A View on Future Directions for Macromolecular Science

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Polymer science has in recent years become one of the most dynamic components of materials science [1,2,3], which in turn is a powerful bridge between basic science and advanced technology. The National Science Foundation (NSF) has periodically reviewed the status of polymer science and engineering to ensure that this important field continues to develop in an appropriate fashion. Thus, the NSF asked the U.S. National Academy of Sciences on two previous occasions, in 1981 and again in 1994, to assess progress in polymer science and engineering and to make recommendations for the future. The resulting reports [4,5] received wide circulation in many countries and helped to focus attention on the changing nature of the polymer field. A clear trend that was identified in these reports is the greater commonality with other materials-related disciplines [1-3] and with the biological sciences [1-5]. Increasingly, these changes are being reflected in the programs of government agencies funding polymer research which are tending to be broader and more interdisciplinary than in the past.

Another advisory meeting was convened in 1997 under the auspices of the National Science Foundation acting jointly with the Department of Energy and eight other U.S. government agencies. This time, the meeting took the form of a two-day workshop that brought together over fifty leading researchers and educators with an interest in macromolecular science and engineering [6]. Entitled "Interdisciplinary Macromolecular Science and Engineering," the workshop included not only polymer scientists but also experts from eight other disciplines such as materials science, chemistry, physics, the biological sciences, various branches of engineering, and even specialists in education and international programs. The participants came from academic, industrial, and government laboratories in the U.S. and other countries.

The workshop examined the frontiers of macromolecular science and engineering, and especially those areas that are at the borders of what had traditionally been viewed as polymer science. The aim was to concentrate on the important and rapidly increasing connections of polymer science with other areas of science and engineering. In addition to the participants at the workshop, comments were also widely sought from scientists who were not present and, indeed, many responses were received from across the world. The report resulting from all of

 CCC 1022-1360/00/$ 17.50+.50/0

this varied input comes to a number of important conclusions and makes several worthy recommendations for future action [6]. These are summarized in this article.

Novel Macromolecular Structures

In spite of the highly developed state of polymer synthesis, major opportunities still exist for creating new polymers from known monomers, for example by using new generations of metallocene or other novel types of catalysts. New classes of engineering plastics will thereby be created because of the unprecedented control over the resulting macromolecular architecture. Supramolecular chemistry, which bridges traditional chemistry, biology, materials science, and engineering, offers remarkable new opportunities. Nanobiotechnological systems can be expected to be developed that will have new functionality. Especially promising is the study of macromolecular aggregates that form nanostructures that may be recycled indefinitely because their disassembly does not require a breaking of covalent bonds. Together with synthesis, better methods of characterization as well as powerful modeling, simulation, and theoretical approaches will be need to be developed. Ideally, the design of new polymers, their synthesis, and the characterization of the resulting new materials will work together in a continuously improving feedback loop to give potential users “properties on demand”.

Biomaterials and Macromolecular Biology

The workshop found that the rapidly developing links of polymer science to the biological sciences open many promising opportunities. Macromolecular science seems ideally placed to bridge the wide cultural gap between the physical and the biological sciences, and between the principal drivers of the modern economy, i.e., information- and health-related technologies. However, new educational efforts will have to be devised to serve this role.

Advances in macromolecular science and engineering based on lessons from biology offer the prospect of new catalysts for materials synthesis and environmental remediation, sensors, highly selective membranes, and chromatographic media. Macromolecules hold the key to create connections between cells and computer hardware that could deliver new types of environmental sensors, medical diagnostic equipment, and detectors for biological objects such as viruses and bacteria. The ideal materials to repair human tissues will almost certainly be macromolecular in structure, and their development will require close collaboration among chemists, biologists, materials scientists, and engineers. Great discoveries are likely to emerge from research on the biological control of monomer sequences and molecular self-assembly.

This research will extend beyond proteins to other biological and even synthetic macromolecules with the aim of obtaining precise architectural control of individual macromolecules and of the materials resulting from them.

