depa, K.; Strachota, A.; Šlouf, M.; Hromádková, J.** Fast temperature-responsive nanocomposite PNIPAM hydrogels with controlled pore wall thickness: force and rate of T-response. *European Polymer Journal* 2012, 48, 12, p. 1997-2007. [ASEP \(ID 0382267\)](#)

S30. **Huerta-Angeles, G.; Hishchak, K.; Strachota, A.; Strachota, B.; Šlouf, M.; Matějka, L.** Super-porous nanocomposite PNIPAm hydrogels reinforced with titania nanoparticles, displaying a very fast temperature response as well as pH-sensitivity. *European Polymer Journal* 2014, 59, p. 341-352. [ASEP \(ID 435585\)](#)

Result 9

Epoxy-silica hybrids by nonaqueous sol-gel process

The epoxy-silica hybrids have been prepared by the in situ generation of nanosilica using the non-aqueous (NA) sol-gel process [S10, A56]. The solvent-less technique made it possible to avoid drawbacks of the classical aqueous procedure. The NA process enables a better structure control and the corresponding systems show improved homogeneity and thermomechanical properties. Mechanism of the NA sol-gel process initiated with borontrifluoride monoethylamine and evolution of the hybrid structure during polymerization as well as structure, thermomechanical properties, thermal stability and morphology were determined. The method was employed to prepare high performance hybrids showing high T_g and thermal stability. Tetramethoxysilane was used as a precursor of silica and 3-glycidyloxypropyl trimethoxysilane as a coupling agent to strengthen the interphase interaction with an epoxy matrix. The most efficient reinforcement of the epoxy network was achieved by the combination of both alkoxysilanes, showing synergy effects. The hybrids with a low content (~10 wt. %) of the in situ generated silica exhibit dramatic increase in T_g and the high modulus, 335 MPa, up to the temperature 300 °C [A190].

Concept of the research, synthesis of nanocomposites, structure evolution followed by chemorheology, as well as thermomechanical and morphological characterization of the hybrids were performed in MATER Center.

S10. **Ponyrko, S.; Kobera, L.; Brus, J.; Matějka, L.** Epoxy-silica hybrids by nonaqueous sol-gel process. *Polymer* 2013, 54, 23, p. 6271-6282. [ASEP \(ID 397559\)](#)

A56. **Beneš, H.; Galy, J.; Gérard, J. F.; Pleštil, J.; Valette, L.** Solvent-free synthesis of reactive inorganic precursors for preparation of organic/inorganic hybrid materials. *Journal of Sol-Gel Science and Technology* 2011, 59, 3, p. 598-612. [ASEP \(ID 363826\)](#)

A190. **Ponyrko, S.; Kovářová, J.; Kobera, L.; Matějka, L.** High-T_g, heat resistant epoxy-silica hybrids with a low content of silica generated by nonaqueous sol-gel process. *Journal of Applied Polymer Science* 2014, 131, 20, 40899_1-40899_10. [ASEP \(ID 431458\)](#)

Result 10

Natural oils as reagents for polymer decomposition

Natural oils and their derivatives have been used for decomposition of various polymers. Among them, poly(ethylene terephthalate) [S13], polyurethanes [S28, A74, A80] and polycarbonates seemed to be the most willing to decompose resulting in formation of monomers and/or oligomers. The common features of the processes are high reaction rate and low energy consumption. The European patent for the decomposition of polyurethanes by means of bioreagents has been recently granted [S28] and a pilot-plant utilizing this invention on the base of license is now in development.

The inventors and authors from of the MATER Centre are responsible for the main part of experimental work. Other co-inventor and authors synthesized the reagents and performed some additional analyses.

S13. **Beneš, H.**; Slabá, J.; **Walterová, Z.**; **Rais, D.** Recycling of waste poly(ethylene terephthalate) with castor oil using microwave heating. *Polymer Degradation and Stability* 2013, 98, 11, p. 2232-2243. [ASEP \(ID 397261\)](#)

S28. Vlček, T.; **Beneš, H.**; **Kruliš, Z.** Raw material for polyurethane production and process for its preparing from waste polyurethane Ústav makromolekulární chemie AV ČR, v. v. i. 2013. Číslo patentového spisu: EP2480584. Datum udělení patentu: 20.11.2013. http://worldwide.espacenet.com/publicationDetails/originalDocument?FT=D&date=20141203&DB=worldwide.espacenet.com&locale=en_EP&CC=EP&NR=2480584B1&KC=B1&ND=4 [ASEP \(ID 423478\)](#)

A74. **Beneš, H.**; Vlček, T.; Černá, R.; **Hromádková, J.**; **Walterová, Z.**; **Svitáková, R.** Polyurethanes with bio-based and recycled components. *European Journal of Lipid Science and Technology* 2012, 114, 1, p. 71-83. [ASEP \(ID 371338\)](#)

A80. **Beneš, H.**; Černá, R.; **Đuračková, A.**; **Látalová, P.** Utilization of natural oils for decomposition of polyurethanes. *Journal of Polymers and the Environment* 2012, 20, 1, p. 175-185. [ASEP \(ID 375156\)](#)

Result 11

Complex effect of nanofillers in multiphase polymer systems

The effect of nanoparticles on dynamic phase behaviour in both (a) thermoplastic blends and (b) reaction-induced phase separation in polymer modified thermosets was studied. (a) In the thermoplastic blends the combination of interfacial activity of nanofiller graphite nanoplatelets [S7] with reinforcement brought an additional synergistic effects due to, e.g. core shell structures formation. Combination of elastomers and graphite nanoplatelets leads to a thermoplastic material with enhanced strength, stiffness and toughness. (b) The effect of suitably modified nanofillers in polymer-modified thermosets was found to be more complex due to affecting curing kinetics, nucleation of phase separation etc. In the epoxy/PCL(polycaprolactone) system [S12, S21], both ability of layered silicates to cause phase inversion and a strong affecting of (pseudo)phase diagrams were demonstrated. In the case of the functionalized low molecular weight polyoxypropylene and ATBN (amine terminated polybutadiene-acrylonitrile copolymer) [A86], both their combination and modification with clay lead to self assembled complex organic/inorganic structures like bilayer lamellae and blended inclusions. The combination of nanofillers and polymeric components represents an important tool to tailor performance of polymeric systems. At the same time, especially in thermosets, the numerous, in some cases contradictory clay- induced effects must be harmonised to achieve formation of favourable structures properties.

All the work was performed in MATER Center excluding SAXS measurements.

S7. **Thanh, T. D.**; **Kaprálková, L.**; **Hromádková, J.**; **Kelnar, I.** Effect of graphite nanoplatelets on the

structure and properties of PA6-elastomer nanocomposites. *European Polymer Journal* 2014, 50, January, p. 39-45. [ASEP \(ID 422290\)](#)

S12. **Rotrekl, J.; Sikora, A.; Kaprálková, L.; Dybal, J.; Kelnar, I.** Effect of an organoclay on the reaction-induced phase-separation in a dynamically asymmetric epoxy/PCL system. *Express Polymer Letters* 2013, 7, 12, p. 1012-1019. [ASEP \(ID 397267\)](#)

S21. **Rotrekl, J.; Matějka, L.; Kaprálková, L.; Zhigunov, A.; Hromádková, J.; Kelnar, I.** Epoxy/PCL nanocomposites: Effect of layered silicate on structure and behavior. *Express Polymer Letters* 2012, 6, 12, p. 975-986. [ASEP \(ID 381789\)](#)

A86. **Kelnar, I.; Rotrekl, J.; Kaprálková, L.; Hromádková, J.; Strachota, A.** Effect of amine-terminated butadiene-acrylonitrile/clay combinations on the structure and properties of epoxy nanocomposites. *Journal of Applied Polymer Science* 2012, 125, 5, p. 3477-3483. [ASEP \(ID 377314\)](#)

Result 12

Polyurethane degradation in microwave field

The novel fast and low-energy demanding process of recycling of waste polyurethanes was developed in MATER Centre. Its economic and technological feasibility were evaluated thanks to a prototype of semi-lab microwave oven, which enabled to scale-up the process. The originality of developed technology was demonstrated and the European patent was granted [S29]. During the process the waste polyurethane is mixed with a low-molecular-weight polyhydric alcohol and the reaction mixture is subjected to the action of electromagnetic radiation of a frequency ranging from 1 MHz to 10 GHz at the temperature from 50 °C to 300 °C.

The inventors are in majority the members of the MATER Centre.

S29. **Kruliš, Z.; Horák, Z.; Beneš, H.; Hájek, M.** Method of recycling waste polyurethane foams Ústav makromolekulární chemie AV ČR, v. v. i. - Ústav chemických procesů AV ČR, v. v. i. 2014. Číslo patentového spisu: EP2183311. Datum udělení patentu: 03.12.2014. http://worldwide.espacenet.com/publicationDetails/originalDocument?FT=D&date=20141203&DB=worldwide.espacenet.com&locale=en_EP&CC=EP&NR=2183311B1&KC=B1&ND=4 [ASEP \(ID 438317\)](#)

Result 13

Wet-STEM microscopy of polymer nanoparticles

We managed to visualize morphology of polystyrene-block-poly(acrylic acid) vesicles using a novel technique named wet-STEM (wet scanning transmission electron microscopy) [S24]. The wet-STEM microscopy consists in observation of nanoparticles in situ, while they are submerged in thin, electron-transparent layer of the solvent. According to available literature, this was the first time when the wet-STEM microscopy was applied for self-assembled polymer nanoparticles. In the microscopic experiment, we were able not only to see the overall shape and size of the vesicles, but also to follow their shrinkage during the controlled solvent evaporation. After we established the wet-STEM microscopy method in our laboratory, we applied the technique to several other colloidal systems, such as polystyrene nanofibers modified with a photosensitizer [A132], polyelectrolyte-surfactant complexes of poly[3,5-bis(dimethylaminomethyl)-4-hydroxystyrene]-block-poly(ethylene-oxide), where the surfactant was sodium dodecyl sulfate, gold nanorods, which were observed during self-assembly in water/cetyltrimethylammonium bromide solution [A182], and aqueous dispersions of high-molar-mass cellulose-g-polystyrene copolymers. In summary, the data from wet-STEM method contributed to five publications in international journals.

