EXECUTIVE

GENNESYS: A Responsible European Partnership between Nanomaterials Research Labs, Universities, Industry and the European Research Infrastructure

This GENNESYS strategy document is the result of an extensive European-wide study of the needs and opportunities for coordinating future research and development in nanomaterials science and nanotechnology for the advancement of technologies ranging from communication and information, health and medicine, future energy, environment and climate change to transport and cultural heritage. A further focus of this study has been the investigation of the future strategic role of the European research infrastructure, i.e. of the unique analytical potential provided by the European neutron and accelerator-based x-ray facilities in this effort. This study, carried out during 2003 – 2008, brought together leading European scientists and industrial specialists in the fields of materials science, physics, chemistry, biology, and engineering, as well as experts from the neutron and synchrotron radiation facilities. These experts headed thematic task forces with respect to particular research areas – such as information technology, catalysis or functional materials as well as energy and environment issues – and developed roadmaps through numerous informal seminars, workshops and discussion rounds involving colleagues across Europe and the world.

The key objectives of the GENNESYS task forces were:

- To assess the "state of the art" of nanoscience and technology in Europe;
- To identify future needs, opportunities and priorities in the field of nanomaterials science for solving urgent problems in Europe and around the world;
- To articulate fundamental scientific challenges, society needs and industrial potentials in this field;
- To define recommendations and objectives for future research, technologies, and development strategies which will lead to major advances;
- To pinpoint areas of research into nanomaterials science and technology that will most benefit from joint research strategies with synchrotron radiation and neutron facilities;
- To review and forecast the effects that a strategic use of large-scale facilities by nanomaterials scientists will have on the facilities;
- To provide evidence of the societal impact of the field and provide a forum for coordinated community-wide communications between basic researchers, industry, policy-makers and the public, respectively;
- To establish a strategic European research programme encapsulated "Nanomaterials research and technology for future technologies exploiting neutron and accelerator-based x-ray facilities".

The GENNESYS initiative was triggered by the fact that Europe's expertise in nanomaterials science is excellent (highlighted by many revolutionary discoveries during the last two decades) but fragmented into scientific disciplines, sectors and national (often regional) efforts which are – on an international scale – often subcritical; and that Europe would benefit considerably from a strategic pan-European, multi-disciplinary research involving all sectors and the most advanced European research infrastructure for the fine analysis of materials. This pan-European nanomaterials initiative will meet a changing world which will become known as the era of open innovation, with responsible partnering between all scientific and technological sectors. Equally, the rapid development of nanomaterials science and technology will advance our fundamental understanding of the nanoworld and the associated synthesis and characterisation techniques and will open up a whole new field of strategic research for the European research infrastructure, with the goal of developing new applications for the European industry.

The nanomaterials revolution

The end of the 20th Century saw significant advances in the design of 'nanomaterials', i.e. materials, components and products which may have a structure of only a few tens of atoms in size. Tailoring the properties of materials atom-by-atom offers the potential for improvement in device performance for applications across the entire range of human activity: from medicine to cosmetics and food, from informa-

SUMMARY

tion and communication to entertainment, from earth-bound transport to aerospace, from future energy concepts to environment and climate change, from security to cultural heritage. Nanomaterials will lead to a radically new approach to manufacturing materials and devices. Faster computers, advanced pharmaceuticals, controlled drug delivery, biocompatible materials, nerve and tissue repair, crack-proof surface coatings, better skin care and protection, more efficient catalysts, better and smaller sensors, even more efficient telecommunications, these are just some areas where nanomaterials will have a major impact.

This will affect so many sectors, and in many fields the pace of development will be so rapid, that failure to respond to the challenge with an efficient, timely, and co-ordinated European programme will threaten the future competitiveness of much of the European economy. Sophisticated materials and materials systems with novel properties and unheard-of performance will have to be conceived and designed in the decades to come, if our European high-tech industry is to remain competitive and if a high standard of living is to be assured for the European citizen of this 21st Century. It should be mentioned that at the industrial level, it is not economically competitive to build nanostructures atom by atom; therefore collective processing – where a large number of atoms are processed at the same time to build many nanoscale systems – must be developed.

The role of the European research infrastructure

Future knowledge-based nanomaterials research will critically depend upon materials characterisation methods, from common laboratory techniques to dedicated large-scale facilities. A fleet of sophisticated experimental methods will be needed to study all nano-aspects of new materials over a broad spectrum of length and timescales. No outstanding research on nanomaterials can be delivered without high performance characterisation tools and non-destructive methods.

