Executive Summary

Richard W. Siegel [1]
Rensselaer Polytechnic Institute
Panel Chair

INTRODUCTION

Nanostructure science and technology is a broad and interdisciplinary area of research and development activity that has been growing explosively worldwide in the past few years. It has the potential for revolutionizing the ways in which materials and products are created and the range and nature of functionalities that can be accessed. It is already having a significant commercial impact, which will assuredly increase in the future.

A worldwide study of research and development status and trends in nanoparticles, nanostructured materials, and nanodevices (or more concisely, nanostructure science and technology) was carried out during the period 1996-98 by an eight-person panel under the auspices of the World Technology (WTEC) Division of Loyola College. Led by the National Science Foundation, a wide range of U.S. government agencies commissioned and funded this study: the Air Force Office of Scientific Research, the Office of Naval Research, the Department of Commerce (including the National Institute of Standards and Technology and the Technology Administration), the Department of Energy, the National Institutes of Health, and the National Aeronautics and Space Administration. Their support indicates the breadth of interest in and the far-reaching potential of this burgeoning new field. The purpose of the study was to assess the current status and future trends internationally in research and development in the broad and rapidly growing area of nanostructure science and technology. The goals were fourfold:

1. provide the worldwide science and engineering community with a broadly inclusive and critical view of this field

[1] Although written by the panel chair, this summary includes contributions from the full panel and represents the consensus views of the panel as a whole.

2. identify promising areas for future research and commercial development
3. help stimulate development of an interdisciplinary international community of nanostructure researchers
4. encourage and identify opportunities for international collaboration

This report is the principal volume in a three-part publication of the activities and findings of the WTEC panel; it is an overview of the panel's observations and conclusions regarding nanostructure science and technology worldwide. It includes reviews of panel workshops held in Germany and Sweden, as well as site reports of panel visits to university, government, and industry laboratories in Europe, Japan, and Taiwan. An earlier volume, published in January 1998, reported the proceedings of a WTEC workshop on R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States (Baltimore: Loyola College, International Technology Research Institute, NTIS #PB98-117914). A third volume to be published by WTEC reports the proceedings of a workshop held in St. Petersburg, Russia on related work.

FINDINGS

There are two overarching findings from this WTEC study:

First, it is abundantly clear that we are now able to nanostructure materials for novel performance. That is the essential theme of this field: novel performance through nanostructuring. It represents the beginning of a revolutionary new age in our ability to manipulate materials for the good of humanity. The synthesis and control of materials in nanometer dimensions can access new material properties and device characteristics in unprecedented ways, and work is rapidly expanding worldwide in exploiting the opportunities offered through nanostructuring. Each year sees an ever increasing number of researchers from a wide variety of disciplines enter the field, and each year sees an ever increasing breadth of novel ideas and exciting new opportunities explode on the international nanostructure scene.

Second, there is a very wide range of disciplines contributing to the developments in nanostructure science and technology worldwide. The rapidly increasing level of interdisciplinary activity in nanostructuring is exciting and growing in importance, and the intersections between the various disciplines are where much of the novel activity resides.

The field of nanostructure science and technology has been growing very rapidly in the past few years, since the realization that creating new materials and devices from nanoscale building blocks could access new and improved properties and functionalities. While many aspects of the field existed well before nanostructure science and technology became a definable entity in the past decade, it has only become a coherent field of endeavor through the confluence of three important technological streams:

1. new and improved control of the size and manipulation of nanoscale building blocks
2. new and improved characterization (spatial resolution, chemical sensitivity, etc.) of materials at the nanoscale
3. new and improved understanding of the relationships between nanostructure and properties and how these can be engineered

As a result of these developments, a wide range of new opportunities for research and applications in the field of nanotechnology now present themselves. Table ES.1 indicates some examples of present and potential applications with significant technological impact that were identified in the course of this study. Considerable resources are being expended around the world for research and development aimed at realizing these and a variety of other promising applications. Government funding alone approached half a billion dollars per year in FY 1997: $128 million in Western Europe; $120 million in Japan; $116 million in the United States; and $70 million altogether in other countries such as China, Canada, Australia, Korea, Taiwan, Singapore, and the countries of the former Soviet Union (see Chapter 8).

Table ES.2 presents an overall comparison of the current levels of activity among the major regions assessed (Europe, Japan, and the United States) in the various areas of the WTEC study. These broad areas—synthesis and assembly, biological approaches and applications, dispersions and coatings, high surface area materials, nanodevices, and consolidated materials—constitute the field of nanostructure science and technology. These are the areas around which the study was crafted.

In the synthesis and assembly area (Chapter 2), the United States appears to be ahead, with Europe following and then Japan. In the area of biological approaches and applications (Chapter 7), the United States and Europe appear to be rather on a par, with Japan following. In nanoscale dispersions and coatings (Chapter 3), the United States and Europe are again at a similar level, with Japan following. For high surface area materials (Chapter 4), the United States is clearly ahead of Europe, followed by Japan. On the other hand, in the nanodevices area (Chapter 5), Japan seems to be leading quite strongly, with Europe and the United States following. And finally, in the area of consolidated materials (Chapter 6), Japan is a clear leader, with the United States and Europe following. These comparisons are, of course, integrals over rather large areas of a huge field and therefore possess all of the inevitable faults of such an integration. At best, they represent only a snapshot of the present, and the picture is admittedly incomplete.