Members of the MAER Center have performed microscopic experiments and contributed to the interpretation of the microscopic data and the publication of results. The investigated systems were

prepared at collaborating institutions (Charles University, Czech Technical University).

S24. **Šlouf, M.; Lapčíková, M.**; Štěpánek, M. Imaging of block copolymer vesicles in solvated state by wet scanning transmission electron microscopy. *European Polymer Journal* 2011, 47, 6, p. 1273-1278. [ASEP \(ID 359964\)](#)

A132. Henke, P.; Lang, K.; Kubát, P.; Sýkora, J.; **Šlouf, M.**; Mosinger, J. Polystyrene nanofiber materials modified with an externally bound porphyrin photosensitizer. *ACS Applied Materials and Interfaces* 2013, 5, 9, p. 3776-3783. [ASEP \(ID 392424\)](#)

A182. Novotný, F.; Wandrol, P.; Proška, J.; **Šlouf, M.** In situ WetSTEM observation of gold nanorod self-assembly dynamics in a drying colloidal droplet. *Microscopy and Microanalysis* 2014, 20, 2, p. 385-393. [ASEP \(ID 429824\)](#)

Result 14

Polybutadiene-based polyurethane nanocomposites

The team from MATER has been working on aliphatic PU nanocomposites containing carbon nanofibers (CNF) as the filler [S9]. These all-aliphatic polybutadiene-based polyurethane/carbon nanofiber (PU/CNF) composites were not described in scientific literature yet. The PU matrix was formed from polybutadiene chain end-capped with primary hydroxyl groups, Krasol LBH-P-2000 (Cray Valley Czech, Kralupy n. Vlt.), butane-1,4-diol and 1,6-disocyanatohexane. Due to the filler shape (nanofibers of ca 150 nm in diameter and several micrometers of length), only very low filler loading (up to 2.25 wt. %) was possible without loss of elastomeric properties of the nanocomposite material. The best functional properties was achieved with PU/CNF composite containing 0.75 wt. % of CNF.

Joint paper is the result of the Czech and Slovak cooperation in the framework of priority inter-academic projects between ASCR and SAV. The team of MATER prepared the concept of the work and the manuscript. All syntheses were realized in MATER, partially during visits of Slovak colleagues in IMC. Furthermore, MATER provided the majority of composite characteristic such as all mechanical and thermal analyses and part of microscopy tests (TEM, AFM).

S9. **Špírková, M.**; Duszová, A.; **Poreba, R.**; **Kredatusová, J.**; Bureš, R.; Fáberová, M.; **Šlouf, M.** Thermoplastic polybutadiene-based polyurethane/carbon nanofiber composites. *Composites Part B-Engineering* 2014, 67, December, p. 434-440. [ASEP \(ID 431006\)](#)

Result 15

Nanoparticles for multiple immunolabeling

Reproducible preparation of stable palladium nanoparticles, which are suitable for multiple immunolabeling of biomacromolecules, was developed and described. Our experiments showed that Pd nanoparticles could be conjugated with antibodies and used together with standard Au nanospheres in order to detect multiple molecules within one biological specimen. The Pd nanoparticles could be differentiated from the Au nanoparticles on final TEM micrographs due to their different chemical composition and/or shape. The research resulted in 5 publications, 3 utility models and 1 Czech patent. The nanoparticles were synthesized and characterized in the laboratory of electron microscopy. The paper [S27] described preparation, stability and immunolabeling with Pd-nanospheres, which were prepared by controlled reduction of PdCl₂ with sodium citrate; the nanoparticle size could be tuned by changing pH and concentration of initial solutions. Synthesis of Pd-nanocubes, whose differentiation from Au-nanospheres was simpler and faster, being based on their shape, was described in [A102]. The most promising results were summarized in the publication

[A202].

Members of the Center have performed synthesis and microscopic characterization of Pd nanoparticles, and participated in the preparation and characterization of other nanoparticles, evaluation of results and the publication preparation. Cooperating members from other centers have helped with scattering experiments. The immunolabeling tests have been done by external partners.

S27. **Šlouf, M.; Pavlova, E.; Bhardwaj, M.; Pleštil, J.**; Onderková, H.; Philimonenko, A.; Hozák, P. Preparation of stable Pd nanoparticles with tunable size for multiple immunolabeling in biomedicine. *Materials Letters* 2011, 65, 8, p. 1197-1200. [ASEP \(ID 359122\)](#)

A102. **Šlouf, M.; Hrubý, M.; Bakaeva, Z.; Vlková, H.**; Nebesářová, J.; Philimonenko, A.; Hozák, P. Preparation of stable Pd nanocubes and their use in biological labeling. *Colloids and Surfaces B-Biointerfaces* 2012, 100, 1 December, p. 205-208. [ASEP \(ID 381927\)](#)

A202. Philimonenko, V.; Philimonenko, A.; Šloufová, I.; **Hrubý, M.**; Novotný, F.; Halbhuber, Z.; Krivjanská, M.; Nebesářová, J.; **Šlouf, M.**; Hozák, P. Simultaneous detection of multiple targets for ultrastructural immunocytochemistry. *Histochemistry and Cell Biology* 2014, 141, 3, p. 229-239. [ASEP \(ID 434293\)](#)

Result 16

Blends of cycloolefin copolymers (COC) with processing-improved properties

PP/COC and HDPE/COC blends with the reinforcing COC component were prepared thanks to controlled development of fibrous morphology. In our previous work on PP/COC blends [A54], the carefully prepared blends contained long COC fibers, which substantially improved tensile performance. Considering this result and considerations based on equivalent box model, the research was aimed for the controlled development of fibrous morphology in HDPE/COC blends [S20]. All prepared systems were fully characterized by electron microscopy and physical methods in macro and micro scale as documented in [S20] and [A54]. Moreover, selected macromechanical and micromechanical properties of blends were compared with theoretical predictions given by three models: (i) equivalent box model, which supposes isotropic, particulate morphology, (ii) Halpin-Tsai model, which is based on anisotropic, fibrous morphology, and (iii) rule of mixtures, also known as additivity rule. The mechanical performance of blends was higher than expected by theoretical predictions due to unusually high interface adhesion and consequent synergistic effects.

All authors are from MATER center.

S20. **Vacková, T.; Šlouf, M.; Nevoralová, M.; Kaprálková, L.** HDPE/COC blends with fibrous morphology and their properties. *European Polymer Journal* 2012, 48, 12, p. 2031-2039. [ASEP \(ID 382273\)](#)

A54. **Vacková, T.; Šlouf, M.; Nevoralová, M.; Kaprálková, L.** Processing-improved properties and morphology of PP/COC blends. *Journal of Applied Polymer Science* 2011, 122, 2, p. 1168-1175. [ASEP \(ID 362902\)](#)

Research Report of the team in the period 2010–2014

Institute	Institute of Macromolecular Chemistry AS CR, v.v.i.
Scientific team	4 STRUCTURE

Result 1

Describing structural diversity of nanostructured formulations of active pharmaceutical ingredients (APIs): experimental and computational procedures

Oral administration of ca. 40% of newly discovered chemical entities (potential drugs) is a problematic choice since this may pose a risk of insufficient exposure. Pharmaceutical research thus focuses on increasing the absorbency of these substances by reformulating them into the form of multicomponent nanostructured solids (amorphous or semicrystalline) exhibiting controlled drug release. Therefore, since 2010 the research activities of the Center STRUCTURE have focused on developing the analytical procedures that cover all aspects of physicochemical and structural

characterization of these novel pharmaceutical systems. In this respect, we focused on characterizing structural diversity of strongly disordered and amorphous APIs, and developed the protocol based on principle component analysis of ^{13}C CP/MAS NMR and FTIR making possible to find relations between the molecular structure disorder and a method of the API preparation [S9 [ASEP \(ID 391506\)](#)]. Further, the methodology utilizing ^{19}F MAS NMR spectroscopy and principle component analysis was extended to reveal subtle structural differences in the molecular arrangement of amorphous forms of fluorinated drugs in nanosized domains [S27 [ASEP \(ID 359458\)](#); A122 [ASEP \(ID 383512\)](#)]. We also devoted a lot of time to the synthesis and characterization of novel formulations of APIs as solid dispersions in polymer matrices. In this respect, we demonstrated extreme structural diversity of this drug formulation. Consequently we optimized an NMR methodology for reliable and time-saving discrimination of different types of these pharmaceutical dispersions [S2 [ASEP \(ID 426114\)](#)]. Because unambiguous x-ray identification of crystalline compounds dispersed in polymeric crystalline matrix is complicated, NMR crystallography based on the precise measurement of ^1H and ^{13}C NMR chemical shifts represents a powerful alternative. In this context we developed a robust method for the assignment and simulation of 2D heteronuclear ^1H - ^{13}C correlations. The proposed procedure statistically evaluates the differences between measured and GIPAW calculated ^1H and ^{13}C chemical shifts. The values of the covariance of these differences are elucidative for the spectral assignment process [A157 [ASEP \(ID 397104\)](#), A191 [ASEP \(ID 429249\)](#)]. Overall, the obtained data revealed that there is relation between the constitution and molecular weight of polymer excipients and dissolution profiles, confirming thus that the type of solid dispersion can be controlled and fine tuning of the drug release covering a wide range of dissolution rates is accessible.

The contribution from the "STRUCTURE" team in obtaining the presented results was paramount as the syntheses of all investigated systems, the experimental design, all solid-state NMR, FTIR experiments and their interpretations, concluding analyses of all the obtained results as well as the design of structural models, formulations of conclusions and future perspectives were all conducted by the researchers of this team. The DFT analyses were made by collaborating members from another Centre of the Institute.