Major assets in future nanomaterials research within Europe are the well-developed national and international synchrotron radiation, laser and neutron facilities. These facilities have been at the forefront of a wide range of scientific and technological developments over the last twenty years, supporting research in natural sciences (physics, chemistry, and biology), materials science and engineering, and in the development of advanced technologies and analytical techniques. This GENNESYS study has unravelled that these facilities will play in the nanomaterials revolution, and the insight that they can provide into the details of materials behaviour and mechanisms will be essential to realise the future potential of nanotechnologies for solving urgent problems of our society.

The analytical technologies provided by European research infrastructure offer a unique potential for the future development of nanomaterials: Highly brilliant and focused x-ray and neutron beams are able to interrogate all nanoscopic aspects of a given nanosystem ranging from structural, chemical, electronic, and magnetic to thermal properties. The tunability of all beam properties (energy, wavelength, focus, time structure, polarisation) allows one to explore a material with highest precision on a quantitative level. The penetrating power of high-energy x-rays and neutrons makes it possible to access deeply buried nanostructures and nanophenomena, and to study nanomaterials under industrially and environmentally relevant conditions in a non-destructive manner. The facilities offer dedicated support from sample environments via detector technology up to data analysis software.

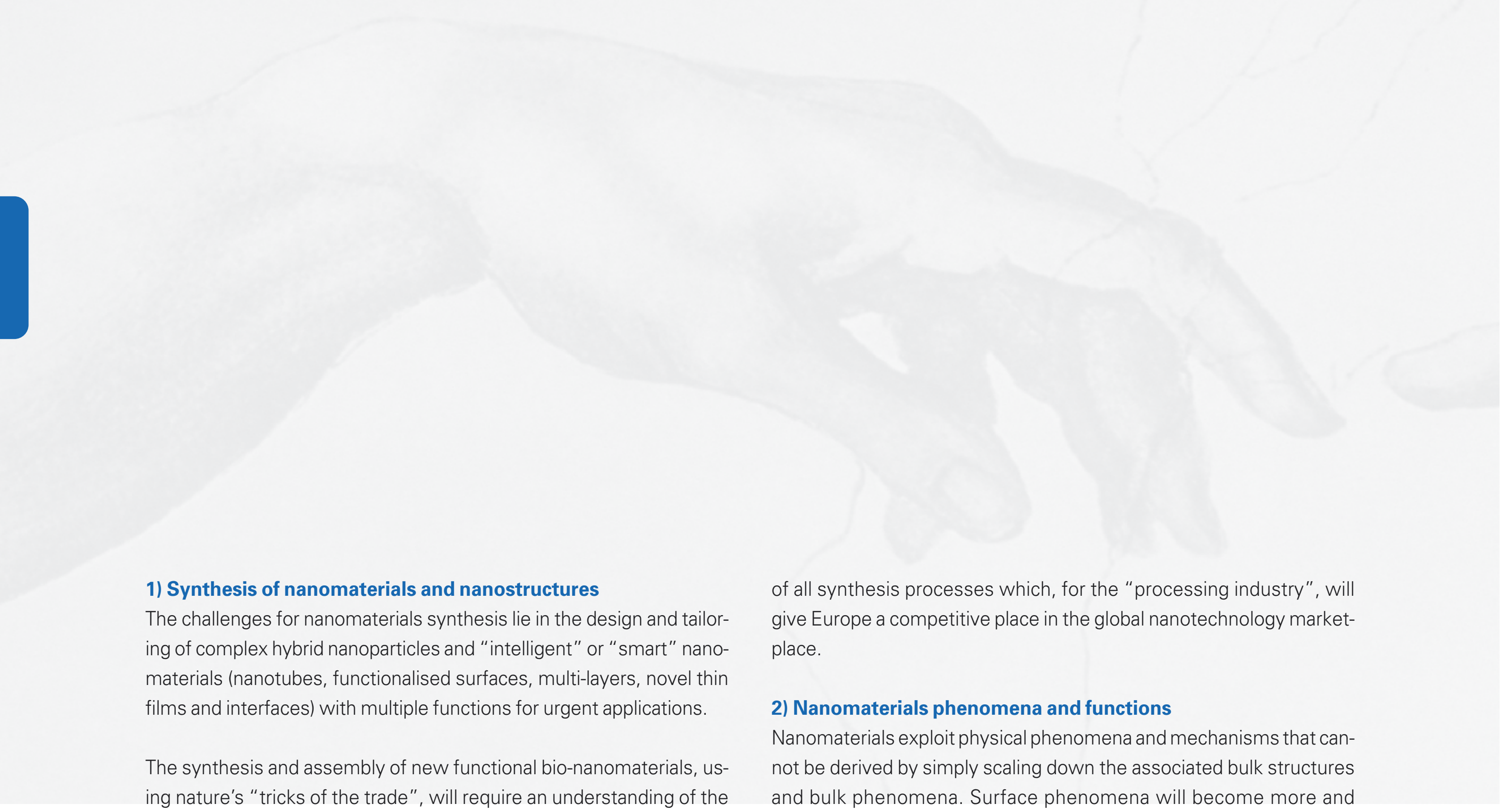
The GENNESYS study has identified the urgent need for facilities which combine new instrumentation and beam lines with dedicated experimental support facilities, including modelling capabilities for the study of nanomaterials under real processing and operating conditions that are relevant to industrial research and development. GENNESYS has also disclosed those areas where dedicated upgrading of experimental methodology, instrument design, support structures and training of personnel must be addressed in order to render neutron and synchrotron radiation facilities most efficient to address future research needs for the development of nanomaterials and nanotechnology.