TABLE ES.1. Technological Impact: Present and Potential

Technology	Present Impact	Potential Impact
Dispersions and Coatings	Thermal barriers	Targeted drug delivery/gene therapy
	Optical (visible and UV) barriers	Multifunctional nanocoatings
	Imaging enhancement	
	Ink-jet materials	
	Coated abrasive slurries	
	Information-recording layers	
High Surface Area Materials	Molecular sieves	Molecule-specific sensors
	Drug delivery	Large hydrocarbon or bacterial filters
	Tailored catalysts	Energy storage
	Absorption/desorption materials	Grätzel-type solar cells
Consolidated Materials	Low-loss soft magnetic materials	Superplastic forming of ceramics
	High hardness, tough WC/Co cutting tools	Ultrahigh-strength, tough structural materials
	Nanocomposite cements	Magnetic refrigerants
		Nanofilled polymer composites
		Ductile cements
Nanodevices	GMR read heads	Terabit memory and microprocessing
		Single molecule DNA sizing and sequencing
		Biomedical sensors
		Low noise, low threshold lasers
		Nanotubes for high brightness displays
Additional Biological Aspects	Biocatalysis	Bioelectronics
		Bioinspired prostheses
		Single-molecule-sensitive biosensors
		Designer molecules

TABLE ES.2. Comparison of Activities in Nanostructure Science and Technology in Europe, Japan, and the United States

Level	1 **Highest**	2	3
Synthesis & Assembly	U.S.	Europe	Japan
Biological Approaches & Applications	U.S./Eur	Japan	
Dispersions and Coatings	U.S./Eur	Japan	
High Surface Area Materials	U.S.	Europe	Japan
Nanodevices	Japan	Europe	U.S.
Consolidated Materials	Japan	U.S./Eur	

More detailed findings in each of these major areas are included in the individual chapters of this report, along with additional general findings and observations in Chapter 1. Chapter 8 compares the scope and funding levels for the relevant nanostructure science and technology R&D programs around the world. The appendices give details on the site visits and workshops of the panel: B contains the Europe site reports, C contains notes on workshops held in Germany and Sweden, D contains the Japan site reports, and E contains the Taiwan site reports. Appendix A lists the professional experience of panelists and other members of the traveling team.

CHALLENGES

We are now at the threshold of a revolution in the ways in which materials and products are created. How this revolution will develop, how great will be the opportunities that nanostructuring can yield, and how rapidly we progress, will depend upon the ways in which a number of challenges are met.

Among the challenges facing us are those concerned with making the necessary advances in enabling technologies in order for rapid progress to continue in this field. We must increase characterization capabilities in visualization and chemical analysis at ever finer size scales. We must be able to manipulate matter at ever finer size scales, and we must eventually use computational approaches in directing this, if we are really going to take full advantage of the available opportunities. Experiment simply cannot do it alone. Theory and modeling are essential. Fortunately, this is an area in which the sizes of the building blocks and their assemblies are small enough that one can, with the ever increasing capabilities in computational sciences, now start doing very serious controlled modeling experiments to guide us in the nanostructuring of matter. Hence, multiscale modeling of nanostructuring and the resulting materials properties across the hierarchy of length scales from atomic, to mesoscopic, to macroscopic is an absolute necessity as we go down the road in the next decades to realizing the tremendous potential of nanostructure science and technology.

Furthermore, we need to understand the critical roles that surfaces and interfaces play in nanostructured materials. Nanoparticles have very high specific surface areas, and thus in their assembled forms there are large areas of interfaces. We need to know in detail not only the structures of these interfaces, but also their local chemistries and the effects of segregation and interaction between the nanoscale building blocks and their surroundings. We need to learn more about the control of nanostructure size and size distribution, composition, and assembly. For some applications, there are very stringent conditions on these parameters; in other applications less so. We must therefore understand the relationships between this stringency and the desired material or device properties.

We also need to be concerned with the thermal, chemical, and structural stability of nanostructured materials and the devices made therefrom, in the face of both the temperature and changing chemistries of the environments in which these nanostructures are asked to function. A nanostructure that is only a nanostructure at the beginning of a process is not of much use to anybody, unless the process is over in a very short time or the process itself is the actual nanostructure advantage. So for many applications, stability is an important consideration, and we must investigate whether natural stability is sufficient or whether we must additionally stabilize against changes that we cannot afford.

To effectively commercialize and utilize the nanostructuring of matter we also need enhancements in statistically driven process control. Achieving reproducibility and scalability of nanoparticle synthesis and consolidation processes in nanostructuring are paramount if successful scale-up is to be effected and if what we do in the laboratory is to contribute to the society that pays for this research. Given a commercial need, the viability of nanostructure production and utilization is wrapped up in the costs of precursors or raw materials, processing costs, and also the costs of dealing with effluent. It is the total integrated cost, in terms of raw materials, synthesis of the building blocks, manufacture of parts from those building blocks, and effluent clean-up costs, that is important and that will ultimately determine commercial viability.

Finally, in order for the field of nanostructure science and technology to truly reach fruition, it is an absolute necessity to create a new breed of researchers who can work across traditional disciplines and think "outside the box." Educating this new breed of researchers, who will either work across disciplines or know how to work with others in the interfaces between disciplines, is vital to the future of nanostructure science and technology. People must start thinking in unconventional ways if we are to take full advantage of the opportunities in this new and revolutionary field.