S2. **Policianová, O.; Brus, J.; Hrubý, M.; Urbanová, M.; Zhigunov, A.; Kredatusová, J.; Kobera, L.** Structural diversity of solid dispersions of acetylsalicylic acid as seen by solid-state NMR. *Molecular Pharmaceutics* 2014, 11, 2, p. 516-530. [ASEP \(ID 426114\)](#)

S9. **Urbanová, M.; Štuncová, A.; Brus, J.; Beneš, H.; Skořepová, E.; Kratochvíl, B.; Čejka, J.; Šeděnková, I.; Kobera, L.; Policianová, O.; Štunc, A.** Characterizing crystal disorder of trospium chloride: a comprehensive, ^{13}C CP/MAS NMR, DSC, FTIR, and XRPD study. *Journal of Pharmaceutical Sciences* 2013, 102, 4, p. 1235-1248. [ASEP \(ID 391506\)](#)

S27. **Brus, J.; Urbanová, M.; Šeděnková, I.** Brusová, H. New perspectives of ^{19}F MAS NMR in the characterization of amorphous forms of atorvastatin in dosage formulations. *International Journal of Pharmaceutics* 2011, 409, 1/2, p. 62-74. [ASEP \(ID 359458\)](#)

A122. **Urbanová, M.; Brus, J.; Šeděnková, I.; Policianová, O.; Kobera, L.** Characterization of solid polymer dispersions of active pharmaceutical ingredients by ^{19}F MAS NMR and factor analysis. *Spectrochimica Acta Part A-Molecular and Biomolecular Spectroscopy* 2013, 100, 1 January, p. 59-66. [ASEP \(ID 383512\)](#)

A157. **Czernek, J.; Brus, J.** Theoretical predictions of the two-dimensional solid-state NMR spectra: a case study of the ^{13}C - ^1H correlations in metergoline. *Chemical Physics Letters* 2013, 586, 24 October, p. 56-60. [ASEP \(ID 397104\)](#)

A191. **Czernek, J.; Brus, J.** The covariance of the differences between experimental and theoretical chemical shifts as an aid for assigning two-dimensional heteronuclear correlation solid-state NMR spectra. *Chemical Physics Letters* 2014, 608, 21 July, p. 334-339. [ASEP \(ID 429249\)](#)

Result 2

Insights into the structure and phase transformations of inorganic polymers

Nanostructured materials offer enhanced physicochemical properties because of the large interfacial area. Typically inorganic aluminosilicate polymers (geopolymers) with specifically synthesized nano-sized zeolites are promising materials not only for building industry but also for catalysis or sorption of pollutants. The structural characterization of these aluminosilicates, however, continues to be a challenge. To circumvent complications resulting from the amorphous and semicrystalline character of the aluminosilicate matrix, and from the low concentrations of nano-sized crystallites, we have proposed and successfully applied several experimental procedures. First we optimized ss-NMR procedures for detail structural characterization of the inorganic matrix [S26 [ASEP \(ID 379050\)](#)]. In this respect, we performed a comprehensive structural study of these systems by employing a wide range of advanced ss-NMR techniques. The application of ^{27}Al MQ/MAS and $\{^1\text{H}\}$ -REDOR- ^{27}Al MQ/MAS NMR spectroscopies combined with the recently developed biaxial shearing transformations [S31 [ASEP \(ID 425217\)](#)] significantly improved understanding of the recorded spectra. The two-component character of the prepared systems was revealed and the ^{27}Al resonances of Brønsted- and Lewis-acid sites were clearly identified. Moreover, we found out that the synthesis of nanosized zeolites in the amorphous matrix can be controlled and artificially initiated. The tendency for the nanozeolites to be specifically synthesized in the amorphous matrix can be attributed to the formation of partially arranged domains, immobilization of water molecules and the formation of Brønsted- or Lewis-acid sites. If all these factors synergistically cooperate, the normally amorphous systems can be converted to the semicrystalline materials with controllable amounts of nanosized zeolitic domains. The aluminosilicate geopolymers generally exhibit extreme variability in their structure. This fact call for the development of a fast procedure allowing reliable characterization of these systems that can be: *i)* completely amorphous; *ii)* x-ray amorphous with a nanocrystalline phase; and/or *iii)* semicrystalline. Although ^{27}Al MAS NMR spectra can be recorded within extremely short experimental time their lineshape is usually featureless and complicated by quadrupolar interactions. In this respect, however, we found out that principle component of these ^{27}Al MAS NMR spectra provides unambiguously distinguished all these materials [A158 [ASEP \(ID 397219\)](#)]. Because of the measurement time of ^{27}Al MAS NMR spectra is significantly shorter than that of ^{29}Si MAS NMR data the proposed procedure is particularly suitable for the analysis of large sets of specifically synthesized geopolymers in which formation of limited fractions of nanocrystalline phase is desired.

The contribution from the "STRUCTURE" team in obtaining the demonstrated results was substantial and key for formulating the conclusions. The design of the syntheses of the inorganic polymers, solid-state NMR experiments and their interpretations, as well as concluding remarks were all conducted by the researchers of this team. Mechanical testing and x-ray powder diffraction analyses were provided by the colleagues from the collaborating teams.

S26. **Brus, J.; Kobera, L.; Urbanová, M.**; Koloušek, D.; **Kotek, J.** Insights into the structural transformations of aluminosilicate inorganic polymers: a comprehensive solid-state NMR study. *Journal of Physical Chemistry C* 2012, 116, 27, p. 14627-14637. [ASEP \(ID 379050\)](#)

S31. **Kobera, L.; Brus, J.**; Klein, P.; Dědeček, J.; **Urbanová, M.** Biaxial Q-shearing of ^{27}Al 3QMAS NMR spectra: insight into the structural disorder of framework aluminosilicates. *Solid State Nuclear Magnetic Resonance* 2014, 57-58, February–April, p. 29-38. [ASEP \(ID 425217\)](#)

A158. **Urbanová, M.; Kobera, L.; Brus, J.** Factor analysis of ^{27}Al MAS NMR spectra for identifying nanocrystalline phases in amorphous geopolymers. *Magnetic Resonance in Chemistry* 2013, 51, 11, p. 734-742. [ASEP \(ID 397219\)](#)

Result 3

Control over the self-assembly and dynamics of metallacarborane nanorotors

Metallacarboranes, as bulky compounds with delocalized charge that participate in weak non-covalent interactions represent a unique class of building blocks for nanochemistry. We utilized the aforementioned features in hybrid metallacarborane/polymer nanocomposites prepared *via* the spontaneous precipitation of the cobalt bis(dicarbollide)(-1) anion with nonionic PEO and two isomers of polycationic PVP. The advanced techniques of solid-state NMR spectroscopy, combined with WAXS measurements and quantum chemical calculations revealed considerable versatility in the packing, dynamics and binding capability of CoD^- ions upon forming the nanocomposites. The formation of $\text{PEO}/\text{Na}^+/\text{CoD}^-$ is based on weak dihydrogen interactions with the PEO matrix, resulting in evenly dispersed and uniquely organized Na^+ and CoD^- ions adopting unique periodic long-range order, resembling thus formation of unusual flexible (plastic) crystals [S25 [ASEP \(ID 360030\)](#)]. In contrast, the presence of positive charges in the protonated PVP leads to the accumulation of substantially larger amounts of CoD^- ions within the $\text{PVP}/\text{H}^+/\text{CoD}^-$ composites. The metallacarboranes are packed in nanosized-domains along the charged and fairly rigid PVP chains. We established that the charges position in the macromolecules has a great impact on the CoD^- assembly. Although the charge is somehow separated from the periphery of the P2VP chain, thereby preventing direct contact with the CoD^- anions, $\text{N}=(\text{H}^+)$ groups interact directly with the CoD^- anions in $\text{P4VP}/\text{H}^+/\text{CoD}^-$. Furthermore, CoD^- anions are aligned parallel to the main chain in the P2VP-nanocomposite, but in the case of the P4VP system, the anions are arranged perpendicular to the main chain [S24 [ASEP \(ID 432034\)](#)]. Consequently, through selection of the polymer matrix, one can control not only the self-assembly process, but also the segmental dynamics of all of the subunits within the metallacarborane/polymer nanocomposites. It was revealed that the CoD^- ions execute uniaxial rotational motions and large-amplitude uniaxial fast jumps in all of the nanocomposites. Macromolecules thus represent a rigid stator providing sufficient free volume for CoD^- rotators. This indicates that the nanocomposites represent nanorotors with motional amplitudes that are controllable by the nature of the polymer matrix. Overall, we found out that the highly regular, periodically ordered structures are formed when the strong electrostatic interactions $\text{CoD}^- \dots \text{Na}^+$ are balanced by the relatively weak bonding $\text{PEO} \dots \text{CoD}^-$ during the two-step self-assembly process. In contrast, as a result of unbalanced polymer/metallacarborane interactions combined with structural imperfections of PVP polymer chains, such as atacticity, random-coil conformation and restricted conformation flexibility, the creation of long-range ordered structures is prevented. These findings encourage us to study new types of polymer/metallacarborane amphidynamic nanocomposites. Supramolecular synthesis that relies on weak non-covalent interactions, however, must overcome many fundamental obstacles and requires detail understanding of interaction possibilities of the building blocks. In this respect, we have made first steps in understanding the role of alkali metal ions in self-assembly processes [S30 [ASEP \(ID 360502\)](#)].

The contribution from the "STRUCTURE" team in obtaining the demonstrated results lies in the design, practical implementation, analysis, interpretation of all the applied solid-state NMR experiments, as well as concluding remarks and future perspectives in the synthesis of molecular machines were all conducted by the researchers of this team. In particular, analysis of segmental dynamics conducted by the researchers of this team represents the key information for the understanding of physicochemical behavior of the prepared complex. Synthesis of the systems and x-ray diffraction analysis was carried out by the colleagues from the collaborating teams.