The range of applications for nanotechnologies

In order to structure the large field of nanomaterials and nanotechnologies, GENNESYS has subdivided the different areas of application of nanomaterials into research and technology fields For each of these fields, the key research challenges have been defined, the roles of synchrotron, x-ray and neutron methods identified, and a research roadmap for the next two decades outlined.

A. FUNDAMENTAL RESEARCH: GENERIC CHALLENGES

Fundamental research into nanomaterials behaviour is an essential prerequisite for generating the necessary scientific understanding of how nanostructures can be designed, synthesised and modelled. The complexity of this research demands advanced and high-performance analytical techniques to enhance the development and optimisation of the size, shape, structure and performance of nanomaterials.



1) Synthesis of nanomaterials and nanostructures

The challenges for nanomaterials synthesis lie in the design and tailoring of complex hybrid nanoparticles and "intelligent" or "smart" nanomaterials (nanotubes, functionalised surfaces, multi-layers, novel thin films and interfaces) with multiple functions for urgent applications.

The synthesis and assembly of new functional bio-nanomaterials, using nature's "tricks of the trade", will require an understanding of the complex relations between nanoscale structure and function in biological materials, and will enable advances in nanomedicine, bio- and biomimetic materials. This will lead to new applications in biosensors, implants, and tissue engineering, the development of which requires an understanding of the dynamic processes that are found in nature.

The tailored synthesis and processing of new particles and materials with multiple functions ("3rd generation nanomaterials") requires:

- Combinations of different synthesis techniques;
- In-situ characterisation under various environments and external fields, (e.g. gases, high pressure and temperature, biomedical applications, etc.);
- Continuous control of particle growth during all individual processing steps;
- Modelling the synthesis process:
  - i) to obtain enhanced understanding of the growth processes;
  - ii) to give guidance to the experimental work, in particular characterisation during synthesis;
  - iii) to develop a better understanding of advanced processing techniques to achieve optimised processing methodology for the fabrication of complex hybrid nanoparticles (incl. reproducibility and reliability);
  - iv) to tackle scale-up from the laboratory to industrial-scale synthesis.

The controlled design of novel nanomaterials requires a coordinated European effort. Synchrotron and neutron radiation facilities should offer their unique analytical potential to study in-situ the processes occurring during synthesis, and allow new developments for the creation of new nanomaterials. Future nanomaterials will be complex and multi-functional in nature, and the structures and properties required for particular functions will be derived by careful 'tuning' of their structure in the processing. To reach this goal, it will be important to be able to follow nanomaterials at all stages of their synthesis and processing.

A new European nanomaterials synthesis laboratory is proposed to keep Europe in a forerunner position for fundamental understanding of all synthesis processes which, for the "processing industry", will give Europe a competitive place in the global nanotechnology marketplace.

2) Nanomaterials phenomena and functions

Nanomaterials exploit physical phenomena and mechanisms that cannot be derived by simply scaling down the associated bulk structures and bulk phenomena. Surface phenomena will become more and more important compared to bulk phenomena. Furthermore, new quantum effects come into play which changes the way nanosystems work. It is the exploitation of these emerging nanoscale interactions which underpins all nanomaterials design. It is an essential challenge to understand the behaviour of given materials on all length scales, from the nanostructure up to the macroscopic response; and at timescales ranging from pico- and sub-picoseconds in molecular and electronic relaxation processes to micro- and nanoseconds in self-assembly processes, to days for long-term relaxation and degradation. The analytical access to this range of length and timescales, from the ultrashort to the ultralong, will be a future challenge for accelerator-based x-ray and neutron technologies in combination with complementary techniques.