Environmental Macromolecular Science and Engineering

Macromolecular science and engineering will have a critical impact on the global environment in such areas as: the possibility of using plants, microbes, or other living organisms to synthesize technologically useful macromolecules; in environmental cleanup by the use of highly active and selective materials to remove toxic matter from water; biodegradable polymers with new architectures; and new processes and materials that permit multiple loops of recycling without loss of important properties. The use of the available solvents for environmentally benign synthesis and processing (e.g., water and carbon dioxide) will increase, and techniques for producing more types of polymeric materials in them will need to be developed. The interaction of polymers with ecosystems – e.g., toxicity, hormonal activity, and other health-related effects about which relatively little is known at the present time – will require further study.

Innovative Fabrication of Macromolecular Products

New processing methodologies for polymers are critically needed for the emerging synthetic techniques of self-assembly and supramolecular chemistry as well as for the new biomaterials. Environmental considerations in processing will assume much greater importance. Rational modeling of the new polymer architectures and of flow behavior under realistic, rather than idealized, processing conditions will be needed to take full advantage of their structures. Innovative processing techniques must be developed for all the various forms in which polymeric materials are used, e.g., thin films, fibers, and foams. Such tools as the application of external electric and magnetic fields will be further refined. Precise control of microscale and nanoscale patterning of macromolecular products should result in entirely new devices as well as in improved performance. Finally, computer-designed and optimized macromolecular materials will become ever more prominent.

General Recommendations

The report recommends that funding by government agencies follow the many exciting opportunities (including nanoscience and nanotechnology, see below) that are opening up both in respect to the science and the educational underpinnings for it. It particularly notes the need for the various government agencies to work together to create joint programs. Even within a single government agency, such as the NSF, the various disciplinary programs should continue to work closely together for the benefit of all. Similar considerations are expected to apply in the funding of programs in other countries.

Educational activities should be better integrated into research, particularly to train a new generation of scientists and engineers who will have broader knowledge and be more comfortable working in an interdisciplinary environment. For example, scientists and engineers conversant in both the physical and the biological sciences will be in great demand, and educational experiments to develop and test the necessary cross-disciplinary programs are acutely needed. At the same time, closer interactions and collaborations between academia and industry will be required to ensure that any scientific breakthroughs result in innovative applications. New entrepreneurial companies can be expected to contribute to the field and to the economy at large.

The above is but a brief overview of the many examples of potential advances in macromolecular science and engineering cited in the report and of the recommendations to help bring these about. The full report should be consulted, especially by the younger scientists and engineers who will have the task of carrying our field into the future.

Nanoscience and Nanotechnology

The success of the workshop on macromolecular science and engineering had an additional outcome, namely to serve as a model for a new interdisciplinary initiative on nanoscience and nanotechnology recently announced by the U.S. government. This initiative, which largely incorporates the workshop's major areas of emphasis, involves many of the same disciplines as well as six agencies under the leadership of the National Science Foundation. The initiative's underlying scientific and technological details are contained in a number of current reports [7-10].

This new program has the potential to bring about unprecedented understanding and control in the range from atoms and molecules (i.e., the fundamental building blocks of materials) to *ca.* 100 nm (i.e., the realm of thin films, interfaces, clusters, and other technologically important morphological forms). Macromolecular science and engineering are expected to play central roles in this new activity. Because both the science and the program to support it are evolving so rapidly, the reader is directed to the web sites of the initiative [10] and of the NSF [11] for the latest information.

Acknowledgments: The opinions and conclusions presented are those of the authors and do not necessarily reflect either NSF or U.S. government policy. We wish to express our immense gratitude to the Chair of the workshop, S.I. Stupp, and to the other Members of the Organizing Committee, R.H. Grubbs, L.W. Jelinski, S.T. Milner, E.L. Thomas, and D.A. Tirrell, for their invaluable contributions. The help and input of the other participants at the workshop as well as of those who wrote to comment on its findings is also gratefully acknowledged; their names can be found in ref. 6.

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