S24. **Brus, J.; Zhigunov, A.; Czernek, J.; Kobera, L.;** Uchman, M.; Matějčiček, P. Control over the self-assembly and dynamics of metallacarborane nanorotors by the nature of the polymer matrix: a solid-state NMR study. *Macromolecules* 2014, 47, 18, p. 6343-6354. [ASEP \(ID 432034\)](#)

S25. Matějčiček, P.; **Brus, J.; Jigounov, A.; Pleštil, J.;** Uchman, M.; Procházka, K.; Gradzielski, M. On the structure of polymeric composite of metallacarborane with poly(ethylene oxide). *Macromolecules*

2011, 44, 10, p. 3847-3855. [ASEP \(ID 360030\)](#)

S30. **Kříž, J.; Dybal, J.**; Makrlík, E.; Vaňura, P.; Moyer, B. A. Interaction of cesium ions with calix[4]arene-bis(t-octylbenzo-18-crown-6): NMR and theoretical study. *Journal of Physical Chemistry B* 2011, 115, 23, p. 7578-7587. [ASEP \(ID 360502\)](#)

Result 4

Aniline oligomers and their role in the formation of polyaniline nanostructures

The molecular structure of the aniline oligomers produced in the first part of the reaction and their aggregation has been studied in several experiments using vibration spectroscopy. The oligomers created on a gold support were studied using surface resonance Raman spectroscopy in S1 [[ASEP \(ID 424583\)](#)]. This material is very perspective in the preparation of nanocomposites, electronic devices, sensors, optical emitters and many other fields. A new insight into the structure of the early products of aniline oxidation based on their Raman spectra is reported in S5 [[ASEP \(ID 426946\)](#)]. The aniline oligomer microspheres prepared at various basicity of the medium were transformed into carbon-like structure. The changes in the molecular structure occurring during the carbonization have been observed by Raman and Fourier transform infrared spectroscopies in S7 [[ASEP \(ID 389210\)](#)]. The progress of aniline oxidation with ammonium peroxydisulfate in alkaline media when microspheres are the main morphology was monitored using in-situ ATR FTIR spectroscopy developed in our laboratory in A217 [[ASEP \(ID 438333\)](#)]. Several processes connected with the various stages of aniline oxidation have been detected in the spectra in real time.

The spectroscopic analysis and complete interpretation of the obtained spectra were provided by the members of the Centre. Vibrational spectra were calculated by the quantum chemical methods at the density functional theory (DFT) level also by the member of the Centre. The samples were prepared by collaborating members from another Centre of the Institute.

S1. **Trchová, M.; Morávková, Z.; Dybal, J.; Stejskal, J.** Detection of aniline oligomers on polyaniline-gold interface using resonance Raman scattering. *ACS Applied Materials and Interfaces* 2014, roč. 6, č. 2, s. 942-950. ISSN 1944-8244. [ASEP \(ID 424583\)](#)

S5. **Trchová, M.; Morávková, Z.; Bláha, M.; Stejskal, J.** Raman spectroscopy of polyaniline and oligoaniline thin films. *Electrochimica Acta* 2014, 122, 10 March, p. 28-38. [ASEP \(ID 426946\)](#)

S7. **Morávková, Z.; Trchová, M.; Tomšík, E.; Zhigunov, A.; Stejskal, J.** Transformation of oligoaniline microspheres to platelike nitrogen-containing carbon. *Journal of Physical Chemistry C* 2013, 117, 5, p. 2289-2299. [ASEP \(ID 389210\)](#)

A217. **Šeděnková, I.; Stejskal, J.; Trchová, M.** In situ infrared spectroscopy of oligoaniline intermediates created under alkaline conditions. *Journal of Physical Chemistry B* 2014, 118, 51, p. 14972-14981. [ASEP \(ID 438333\)](#)

Result 5

Carbonization of aniline oligomers and conjugated polymers

The carbonization of conducting polymers, such as polyaniline, leads to new materials, nitrogen-containing carbons, which represent the crossroads between conducting polymers and carbons. They have also recently become popular catalyst supports. It is an important fact that the morphology of the original polymer is preserved after carbonization. The changes in the molecular structure occurring during the carbonization were conveniently observed by Raman spectroscopy in [[ASEP \(ID](#)

[360012](#), [ASEP \(ID 378731\)](#)]. The influence of aniline oligomers on the stability of polyaniline and its films on the various substrates was detected. The enhanced thermal stability of polyaniline coatings and the role of ethanol on chain ordering of carbonized polyaniline were elucidated in [[ASEP \(ID 378721\)](#), [ASEP \(ID 392165\)](#)].

The spectroscopic analysis and complete interpretation of the obtained infrared and Raman spectra were provided by the members of the Centre. Carbonization of samples was realized by other collaborating members from other Centres of the Institute.

A62. **Rozlívková, Z.; Trchová, M.; Exnerová, M.; Stejskal, J.** The carbonization of granular polyaniline to produce nitrogen-containing carbon. *Synthetic Metals* 2011, 161, 11/12, p. 1122-1129. [ASEP \(ID 360012\)](#))

A109. **Morávková, Z.; Trchová, M.; Exnerová, M.; Stejskal, J.** The carbonization of thin polyaniline films. *Thin Solid Films* 2012, 520, 19, p. 6088-6094. [ASEP \(ID 378731\)](#)

S13. **Morávková, Z.; Trchová, M.; Tomšík, E.; Čechvala, J.; Stejskal, J.** Enhanced thermal stability of multi-walled carbon nanotubes after coating with polyaniline salt. *Polymer Degradation and Stability* 2012, 97, 8, p. 1405-1414. [ASEP \(ID 378721\)](#)

A141. **Morávková, Z.; Trchová, M.; Tomšík, E.; Stejskal, J.** Influence of ethanol on the chain-ordering of carbonised polyaniline. *Chemical Papers* 2013, 67, 8, s. 919-932. [ASEP \(ID 392165\)](#)

Result 6

Role of hydration in micellization of Pluronic block copolymers

The role of hydration in the process of micellization of block copolymers was explored by vibrational spectroscopy and DFT calculations for a series of Pluronics [S5] and in the modified Pluronic P85 with carboxyl groups at each end of the chain (CAE85) [A85, S25]. It was found that interacting water in solutions of Pluronics is adequately described by five coordination types determined by the number of donor/acceptor hydrogen bonds. Upon micellization of the modified Pluronic, carboxyl end groups are dissociated due to energy change accompanying the formation of micelle interface and hydrogen bonded structures in the hydration shell. Unlike P85, CAE85 does not form gel: the mesoscale event of micellization altered the nanoscale charge formation as well as the macroscale process of gelation.

Members of the Centre have performed characterization of the systems by ATR FTIR and Raman spectroscopy, and by quantum chemical calculations. The chemical modification of the Pluronic sample and X-ray scattering measurements were provided by collaborating members from other Centres of the Institute.

S5. **Šturcová, A.; Dybal, J.; Zhigunov, A.; Kotov, N.; Braunová, A.** The effect of micellization-induced deprotonation on the associative behavior of a carboxyl modified Pluronic P85. *Soft Matter* 2014, 10, 40, p. 8011-8022. [ASEP \(ID 432036\)](#)

S25. **Šturcová, A.; Schmidt, P.; Dybal, J.** Role of hydration and water coordination in micellization of Pluronic block copolymers. *Journal of Colloid and Interface Science* 2010, 352, 2, 415-423. [ASEP \(ID 348377\)](#)

A85. **Šturcová, A.; Dybal, J.; Braunová, A.; Pechar, M.** Micellization-induced deprotonation of thermoresponsive surfactant CAE-85 — the telechelic carboxylic group derivative of Pluronic P85. *Vibrational Spectroscopy* 2011, 57, 2, p. 300-305. [ASEP \(ID 365712\)](#)

Result 7

Quantitative MALDI-TOF mass spectrometry of modified polymers and oligomers

To be used in advanced applications as compatibilizers, drug carriers etc. modified polymers have to be adequately characterized. Matrix assisted laser desorption/ionization (MALDI), usually coupled to time-of-flight (TOF) analyzer, has become the major method of analyzing synthetic polymers, including those modified, with mass spectrometry. This analytical technique generates a mass spectrum that gives information about repeat units, end groups, and the molecular weight distribution. Some major drawbacks still remain as, for instance, the inhomogeneous crystallization of sample/matrix mixtures, frequently associated with fractionation according to molecular weight or composition. Resulting variability of signal intensities and resolution between different spots of the same sample leads to shot-to-shot and spot-to-spot lack of reproducibility being one of the major factors limiting the application of MALDI mass spectrometry for quantitation purposes. The problem was analyzed both theoretically and experimentally, the recommendation for dealing with this shortcoming were established and an analytical procedure allowing for modified polymers quantification was designed and verified that combine the method of standard addition with the method of internal standard. [ASEP (ID 359037)] Subsequently the results were used in MALDI-TOF mass spectrometric analysis of acetylated maltodextrins [ASEP (ID 393110)], thermosensitive telechelic poly(ethylene glycoles) [ASEP (ID 431359)] and products of aniline polymerization [ASEP (ID 427487)].

The project was designed and carried out solely by members of the Center.