Materials will be studied in the solid, liquid and gaseous phases, and at the interfaces between solids and liquids, and liquids and gases. Nanofluidics and nanomechanics play an important role for controlling the physico-chemical processes that are important for many advanced applications such as catalysis, energy conversion or storage using new nanotechnological approaches. It will be necessary to have beam lines at synchrotron radiation and neutron sources which can provide nanoscopic insight into the degradation processes of nanomaterials through in-situ experiments, with the necessary support equipment to perform experiments in 'real' sample environments, and simulate 'extreme' temperature, pressure, magnetic field, and corrosion.

3) Nanomaterials modelling

Modelling and computer-based materials design algorithms will become mandatory tools in testing our understanding of nanoscale processes and phenomena, which can be used in the development of tailored synthesis of nanomaterials, inhibition of degradation processes, and the planning of experimental programmes for nanomaterials development and assessment. For that reason, dedicated characterisation tools are needed, both to adjust model parameters and to check that the theory works or is correctly implemented in computer codes for simulation models.

There will be an increasing need to enhance our theoretical understanding of why particular phenomena arise in order to optimise synthetic processes, explain the mechanisms that lead to material degradation, and predict how nanomaterials properties can be improved. New ab initio models, where fundamental physical principles are used to predict the behaviour of materials at the nanoscale, will take advantage of the increased computing power available.

GENNESYS concludes that the creation of a European database of experimental data and modelling tools for nanomaterials and nanoscale physics is a strategic importance to underpin a sustainable development of key technologies. The database must be validated and data analysis methods must be standardised and easily accessible to all laboratories. The continuous development of this nanomaterials database und its use will be a vital tool for scientists and industrialists who will benefit from existing, ongoing and future research work in the nanomaterials domain.

GENNESYS study showed that a clever knowledge-based design concept must be implemented in which nanomaterials synthesis, the analysis of its atomistic structure, associated function and materials-specific modelling build a closed loop which leads to made-to-measure nanomaterials with highest efficiency. As this loop requires in particular the best analytic technology available, such a European nanomaterials synthesis centre should be built in close proximity and interaction with a large-scale facility for fine analysis of matter. Networks of the existing facilities should be quickly realised in order to be as efficient as possible and to avoid several laboratories to the same goals while other problems are not treated because of the lack of laboratories working on the subject.

B. NANOMATERIALS DESIGN

The GENNESYS study has reviewed a wide range of nanomaterials classes, and has highlighted the impact and novelty that their properties offer, and the potential they have in the production of new materials and designs. The study produced roadmaps for the whole spectrum of nanomaterials research, detailing the research avenues that should be pursued for the discovery and design of novel materials exploiting nanoscale phenomena. Synchrotron radiation, laser and neutron techniques must offer their unique capabilities for quantitative studies at a wide range of length and timescales for all the nanomaterials specified below.

In nanomaterials science, the development of new materials drives many fields of engineering; i.e. alloys with improved mechanical properties and reduced weight, e.g. to increase stiffness and at the same time save weight in aerospace or automotive industries. Composite materials follow the same trend, many of them mimicking the structure of biological tissues like wood, bone, shell, spider silk and many more examples. The use of such new nanomaterials will be essential to address major future global demands such as reducing energy consumption or the ecological impact of almost any product we use.

1) Structural nanomaterials based on metallic, ceramic and polymer systems will provide a step change in mechanical and thermal properties. They will be the basis for a wide range of innovations and new applications exploiting nanoscale effects. There are ambitious research goals in the production of nanostructures which are damage-resilient or even self-healing, materials that use nanostructuring to give dramatic improvements in strength, and the generation of new design concepts for industrial applications in diverse areas such as energy, transport and construction.

2) Functional or 'smart' materials drive forward developments in electronic, photonic, structural and magnetic devices. Nanomaterials will raise the development to a new level, employing novel physical, electrical and mechanical effects to make electronics which will be faster, lighter, cheaper, and easier to manufacture, and which will have low power consumption. Simple devices based on nanomaterials will deliver functions which would ordinarily require a more complex mechanism or component, such as the replacement of electrical connections by optical links and improved non-volatile computer memory. Designing materials operation in stringent environments (temperature, pressure, radiation etc.) is also needed.

3) Polymer nanomaterials will advance dramatically as the chemical and nanoscale structures of polymers are engineered to create new polymers with a multitude of structural and functional applications, ranging from polymers with improved biodegradability to new adhesives and novel electrical conductors. Biopolymers for the life sciences will use the principles of hierarchical assembly in living organisms and apply them to engineered materials and structures. The GENNESYS study concludes that revolutionary advances can be expected in this field.

4) Nanostructured coatings, composites and hybrids can be engineered to exploit a revolutionary combination of tailored properties, between coating and substrate, between composite matrix and rein-

forcement, and between the different components of a hybrid. The GENNESYS study has described how research into these classes of multi-component material systems will provide a new dimension of functionality, as they offer a route to produce combinations of properties that cannot be achieved by any other means. GENNESYS has compiled a roadmap for the development of these novel multi-phase material systems. To understand and tailor such processes will require dedicated analytical tools capable of probing and monitoring them at the nanoscale.

C. ENGINEERING PROPERTIES OF NANOMATERIALS

Nanomaterials research in the past has been directed towards the production of nanostructures as the primary goal, rather than to advance the formation of nanocomponents with defined properties and performance. There will be significant challenges in transferring the knowledge of new nanomaterials properties and mechanisms into the engineering design process, as we are not yet at the stage where nanomaterials can be designed and produced with known properties. Understanding is required of how nanomaterials can be joined without destroying their nanostructure and their function, how nanomaterials fail through corrosion, creep and fatigue, and how nanotribological mechanisms affect friction, adhesion, wear and lubrication. The overall lifecycle of the component must be assessed and understood, if accurate predictions are to be made. This could be demonstrated by monitoring in-situ the crack propagation along grain boundaries in steel alloys during corrosion using synchrotron radiation. This is extremely relevant to understand the mechanisms of material failure due to cracking of stainless steel under mechanical stress. In power plants, three-dimensional x-ray imaging could show: i) where the crack is situated relative to crystallites of different phases in the material; ii) how it propagates along the grain boundaries; and iii) how grain boundaries can be engineered to resist crack propagation. Modelling of materials from the nano-, to the sub-micron and macroscale is extremely important as well as the development of reliable multi-scale simulations for components reliability and lifetime predictions during in service conditions.

The GENNESYS taskforces have identified key research areas in which synchrotron, x-ray and neutron technologies will play a vital role to arrive at breakthroughs in tailoring the design, and in improving the performance in service of a broad spectrum of nanomaterials under real industrial operating conditions.

1) Nanojoining The GENNESYS study has highlighted potential techniques for nanojoining methodologies and technologies, and pinpointed research paths for successful development. Understanding the reliability and strength of nanoscale and nanostructured joints in-service is a great challenge. Existing knowledge and methods for large-scale welding and joining cannot be extrapolated to new methods and nanoscale effects. Synchrotron radiation- and neutron-based combinatorial techniques (imaging, tomography and diffraction) should be devised to measure stress in and around joints and welds, and to provide high-resolution imaging of joint performance and the development of damage during simulated operation.

In designing routes to combine nanostructured materials into larger assemblies, it is necessary to have joining techniques that do not disrupt the nanoscale structure. This is particularly critical as many joining techniques involve heat and/or mechanical deformation. Additionally, there is scope for developing materials which, by virtue of their nanostructure, allow for the creation of stronger joints than is the case with conventional materials.

2) Nanotribology The study of friction, wear and adhesion at the nanometre scale requires knowledge of surface interactions, chemical environment effects, lubrication, mechanical stresses, as well as biochemical concepts. This field is rapidly developing, but most of the applications that can be realised exploiting nanotribological ideas are still in an embryonic stage. Synchrotron, x-ray and neutron facilities are asked to devise appropriate analytical concepts which give new insights into the mechanics of local contacts at the nanoscale for the development of new wear-resistant nanocoatings and nanostructured lubricants, mechanisms of lubrication and wear at the nanoscale to minimise energy losses and damage in moving mechanical system, and mechanisms of local force generation at the nanoscale. Understanding of the latter will be critical in developing methods for molecular assembly by the movement and positioning of individual atoms and molecules. Understanding dissipative mechanisms at the nanoscale is an important challenge for developing useful nanosystems.

3) Life cycle of nanomaterials The lifetime of an operating nanoarchitecture is limited by fracture, fatigue, creep, corrosion that will differ significantly from those that operate in ‘conventional’ structural materials. A mechanistic understanding of the damage mechanisms operating at the nanoscale, obtained using in-situ synchrotron radiation and neutron experimentation, will be critical to generate the knowledge base needed for the reliable application of nanomaterials

in engineering applications. The understanding of nanodamage mechanisms is needed as input in simulation models.