S15. **Walterová, Z.; Horský, J.** Quantification in MALDI-TOF mass spectrometry of modified polymers. *Analytica Chimica Acta* 2011, 693, 1/2, p. 82-88. [ASEP \(ID 359037\)](#)

A147. Smrčková, P.; **Horský, J.**; Šárka, E.; Koláček, J.; **Netopilík, M.**; **Walterová, Z.**; Kruliš, Z.; Synytsya, A.; Hrušková, K. Hydrolysis of wheat B-starch and characterisation of acetylated maltodextrin. *Carbohydrate Polymers* 2013, 98, 1, p. 43-49. [ASEP \(ID 393110\)](#)

A186. **Stejskal, J.**; **Bober, P.**; **Trchová, M.**; **Horský, J.**; **Pilař, J.**; **Walterová, Z.** The oxidation of aniline with p-benzoquinone and its impact on the preparation of the conducting polymer, polyaniline. *Synthetic Metals* 2014, 192, June, p. 66-73. [ASEP \(ID 427487\)](#)

A 206. Sergeeva, O.; Vlasov, P. S.; Domnina, N. S.; **Bogomolova, A.**; Konarev, P. V.; Svergun, D. I.; **Walterová, Z.**; **Horský, J.**; **Štěpánek, P.**; **Filippov, S.** Novel thermosensitive telechelic PEGs with antioxidant activity: synthesis, molecular properties and conformational behaviour. *RSC Advances* 2014, 4, 79, p. 41763-41771. [ASEP \(ID 431359\)](#)

Result 8

Size-exclusion chromatography of complex branched polymers

Most of polymers encountered in everyday life are branched, examples ranging from polyolefins to polysaccharides. Branching is very important in various applications, affecting mechanical and adhesive properties and - in the case of starch - even digestibility. Molecular architecture of a polymer (graft, comb, random etc.), describing how the chain is branching, is essential for advanced applications such as functional supramolecular structures. Size exclusion chromatography (SEC) is a key method for determination of polymer branching and thus for characterization of complex tailored-made polymer systems; nevertheless, many problems remain. The project solved two of them. A new method for the decomposition of non-baseline-resolved multimodal elution curves of SEC with the concentration, light scattering and viscosity detection was developed. The method makes possible the individual characterization of the polymer-sample components, represented by the peaks forming multimodal elution curves, and reduces the error in the calculation of molecular-

weight averages. The procedure was demonstrated on narrow molecular-weight distribution polystyrene standards and their mixture as well as on a grafted polymer sample. [\[ASEP \(ID 424807\)\]](#) Further, the SEC separation of a randomly branched polymer was theoretically examined. A model of the SEC separation of randomly branched polymer with tetrafunctional branch points enabling the estimation of local dispersity was developed. Local dispersity was demonstrated to depend on elution volume and degree of branching and to reach non-negligible values in the area of the beginning of the elution curve. [\[ASEP \(ID 380707\)\]](#)

The project was designed and carried out by a member of the Centrum, Dr. Netopilík, except the preparation of a graft copolymer.

S3. **Netopilík, M.; Janata, M.** Decomposition of size-exclusion chromatography elution curves of complex branched polymers. *Journal of Chromatography A* 2014, 1330, 21 February, p. 14-19. [ASEP \(ID 424807\)](#)

S11. **Netopilík, M.** Size-exclusion-chromatography separation of randomly branched polymers with tetrafunctional branch points and local dispersity. *Journal of Chromatography A* 2012, 1260, 19 October, p. 97-101. [ASEP \(ID 380707\)](#)

Result 9

Elucidation of structure and function of multifunctional nuclease TBN1 with phospholipase activity

With use of X-ray structure analysis we described the three-dimensional structure of plant nuclease TBN1 with confirmed anticancer effects. Nuclease TBN1 inhibits growth of human tumors grafted on mouse models. We explained the structural reasons behind the enzyme stability and the role of glycosylation in it. Our results also proved that TBN1 is not only capable of cleavage of double and single strand DNA and RNA but also shows phospholipase C-like activity. The described details of the active site and its closest surroundings clearly uncover the principles of interaction of this nuclease with structured nucleic acids and explaining the unusually broad spectrum of activity of this nuclease. Our discovery of the phospholipase C-like activity also suggests a new mechanism of involvement in apoptotic processes and senescence of plant cells. Our results were used for site-directed mutagenesis and further studies of application against cancer. [\[ASEP \(ID 388502\)\]](#).

Our laboratory performed all the experiments and interpretations of the structural studies and also manuscript preparation. Work on these enzymes was done in long term collaboration with the Biology Centre in České Budejovice and Institute of Chemical Technology in Prague.

S6. **Koval, T.;** Lipovová, P.; Podzimek, T.; Matoušek, J.; **Dušková, J.;** **Skálová, T.;** **Štěpánková, A.;** **Hašek, J.;** **Dohnálek, J.** Plant multifunctional nuclease TBN1 with unexpected phospholipase activity: structural study and reaction-mechanism analysis. *Acta Crystallographica Section D-Biological Crystallography* 2013, 69, 2, p. 213-226. [ASEP \(ID 388502\)](#)

Result 10

Explanation of the role of protein HeID of bacterial RNA polymerase

We have explained the function of protein factor HeID in transcription catalyzed by RNA polymerase of *B. subtilis* [\[ASEP \(ID 435141\)\]](#). It was proved that HeID interacts with RNAP between the second channel and the alpha subunit of this multiprotein complex and its effect can be enhanced by the delta subunit of RNAP. HeID stimulates recycling of DNA template in transcription in

an ATP-dependent manner. This contribution in the research of bacterial transcription is potentially significant for inhibition of some pathogens.

Our laboratory has performed bioinformatics analysis, some protein production and purification steps, activity data analysis, and preparation of parts of the manuscript.

Wiedermannová, J.; Sudzinová, P.; **Koval', T.**; Rabatinová, A.; Šanderová, H.; Ramaniuk, O.; Rittich, Š.; **Dohnálek, J.**; Fu, Z.; Halada, P.; Lewis, P.; Krásný, L. Characterization of HelD, an interacting partner of RNA polymerase from *Bacillus subtilis*. *Nucleic Acids Research* 2014, 42, 8, p. 5151-5163. [ASEP \(ID 435141\)](#)

Result 11

Explanation of structure and function of receptors and ligands involved in recognition of malignant cells by NK cells

With use of x-ray diffraction methods we determined five structures of protein ligands involved in interaction with surface receptors of natural killer cells and two structures of extracellular parts of a mouse NK receptor Klrb1. Our contribution includes the first structure of NK receptor of the Klrb family of receptors relying on the C-type lectin-like fold. Our structures deposited in the Protein Data Bank represent a significant portion (~ 25 %) of the overall structural knowledge on ligands of the NK cell receptors of this type. These include the extracellular part of mouse Clr-g, a ligand of the activation receptor NKR-P1F and of protein LLT1 – a ligand of receptor Klrb1 of human NK cells. [\[ASEP \(ID 212952\)\]](#).

Members of our team performed all crystallographic tasks, including structure interpretation and completion of results and manuscript preparation. The results were obtained in a long term collaboration with colleagues from the Charles University in Prague and the Institute of Microbiology AS CR in Prague

S17. **Kolenko, P.**; Rozbeský, D.; Vaněk, O.; Kopecký, V. Jr.; Hofbauerová, K.; Novák, P.; Pompach, P.; **Hašek, J.**; **Skálová, T.**; Bezouška, K.; **Dohnálek, J.** Molecular architecture of mouse activating NKR-P1 receptors. *Journal of Structural Biology* 2011, 175, 3, p. 434-441. [ASEP \(ID 363604\)](#)

A88. **Kolenko, P.**; Rozbeský, D.; Vaněk, O.; Bezouška, K.; **Hašek, J.**; **Dohnálek, J.** Structure of the H107R variant of the extracellular domain of mouse NKR-P1A at 2.3 Å resolution. *Acta Crystallographica Section F* 2011, 67, 12, p. 1519-1523. [ASEP \(ID 369318\)](#)

S10. **Skálová, T.**; Kotýnková, K.; **Dušková, J.**; **Hašek, J.**; **Koval, T.**; **Kolenko, P.**; Novák, P.; Man, P.; Hanč, P.; Vaněk, O.; Bezouška, K.; **Dohnálek, J.** Mouse Clr-g, a ligand for NK cell activation receptor NKR-P1F: crystal structure and biophysical properties. *Journal of Immunology* 2012, 189, 10, p. 4881-4889. [ASEP \(ID 212952\)](#)

Result 12

Explanation of influence of chitin nanofibers on rheological properties of chitosan

We have explained changes of rheological properties of chitosan water solutions with chitin nanofibers, glycerol and polyethyleneglycol. Addition of nanofibers with modified surface leads to formation of oriented microdomains in the polycation solution, that fill the entire volume already at nanofiber concentration around 8% and bring significant thixotropic properties of the system [\[ASEP \(ID 236673\)\]](#). Polyethyleneglycol and glycerol increase viscosity of chitosan solution and by influencing the dielectric constant decrease the size of the organized domains around the nanoparticles. The newly found experimental and theoretical data provide a basis necessary for targeted preparation of oriented chitosan nanofibers and foils with required properties. Chitosan-

based materials are suitable for production of biocompatible compounds, for targeted drug delivery and, with respect to relatively low price, also as foil packaging for food industry.

Our laboratory has prepared the samples for analyses, performed interpretation of X-ray scattering and diffraction data, formulated principles of microdomains behavior and prepared the manuscript.

A197. **Mikešová, J.; Hašek, J.; Tishchenko, G.**; Morganti, P. Rheological study of chitosan acetate solutions containing chitin nanofibrils. *Carbohydrate Polymers* 2014, 112, 4, p. 753-757. [ASEP \(ID 430054\)](#)

Research Report of the team in the period 2010–2014

Institute	Institute of Macromolecular Chemistry AS CR, v.v.i.
Scientific team	5 OPTOEL

Result 1 **Hybrid conducting polymer–silver composites**

Conducting polymers, such as polyaniline, have conductivity at the semiconductor level, i.e. units of S/cm. The level of conductivity has to be increased for some applications, viz. for conducting inks used for printing of flexible electronics. The preparation of composites with metals, such as silver, seems to be the obvious route and was reviewed [ASEP \(ID 392164\)](#). Polyaniline and polypyrrole have been used in the preparation of such composites. Two research strategies have been tested [ASEP \(ID 426956\)](#). In the first, respective monomers have been oxidized with silver nitrate to corresponding polymer–silver composites in a single step. The second approach used the separate preparation of conducting polymers followed by their ability to reduce silver ions to metallic silver. All together 23 research papers have been published on this topic in 2010–2014 by members of the Centre. Even

though the conductivities over 1000 S/cm have been found for many composites [ASEP \(ID 353218\)](#), the mass content of silver had to be high to reach the volume fraction corresponding to the percolation threshold [ASEP \(ID 368432\)](#).

Members of the Centre have performed the preparation of materials, their processing, and determination of the colloidal particles sizes by dynamic light scattering. Cooperating members from other Centres of the Institute have provided the spectroscopic characterization and morphology assessment. The conductivity measurements have been carried out the help of external partners.

S29. **Bober, P.; Stejskal, J.; Trchová, M.;** Prokeš, J. Polyaniline-silver composites prepared by the oxidation of aniline with mixed oxidants, silver nitrate and ammonium peroxydisulfate: the control of silver content. *Polymer* 2011, 52, p. 5947-5952. [ASEP \(ID 368432\)](#)

S45. **Bober, P.; Stejskal, J.; Trchová, M.;** Prokeš, J. *In-situ* prepared polyaniline-silver composites: single- and two-step strategies. *Electrochimica Acta* 2014, 122, p. 259-266. [ASEP \(ID 426956\)](#)

S47. **Bober, P.; Stejskal, J.; Trchová, M.;** Prokeš, J.; Sapurina, I. Oxidation of aniline with silver nitrate accelerated by p-phenylenediamine: A new route to conducting composites. *Macromolecules* 2010, 24, p. 10406-10413. [ASEP \(ID 353218\)](#)

A230. **Stejskal, J.** Conducting polymer-silver composites. *Chemical Papers* 2013, 67, 8, p. 814-848. [ASEP \(ID 392164\)](#)

Result 2 Nitrogen-containing carbons

Conducting polymer, such as polyaniline or polypyrrole can conveniently be converted to nitrogen-enriched carbons by pyrolysis above 600 °C in inert atmosphere. It is important that the general features of morphology become preserved after this process [ASEP \(ID 343889\)](#), and, e.g., polypyrrole nanotubes yield corresponding carbon nanotubes [ASEP \(ID 429821\)](#). The preparation of polyaniline nanostructures and subsequent carbonization methods have been reviewed [ASEP \(ID 349446\)](#). The latter materials are of interest as electrodes in energy-conversion devices or as catalysts supports in fuel cells. Various forms of conducting polymers, such as colloidal particles or thin films [ASEP \(ID 378731\)](#), have been investigated. The conditions which are suitable for the carbonization but do not destroy the structure completely have been found. The carbonization of related materials, such as aniline oligomers has also been tested [ASEP \(ID 389210\)](#).

Members of the Centre have carried out the synthesis of polypyrrole or polyaniline in required morphology, their processing, and preparative carbonization. Cooperating members from other Centres of the Institute have provided the characterization by Raman spectroscopy. The application of resulting materials in electrorheology or in sensors has been performed in cooperation with external partner institutions.

S44. **Stejskal, J.;** Sapurina, I.; **Trchová, M.** Polyaniline nanostructures and the role of aniline oligomers in their formation. *Progress in Polymer Science* 2010, 35, p. 1420-1481. [ASEP \(ID 349446\)](#)

A35. **Stejskal, J.; Trchová, M.; Hromádková, J.; Kovářová, J.; Kalendová, A.** The carbonization of colloidal polyaniline nanoparticles to nitrogen-containing carbon analogues. *Polymer International* 2010, 59, p. 875-878. [ASEP \(ID 343889\)](#)

A179. **Morávková, Z.; Trchová, M.; Exnerová, M.; Stejskal, J.** The carbonization of thin polyaniline films. *Thin Solid Films* 2012, 520, 19, p. 6088-6094. [ASEP \(ID 378731\)](#)

A217. **Morávková, Z.; Trchová, M.; Tomšík, E.; Zhigunov, A.; Stejskal, J.** Transformation of oligoaniline microspheres to platelike nitrogen-containing carbon. *Journal of Physical Chemistry C* 2013, 117, p. 2289-2299. [ASEP \(ID 389210\)](#)

A284. Ciric-Marjanovic, G.; Mentus, S.; Pašti, I.; Gavrilov, N.; Krstic, J.; Travas-Sejdic, J.; Strover, L. T.;

Kopecká, J.; Morávková, Z.; Trchová, M.; Stejskal, J. Synthesis, characterization, and electrochemistry of nanotubular polypyrrole and polypyrrole-derived carbon nanotubes. *Journal of Physical Chemistry C* 2014, 118, p. 14770-14784. [ASEP \(ID 429821\)](#)

Result 3 Novel luminescent and low-bandgap donor-acceptor conjugated copolymers

Novel luminescent carbazole-containing copolymers, fluorene-bithiophene copolymers with various molecular weights and polysilanes modified with dansyl fluorophores (PMPSi-*n*-DNS) on various spacer (*n*) were synthesized [S2, S26, O1]. Influence of alkyl chain length and molecular weight on photophysical properties was shown. Using new carbazole-containing polymer PCzE-PPV [S2] or fluorene-bithiophene copolymer CF16BT [O1] light-emitting devices (LEDs) with a luminance higher than 3000 cd m⁻² and low onset voltages were fabricated. In PMPSi-*n*-DNS the excitation energy transfer from the polysilane backbone to dansyl fluorophore was proved. Polymer LEDs made of PMPSi-DNS and electroluminescent (EL) M3EH-PPV blend layer exhibited significant improvements of EL efficiency and stability [S26].

Novel soluble conjugated donor-acceptor copolymers containing 4,6-di(thien-2'-yl)thieno[3,4-c][1,2,5]thiadiazole (T) derivatives (with linear alkyl chains or branched 2-ethylhexyls attached to the thiophene rings) as electron-acceptor units and various electron-donor units (9,9-bis(2-ethylhexyl)fluorene, 9,9-dioctylfluorene, 2,5-bis(dodecyloxy)benzene, 2,5-didodecylbenzene, 3,3'-didodecyl-2,2'-bithiophene, 9-(2-ethylhexyl)carbazole or dithieno[3,2-*b*:2',3'-*d'*]silole derivatives) were synthesized [S25, S37, O1]. Effects of intramolecular charge transfer strength and side-chain nature and length on photophysical, electrochemical and photovoltaic properties were revealed. The copolymers possess low-band gap and high electron affinity, and also exhibit solvatochromic, thermochromic and reversible electrochromic behaviour. They are of interest for optoelectronic applications.

S2. Cimrová, V.; Ulbricht, Ch.; Dzhabarov, V.; Výprachtický, D.; Egbe, D. A. M. New electroluminescent carbazole-containing conjugated polymer: synthesis, photophysics, and electroluminescence. *Polymer* 2014, 55, 24, p. 6220-6226. [ASEP \(ID 434345\)](#)

S25. Cimrová, V.; Kmínek, I.; Pavlačková, P.; Výprachtický, D. Low-bandgap donor-acceptor copolymers with 4,6-bis(3'-(2-ethylhexyl)thien-2'-yl)thieno[3,4-c][1,2,5]thiadiazole: synthesis, optical, electrochemical, and photovoltaic properties. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 49, 15, p. 3426-3436. [ASEP \(ID 360802\)](#)

S26. Cimrová, V.; Výprachtický, D.; Hörhold, H. H. Poly[methyl(phenyl)silanediy] modified with dansyl fluorophore: synthesis and photophysics. *Journal of Polymer Science. Part A - Polymer Chemistry* 2011, 49, 10, p. 2233-2244. [ASEP \(ID 358851\)](#)

S37. Kmínek, I.; Výprachtický, D.; Kříž, J.; Dybal, J.; Cimrová, V. Low-band gap copolymers containing thienothiadiazo units: Synthesis, optical, and electrochemical properties. *Journal of Polymer Science. Part A - Polymer Chemistry* 2010, 48, 13, p. 2743-2756. [ASEP \(ID 343355\)](#)

O1. Cimrová, V.; Výprachtický, D.; Kmínek, I.; Dzhabarov, V.; Pokorná, V. Photophysical and electrochemical properties of novel luminescent and photoconductive copolymers. *ECS Transactions*. Pennington: Electrochemical Society, 2014, 58, 28, p. 15-30. [ASEP \(ID 427560\)](#)

Result 4 New chemistry of monomers for conjugated polymers

A novel, short, reasonably efficient synthesis of 3,8-dibromo-1,10-phenanthroline, 3,6-dibromo-1,10-phenanthroline, 3,5,8-tribromo-1,10-phenanthroline, and 3,5,6,8-tetrabromo-1,10-phenanthroline was developed. The crucial role of a new catalyst (sulfur dichloride - SCl₂) in

bromination of 1,10-phenanthroline was discovered. The bromination of 1,10-phenanthroline monohydrate in the presence of SCl_2 and pyridine yielded the brominated compounds, previously only accessible through the complicated multi-step and tedious Skraup synthesis [S5].

We discovered that the *N*-alkyl-2,7-dihalocarbazole (as a main product) was formed by the reaction of 4,4'-dihalo-2-nitrobiphenyl with aromatic nitro compound and trialkyl phosphite. The presence and crucial role of aromatic nitro compound caused simultaneous carbazole ring closure and *N*-alkylation unlike the Cadogan ring closure where non-alkylated carbazole was formed as a main product [S21]. Such findings were utilized in the synthesis of monomer *N*-(2-ethylhexyl)-2,7-diiodocarbazole, previously only accessible via azide strategy (i.e. tedious five-step procedure). First, we developed a new three-step synthesis of *N*-(2-ethylhexyl)-2,7-diiodocarbazole from commercial 4,4'-diiodobiphenyl [S33]. Second, we reduced the synthesis even in two reaction steps. In the first step, the 4,4'-diiodobiphenyl was nitrated to a mixture of 4,4'-diiodo-2-nitrobiphenyl and 4-iodo-4'-nitrobiphenyl. In the second step, the mixture of these compounds was converted by simultaneous carbazole ring closure and *N*-alkylation to the *N*-(2-ethylhexyl)-2,7-diiodocarbazole by means of tris(2-ethylhexyl) phosphite [S13].