D. CHALLENGES IN NANOMATERIALS TECHNOLOGIES

The enormous potential impact of nanomaterials for new technologies has been highlighted by the GENNESYS study. The opportunities for nanomaterials research and development have been defined for a broad spectrum of technological application areas to deliver unprecedented impact in fields encompassing faster information exchange and new multi-functional computer systems enhanced healthcare, with new drugs through bio-nanotechnologies and nanotherapies in medicine; more energy-efficient transport encompassing light-weight structural materials; reduced pollution and carbon emissions; and technologies for safety and risk reduction. The goal is the enhancement of these technologies for improved quality of life, through the development and production of new materials with novel properties. These breakthroughs critically rely upon advancing our fundamental knowledge of nanomaterials. It is the future strategic role of the European research infrastructure to provide this information in due time and develop a responsible partnering with industry for realising the new paradigm of open innovation.

In the decades to come, a series of difficult problems will have to be addressed, from global warming and energy consumption to affordable medical care. In many cases, nanoscience and technology will contribute considerably.

1) Information Technology

The tremendous progress of micro- and optoelectronics in the past decades is driven by the fabrication of ever smaller structures, increasing the number of elements per area and decreasing the cost per element exponentially. Currently, the dimension is in the range, and conventional production will meet its limits in a few years. New concepts such as the use of strained silicon to increase performance have to be pursued further; eventually new materials and completely new device concepts will have to be introduced. Self-organised nanostructures like quantum dots and quantum wires should improve significantly the performance of optical devices such as semiconductor lasers. As we decrease the dimensions of systems, similarly to the sound barrier, we shall soon meet a quantum barrier where basic properties change owing to the appearance of new quantum effects arising from the small size of the system.

The future prosperity of the information technology industry strongly depends on further successful down-scaling processes, creating new devices with higher functionalities, greater flexibility and reliability, and improved performance. Nanoscience and -technology will provide important basic approaches for improved functionalities and new device concepts. The new nanoelectronics will give a step change in functionality – higher speeds, reduced power consumption, reduced complexity – that will provide novel computer, photonics and informatics applications over the next 20 years.

In microelectronics and photonics, new developments such as quantum communication and computing, data storage using new materials, and concepts such as magnetic semiconductors and spintronics, will revolutionise capabilities. Most of these concepts are based on nanostructures, and in most of these cases structural studies using synchrotron and neutron sources are essential.

2) Health: biological and medical applications

The entire scope where nanomaterials impact human health, through medicine, dentistry, cosmetics, food and agriculture, has been evaluated. The healthcare industry is dependent on drugs and drug delivery systems for disease control and improving the quality of life. New drug systems with controlled release can be developed using nanoengineering, and the delivery of drugs into the human body is much simplified by exploiting nanoscale effects i.e. delivering just the amount of drugs necessary to patients allows decreasing the amount of drugs and the impact of pollution since the excess is often released in the environment.New ointments which exploit nanoscale binders will have offshoots into the cosmetics industry, which will be able to exploit the research and development needed for the full exploitation of nanomaterials in healthcare.

Nutrition is critically important for health and the quality of life. Increasing demands for more efficient food production and processing, the possibility of engineering foodstuffs for improved nutrition, and the development of foodstuffs designed to be suitable for people with allergies or nutritional disorders will all require a step change in our ability to manipulate the structure of materials at the nanoscale. In particular, being able to formulate foods which can be successfully processed is of fundamental importance. Prototype production facilities will need to be developed which can be operated at x-ray and neutron facilities for real-time and in-situ studies of the development of relevant structure and the associated mechanisms.

3) Manufacturing engineering

Nanomaterials have to meet the demands facing new structural materials, reduced energy consumption, and reduced life-cycle costs. Advances include reduced fuel consumption and operating costs, reduced or zero emissions, improved capacity and comfort and reduced noise. Breakthroughs in nanomaterials engineering depend on how precise we can "see" the relevant structures and how they change during a process. This puts serious demands on tailored analytical tools ranging from diffraction, imaging, microscopy, tomography and spectroscopy with highest spatial resolution (<50 nm).

Many 'traditional' materials embody the principles of nanomaterials engineering in developing their structure at the nanoscale. There are still significant advances to be made in many fields of metallurgy. Synchrotron, x-ray and neutron methods have been instrumental in many major advances in our understanding of the fundamental mechanisms of materials mechanisms and performance; these instruments and methods will continue to help identifying new mechanisms in nanomaterials, using much higher spatial resolution.

4) Nanomaterials in energy technologies

Climate change and the security of energy supply are two of the most pressing concerns facing both developed and developing countries alike. To tackle energy consumption and associated problems, no other way than using renewable sources and developing nuclear energy will be possible in the medium to long term. Saving energy and an efficient use of it are the basic requirements in this evolution.

The potential impact that nanomaterials can make in this area is truly enormous. If current projections are correct, they could achieve transformational changes in the way we convert and use energy, providing a sustainable, clean, efficient and above all decarbonised energy system.

The study of materials for energy is extremely broad and covers a very diverse set of materials embracing functional, chemical and electronic energy materials. Development of nanomaterials for these applications will require, for all the different materials types, the probing of structure at all length and time scales.

There are many cases where the application of nanomaterials will be central to these transformational changes. Nanomaterials for Li-battery technologies are in development, and nano-LiFePO4 as a cathode is a good start but further developments in nanomaterials are necessary to engineer the high power batteries needed for hybrid electric vehicles.

Improved solar cell concepts are based on semiconductor nanowires (the "high-tech solution") or new organic compounds (the "low-tech solution"). For improved batteries such as Li-ion-cells, covering the electrodes with nanostructures might solve the problem of expansion/contraction during the charging/uncharging cycle, which is at the moment a big issue in battery lifetime and safety. Solar cells will be important in the future but the date at which this will be implemented on a large scale depends much on the cost of photovoltaic cells which are for the moment too expensive. Progress in mastering thin inorganic and organic films is urgently needed.

Nanomaterials are seen as one of the most promising routes to achieving targets for solid state hydrogen storage, and new nanostructures are emerging that offer fast ion transport along interfaces that could revolutionise electrochemical devices such as fuel cells. The application of nanomaterials in photovoltaic devices are as numerous and as important, ranging from nanomaterials for dye-sensitised cells to light concentrators and absorbers.

The importance of all these devices to our society and its future cannot be overstated and whilst conventional materials have an important role to play, only by fundamental studies of nanomaterials the key breakthroughs in energy technologies will be achieved.

All mentioned developments rely heavily on advanced material characterisation; synchrotron radiation and neutron scattering play an important role here, and are especially powerful for the investigation of nanostructures incorporated in a device, eventually even during device operation e.g. change of Si-nanowires in a Li-ion battery during charging/discharging. Neutron and synchrotron x-ray will be the core facilities used to achieve the insights needed for the breakthroughs in these new energy technologies.

5) Environment

In natural and man-made environment, nanotechnology will help to solve problems like soil and groundwater remediation, air purification, pollution detection and sensing. The same is true for man-made waste reduction including nuclear waste which also requires developing safe geological disposal with methods acceptable for society. A better prediction of climate change is directly linked to the understanding of the role of aerosols (nanoparticles) in the atmosphere.

6) Security and safety

Nanotechnology will bring new answers to the prevention and protection against terrorism threats, or against natural and industrial

accidental risks. Nanotechnology will also provide efficient response to the security and safety of critical installations and the environment.

7) Culture and art

Nanoscale and microscale studies of archaeological artifacts or historical objects will help to understand their history, past technological and artistic skills as well as past climate and environment. Nanotechnology will also help in finding new protection of precious objects which are part of cultural heritage and a huge source of revenue from tourism.

E. NANOMETROLOGY RESEARCH AND STANDARDISATION

A new generation of nanomaterials will require a new concept of measurement techniques for the characterisation and the determination of their physical properties. These nanostandardisation methods will also become increasingly important in proving validation of novel measurement techniques in order to assure their reproducibility, quality, robustness and accuracy. Alongside the development of any new measurement technique, it is vital that it is applied in a standard, reproducible way. Modern industry relies heavily on standardisation of measurement, processes, methods and products, and on the use of Standard Reference Materials. GENNESYS strongly recommends exploring the unique analytical portfolio offered by the European research infrastructure to produce new nanostandards.

Good practice in metrology requires standardisation of any new or improved measurement techniques, standardisation in information and data reporting and interpretation, and globally-accepted standards for measurement. All of these are critically important for the study of properties and structures at the nanoscale.

It will therefore be important for new instruments developed at synchrotron radiation and neutron sources to carefully reflect on the requirements of industrial users in having standardised sample environments and software for experimental planning, execution and analysis.

Reference nanomaterial standards will be mandatory to ensure the quality of the scientific deliverables, as they will provide benchmarking of the data generated.

The establishment of a European meeting point for nanomaterials metrology is essential for the exploitation of this emerging discipline, and to help ensure its successful growth and the promotion of the GENNESYS platform.

F. IMPACT, INFLUENCE AND BENEFITS FOR SOCIETY

Nanomaterials may generate products which improve the quality of life for individuals. Thus, it is important to prepare for a European industry which can compete openly in the international market with its products and processes.