S5. **Výprachtický, D.; Kaňková, D.; Pokorná, V.; Kmínek, I.; Dzhabarov, V.; Cimrová, V.** Novel and simple synthesis of brominated 1,10-phenanthrolines. *Australian Journal of Chemistry* 2014, 67, 6, p. 915-921. [ASEP \(ID 428953\)](#)

S13. **Výprachtický, D.; Kmínek, I.; Pokorná, V.; Kaňková, D.; Cimrová, V.** New two-step synthesis of *N*-(2-ethylhexyl)-2,7-diiodocarbazole as a monomer for conjugated polymers. *Designed Monomers and Polymers* 2013, 16, 1, p. 31-37. [ASEP \(ID 382706\)](#)

S21. **Výprachtický, D.; Kmínek, I.; Pokorná, V.; Cimrová, V.** Efficient synthesis of *N*-alkyl-2,7-dihalocarbazoles by simultaneous carbazole ring closure and *N*-alkylation. *Tetrahedron* 2012, 68, 25, p. 5075-5080. [ASEP \(ID 377087\)](#)

S33. **Výprachtický, D.; Kmínek, I.; Pavlačková, P.; Cimrová, V.** A novel three-step synthesis of *N*-(2-ethylhexyl)-2,7-diiodocarbazole. *Synthesis* 2011, 9, p. 1472-1476. [ASEP \(ID 359265\)](#)

Result 5 **Polymer composites with plasmonic nanoparticles**

Significant advances were achieved in the development of the methods of preparation and understanding the properties of nanocomposites of plasmonic metal (Ag and Au) nanoparticles embedded in matrices of conjugated polymers. We contributed with new methods of preparation of NPs with pure surface [A8] for strong interaction with various chromophores and also prepared nanocomposites with the π -conjugated polyelectrolyte (CPE) matrices [A41]. The main advantage of the last system consists in the possibility of processing from solutions in "green" solvents such as alcohols and water, which are fully miscible with hydrosols of plasmonic nanoparticles and aggregate at certain conditions providing an extreme local amplification of the optical field [S31]. Also stable composites with limited nanoparticles aggregation and demixing were prepared, which showed the optical and electrical features of both the semiconducting polymer and the 3D metal nanoparticles array [S9]. The results bring the possibility of preparing plasmonic nanocomposites of semiconducting polymers, in which various photophysical phenomena like the charge transfer and fluorescence can be enhanced or locally quenched. This research resulted in 6 publications in impacted journals.

We designed the concept of the work, prepared the composites and performed the electrical and optical measurements. Cooperating laboratories contributed with TEM and X-ray diffraction. The

polymers were synthesized and XPS and atomic analysis were done with help of an external partner.

S9. **Halašová, K.; Pflieger, J.; Sharf, A.**; Vobecký, M.; **Baldrian, J.**; Ladas, S.; **Hromádková, J.** Optical and electrical properties of gold nanoparticles/poly(3-alkylthiophene) composites. *Science of Advanced Materials* 2013, 5, 1, p. 28-36. [ASEP \(ID 388457\)](#)

S31. **Kazim, S.; Pflieger, J.**; Procházka, M.; Bondarev, D.; Vohlídal, J. Colloidal systems of silver nanoparticles and high-regioregular cationic polythiophene with ionic-liquid-like pendant groups: Optical properties and SERS. *Journal of Colloid and Interface Science* 2011, 354, 2, p. 611-619. [ASEP \(ID 354009\)](#)

A41. Bondarev, D.; Zedník, J.; Šloufová, I.; **Sharf, A.**; Procházka, M.; **Pflieger, J.**; Vohlídal, J. Synthesis and properties of cationic polyelectrolyte with regioregular polyalkylthiophene backbone and ionic-liquid like side groups. *Journal of Polymer Science. Part A - Polymer Chemistry* 2010, 48, 14, p. 3073-3081. [ASEP \(ID 345579\)](#)

A8. **Šišková, K.; Pflieger, J.**; Procházka, M. Stabilization of Au nanoparticles prepared by laser ablation in chloroform with free-base porphyrin molecules. *Applied Surface Science* 2010, 256, 9, p. 2979-2987. [ASEP \(ID 339581\)](#)

Result 6 **Materials for organic field-effect transistors**

We performed a comparative study of arylene bisimide, diketopyrrolo-pyrrole and alkyl-substituted oligothiophene derivatives with regards to their applicability as charge transporting materials in organic field effect transistors. Based on the DFT calculations we elucidated the conformational and electronic properties significant for determination of the substituent-induced shifts of the HOMO and LUMO levels and for the intermolecular arrangement of the molecule in thin films and related it to the experimental spectroscopic, electrochemical, structural and charge transport data [S6, S7, S38]. We interpreted the STM images of naphthalene bisimides [S7] showing differences in self-assembly patterns resulting in different electrical transport properties. Calculations confirmed the frontier orbital localization on distinct parts of the molecule, which were registered in the STM images as black and white spots.

We performed all the theoretical calculations and correlation of the theoretical data to the experimental results and partially performed the charge carrier transport measurements. The material were synthesized and other experiments done in the laboratories cooperating within EU project NoE „FLEXNET“and GAČR project.

S6. Kurach, E.; Kotwica, K.; Zapala, J.; Knor, M.; Nowakowski, R.; Djurado, D.; **Toman, P.; Pflieger, J.**; Zagorska, M.; Pron, A. Semiconducting alkyl derivatives of 2,5-bis(2,2'-bithiophene-5-yl)-1,3,4-thiadiazole-effect of the substituent position on the spectroscopic, electrochemical, and structural properties. *Journal of Physical Chemistry C* 2013, 117, 29, p. 15316-15326. [ASEP \(ID 394402\)](#)

S7. Rybakiewicz, R.; Zapala, J.; Djurado, D.; Nowakowski, R.; **Toman, P.; Pflieger, J.**; Verilhac, J.-M.; Zagorska, M.; Pron, A. Naphthalene bisimides asymmetrically and symmetrically N-substituted with triarylamine - comparison of spectroscopic, electrochemical, electronic and self-assembly properties. *Physical Chemistry Chemical Physics* 2013, 15, 5, p. 1578-1587. [ASEP \(ID 388199\)](#)

S38. Vala, M.; Vyňuchal, J.; **Toman, P.**; Weiter, M.; Luňák, S. Novel, soluble diphenyl-diketopyrrolopyrroles: Experimental and theoretical study. *Dyes and Pigments* 2010, 84, 2, p. 176-182. [ASEP \(ID 331882\)](#)

Result 7 **Spectroscopy of excited states of substituted metal phthalocyanines**

We performed quantum calculations and spectroscopic studies on derivatives of metal phthalocyanine. It elucidates the effects of the substituents on the particular molecular arrangement of the molecules and relates it to the photophysical behavior of the compounds. On newly synthesized octabutoxy- substituted nickel phthalocyanine we confirmed the presence of J-aggregates, in which the photoexcitation creates triplet states, showing the applicability of this material in photodynamic therapy. On sulfonamide-substituted zinc phthalocyanines we observed a formation of a charge transfer complex with nitrogen dioxide, which results in a change of absorption spectrum and in an increase of electrical conductivity about two orders of magnitude. The effect is applicable in gas sensors.

The authors from IMC designed the concept of study, conducted the experimental part of the ultrafast spectroscopy, and performed the quantum-chemical calculations. The collaborating institution within the Centrum of competence TAČR performed synthesis of the materials and conducted experimental estimation of singlet oxygen photosynthetic yields.

S6. **Rais, D.; Toman, P.; Černý, J.; Menšík, M.; Pflieger, J.** Roles of octabutoxy substitution and J-aggregation in stabilization of the excited state in nickel phthalocyanine. *Journal of Physical Chemistry A* 2014, 118, 29, p. 5419-5426. [ASEP \(ID 431083\)](#)

S20. **Pochekailov, S.; Nožár, J.; Nešpůrek, S.; Rakušan, J.; Karásková, M.** Interaction of nitrogen dioxide with sulfonamide-substituted phthalocyanines: Towards NO₂ gas sensor. *Sensors and Actuators B - Chemical* 2012, 169, 5 July, p. 1-9. [ASEP \(ID 377481\)](#)

Result 8 **Photo-induced and optical phenomena in amorphous chalcogenides**

We demonstrated that the response of the virgin film to annealing and illumination by over gap photons is namely owing to polymerization and healing of defects of the film network which resulted not only to a reduction in the density of the localized states at the band edges, but also to a narrowing of at least the valence band. However illumination by UV photons leads to the film surface oxidation [A63, A12]. Photo-induced phenomena like photo-expansion, photo-depression and ablation, inclusive damage threshold in the bulk and thin film networks of some selected ternary chalcogenides were observed and explained. These materials and phenomena are of considerable interest for optical memories [S24, A248]. A systematic search for new glassy and amorphous chalcogenide materials doped with rare earth elements [S12, A236] and other metals [[ASEP \(ID 342108\)](#)] has been done in the last years. A strong luminescence between 1100–1450, 1500–1700, 1750–2000, 2000–2600 and 3600–5200 nm, was found in some of them [S12]. Very important is the luminescence in the mid-IR region that can be applied for analysis of gasses, liquids, vapors, for environmental, security and biological applications. Studied glasses are promising as luminescence materials for amplification and generation of light.

Members of the Centre performed syntheses, studied the ways of preparation of thin films and determined the structure and basic physicochemical properties. Part of the research was done in cooperation with University of Pardubice, Institute of Physics CAS, Pohang University, Korea, and East China University, Shanghai.

A63. Knotek, P.; **Kincl, M.; Tichý, L.**; Arsova, D.; Ivanova, Z. G.; Tichá, H. Oxygen assisted photoinduced changes in Ge₃₉Ga₂S₅₉ amorphous thin film. *Journal of Non-Crystalline Solids* 2010, 356, 50-51, p. 2850-2857. [ASEP \(ID 350257\)](#)

A12. Knotek, P.; **Tichý, L.**; Arsova, D.; Ivanova, Z. G.; Tichá, H. Irreversible photobleaching, photorefractive and photoexpansion in GeS₂ amorphous film. *Materials Chemistry and Physics* 2010,

119, 1-2, p. 315-318. [ASEP \(ID 341644\)](#)

S24. Knotek, P.; **Tichý, L.** On photo-expansion and microlens formation in $(\text{GeS}_2)_{0.74}(\text{Sb}_2\text{S}_3)_{0.26}$ chalcogenide glass. *Materials Research Bulletin* 2012, 47, 12, p. 4246-4251. [ASEP \(ID 383900\)](#)

A248. Knotek, P.; **Tichý, L.** Explosive boiling of $\text{Ge}_{35}\text{Sb}_{10}\text{S}_{55}$ glass induced by a CW laser. *Materials Research Bulletin* 2013, 48, 9, p. 3268-3273. [ASEP \(ID 394617\)](#)

S12. **Frumarová, B.**; Frumar, M.; Oswald, J.; **Kincl, M.**; Parchanski, V. Preparation and physical properties of luminescent $80\text{GeSe}_2(20-x)\text{Sb}_2\text{Se}_3-x\text{Sb}_2\text{Te}_y\text{:Pr}_2\text{Se}_3$ glasses; $x=0, 1, 3, 10$; $y=2, 3, 4$. *Journal of Luminescence* 2013, 134, Feb 2013, p. 558-565. [ASEP \(ID 389784\)](#)

A236. **Frumarová, B.**; Frumar, M.; Staňková, P.; Parchanski, V.; **Vlček, M.**; Pavlišta, M. Preparation of As-In-S: Sm thin films and a study of their properties. *Thin Solid Films* 2013, 548, 2 December, p. 429-436. [ASEP \(ID 423212\)](#)

Result 9 **Metal organophosphonates for optical and electrical applications**

The research program of the group is aimed at the preparation of new metal phosphonates of alkaline-earth metals (S8, [ASEP \(ID 359896\)](#), [ASEP \(ID 342086\)](#), [ASEP \(ID 342099\)](#)), functionalized phosphonates of tetravalent metals (S14, [ASEP \(ID 381498\)](#), [ASEP \(ID 392498\)](#)) and copper phosphonates (S19). We prepared and characterized materials interesting from the point of their optical properties (S1, S8) and intercalation chemistry ([ASEP \(ID 359896\)](#), S14, S1). It was shown that zirconium 4-sulfophenylphosphonate and strontium methylphosphonate can serve as host materials for preparation of intercalates. New intercalation compounds containing tripodal push-pull molecules of $(A-\pi)_3D$ type were prepared and characterized. The described materials represent the first case when a tripodal push-pull system was incorporated in a system with restricted geometry with the aim to influence its optical properties. Layered zirconium 4-sulfophenylphosphonate and mixed zirconium phosphate 4-sulfophenylphosphonate interesting from the point of their electrical properties were also prepared and their ionic conductivity was determined (A34). Due to their insolubility in water, good thermal stability and considerably high protonic conductivity, the described layered compounds are promising candidates for application as components of composite proton exchange membranes in fuel cells. This research resulted in publication of 10 papers in impacted journals.

Members of the Centre prepared most of the studied materials, performed all intercalation reactions, carried out characterization of the materials, determined their electrical properties and participated in the determination of optical properties.

S8. **Zima, V.**; Raja, D. S.; Lee, Y. S.; Chang, T. G.; Wu, Ch. Y.; Hu, Ch. Ch.; Lee, K. R.; Lai, J. Y.; Yeh, J. M.; Lin, Ch. H. Alkaline-earth metal phosphonocarboxylates: synthesis, structures, chirality, and luminescence properties. *Dalton Transactions* 2013, 42, 43, p. 15332-15342. [ASEP \(ID 422324\)](#)

S14. **Svoboda, J.**; **Zima, V.**; **Melánová, K.**; Beneš, L.; **Trchová, M.** Intercalation chemistry of zirconium 4-sulfophenylphosphonate. *Journal of Solid State Chemistry* 2013, 208, December, p. 58-64. [ASEP \(ID 423537\)](#)

S19. **Zima, V.**; **Svoboda, J.**; Yang, Y.-Ch.; Wang, S.-L. New copper aryl phosphonates with auxiliary nitrogen ligands. *CrystEngComm* 2012, 14, 10, p. 3469-3477. [ASEP \(ID 379826\)](#)

S1. **Melánová, K.**; Cvejn, D.; Bureš, F.; **Zima, V.**; **Svoboda, J.**; Beneš, L.; Mikysek, T.; Pytela, O.; Knotek, P. Organization and intramolecular charge-transfer enhancement in tripodal tris[(pyridine-4-yl)phenyl]amine push-pull molecules by intercalation into layered materials bearing acidic functionalities. *Dalton Transactions* 2014, 43, 27, p. 10462-10470. [ASEP \(ID 430254\)](#)

A34. **Zima, V.**; **Svoboda, J.**; **Melánová, K.**; Beneš, L.; Casciola, M.; Sganappa, M.; Brus, J.; **Trchová, M.**

Synthesis and characterization of new zirconium 4-sulfophenylphosphonates. *Solid State Ionics* 2010, 181, 15-16, p. 705-713. [ASEP \(ID 343449\)](#)

Result 10 Polymer membranes for energy storage

Excess electricity from renewable resources such as solar and wind may be used for hydrogen production by water electrolysis. The hydrogen functions as an energy storage medium as it can be converted back to electricity in fuel cells. It has been proven in a number of pilot plants that such systems are feasible but it is necessary to improve the existing electrolyzers and fuel cells. Especially, current asbestos diaphragms in electrolyzers must be replaced by anion-conductive membranes, anion-conductive catalyst binders are to be prepared and efficient, cheap and resistant proton-conductive membranes for fuel cells must be developed.

New anion-conductive membranes were prepared by blending small anion-exchange particles, polyolefin and a water-soluble additive. The prepared membranes were highly effective in electrolysis [S18]. New anion-conductive binders based on quaternized poly(phenylene oxide), polysulfone or block copolymers of styrene were prepared. The high ionic conductivity of block copolymers results from the domain structure of functionalized block copolymers [S41] and the binders based on quaternized block copolymers meet all the requirements. New proton-conductive membranes containing sulfonic acid groups, phosphonic acid groups or ionic liquids were developed [S27].

This research resulted in 13 publications in impacted journals.

The new polymer synthesis and membrane preparation were carried out at Optoel center. Cooperating members from other Centres of the Institute have characterized prepared materials. Electrochemical characterizations was carried out at the University of Chemistry and Technology, Prague.

S18. **Schauer, J.**; Hnát, J.; **Brožová, L.**; **Žitka, J.**; Bouzek, K. Heterogeneous anion-selective membranes: Influence of a water-soluble component in the membrane on the morphology and ionic conductivity. *Journal of Membrane Science* 2012, 401/402, 15 May, p. 83-88. [ASEP \(ID 375924\)](#)

S27. **Schauer, J.**; **Sikora, A.**; Plíšková, M.; Mališ, J.; Mazúr, P.; Paidar, M.; Bouzek, K. Ion-conductive polymer membranes containing 1-butyl-3-methylimidazolium trifluoromethanesulfonate and 1-ethylimidazolium trifluoromethanesulfonate. *Journal of Membrane Science* 2011, 367, 1/2, p. 332-339. [ASEP \(ID 353612\)](#)

S41. **Schauer, J.**; Llanos, J.; **Žitka, J.**; Hnát, J.; Bouzek, K. Cation-exchange membranes: comparison of homopolymer, block copolymer, and heterogeneous membranes, *Journal of Applied Polymer Science* 2012, 124, SI 1, p. E66-E72. [ASEP \(ID 376126\)](#)

Result 11 Polymer membranes for gas and vapor separation

Chemical technologies require gas and vapor separation membranes with better permeabilities and selectivities and this demands for the development of new polymer materials or the modification of current polymer materials.

(a) The thermal rearrangement of polymers is recognized as a suitable method to improve separation efficiency of gas separation membranes. A novel method of such conversion was introduced. The pre-formed films based on the derivatives of polyanthranilamide dicarboxylic acid were converted by thermal treatment into the polybenzoxazinone films. The change of the films structure lead to an increase in fractional free-volume and, according to the theoretical assumption,

to an increase in gas permeability and selectivity [S11].

(b) It is well known that some fillers (carbon black) interact with polymers and thus they change their properties. In this work, a series of carbon nanoparticles (carbon nanotubes, fullerene, graphene, and their derivatives) was utilized. Homogeneous poly (phenylene isophthalamide) membranes were filled with multi-walled carbon nanotubes or with fullerene C-60. Similarly, poly(phenylene oxide) membranes were filled with carbon nanoparticles. The filled and unfilled membranes were compared in pervaporative separation of various organic solvents/water mixtures or organic solvent/organic solvent mixtures. The membranes filled with carbon nanoparticles showed better performance than the same membranes without carbon nanoparticles [A26, A7, A80].

This research resulted in 6 publications in impacted journals.

Membrane preparation and gas transport characterization were carried out at OPTOEL center. New polymer material synthesis and its characterization were carried out at cooperating Institute of Macromolecular Compounds, St. Petersburg.

S11. **Pientka, Z.; Brožová, L.;** Pulyalina, A. Y.; Goikhman, M. Y.; Podeshvo, I. V.; Gofman, I. V.; Saprykina, N. N.; Polotskaya, G. A. Synthesis and characterization of polybenzoxazinone and its prepolymer using gas separation. *Macromolecular Chemistry and Physics* 2013, 214, 24, p. 2867-2874. [ASEP \(ID 421782\)](#)

A26. Polotskaya, G. A.; Penkova, A. V.; **Pientka, Z.;** Toikka, A. M. Polymer membranes modified by fullerene C-60 for pervaporation of organic mixtures. *Desalination and Water Treatment* 2010, 14, 1-3, p. 83-88. [ASEP \(ID 342601\)](#)