Nanomaterials will bring benefits throughout society and its activities:

- In economy, science and technology are the principal drivers of economic growth and quality of life. Research, particularly nanomaterials research, has widespread impact in health, information, energy, and many other fields where there is major economic benefit to the commercialisation of new technologies.
- Concerning energy efficiency, nanomaterials research will have a great impact, as new nanomaterials will allow higher temperatures and hence a more efficient operation of power plants, and enable the development of new energy production systems based on nuclear, solar, and renewable sources.
- In medicine and health care, nanomaterials will provide new drugs and new therapies, and cures for currently chronic and fatal illnesses. Important areas of research will be the application of nanomaterials in tissue engineering and medical imaging. The potential application of nanotechnologies has immense capability and promise for advanced diagnostics, improved public health and new therapeutic treatments.

Nanomaterials technology will reach large-scale production if one or more of the three following conditions are fulfilled:

- Nanomaterials give the same performance as conventional materials at a reduced cost;
- Nanomaterials give a better performance at the same cost or a price marginally higher;

Apart from the unquestionable benefits, the risks associated with nanoscale materials have also to be addressed. History has shown that new science and technology often cause fear and misunderstanding in society. This holds also and in particular for the field of nanomaterials, because their developments also constitute ‘unknown’ and invisible aspects. Nanomaterials processing techniques can be dangerous for health and studies on animals have demonstrated this. Great research efforts should be made to investigate health impacts and methods to prevent them.

Synchrotron radiation and neutrons may help in defining the boundary conditions for risks and to build up a robust database for a mecha-

nistic understanding of nanomaterials behaviour. The use of advanced, established experimental techniques may help to alleviate some of the perceived problems with employing nanomaterials in consumer products.

Systematic fundamental research is needed for understanding toxicity and the impact of nanomaterials in the human environment. Research is also required into how and why public perceptions of nanomaterials and nanotechnologies are formulated, and what steps are required to reassure the public. Public education of the scientific facts about nanomaterials, and the benefits to health, the environment and to economic prosperity, need to be communicated clearly.

A close collaboration between scientists, industrialists and government is needed to safeguard this new nanomaterials research field. To stay competitive on a global market, to secure energy supply, and to meet the environmental challenges of our industrial society are the main socio-economic driving forces for the future development of the European economy. The potential impact and benefits of nanomaterials simply cannot be ignored.

G. IMPLICATIONS OF GENNESYS FOR EDUCATION AND TRAINING

The GENNESYS conclusions on the need for a pan-European strategic action plan for the development of tailored nanomaterials and nanoarchitectures, in order to specifically contribute to solve or mitigate an urgent technological problem requires breakthroughs in nanomaterials research by an interdisciplinary and cross-sectorial effort. This in turn requires that the materials scientists and engineers involved in this endeavour are experts in their field and have the necessary literacy in neighbouring fields as well as in industrial practice. Furthermore, they should be able to move freely within Europe and understand managerial, economical and societal issues.

During their work, the GENNESYS task forces understood from industry that this type of scientist is rarely available today. GENNESYS has thus devised a new education scheme and training structure and has made a distinct proposal of how to establish a European education in nanomaterials science which involves all sectors engaged in the GENNESYS initiative (see below).

For Europe to continue to compete alongside prestigious international institutions and programmes on nanomaterials, it is important to create a "Europe Elite College".

1) European Nanomaterials College

This type of nanomaterials scientist and engineer with the expertise and skills mix described above is currently not produced in any of the universities in Europe. GENNESYS has devised a syllabus for a European Master's and PhD course which assures a research-focused education, a close involvement of industry and national and European research labs, as well as the necessary literacy to work efficiently in a multi-disciplinary research and engineering consortium. This new syllabus is the mission of a new European Nanomaterials College. This should be a new institution, involving 'satellites' of leading Universities and other institutions throughout Europe. The partner of this new college should be the GENNESYS institutions, i.e. the European universities, national and European research labs, industry and the European research infrastructure.

2) International collaboration

The GENNESYS foresight and strategy document addresses urgent problems which have a global dimension, such as new concepts for future energy and environment. Thus, it is very strongly recommended to establish international collaborations with United States and Asia as well as other industrial countries.

3) Industry partnerships

Nanomaterials and technologies have great potential for the future, and a correspondingly strong demand for advanced analytical techniques. This has long been realised by the pharmaceutical, cosmetics and information-technology industries, with future applications in the energy, aerospace, chemical engineering and automotive sectors.

In a future new era of open innovation, partnerships across disciplines and among universities, government laboratories and industry are essential to leverage resources and strengthen interdisciplinary research and connections to technology. A responsible partnering between academia and industry will enable cross-disciplinary research and provide awareness of technological drivers and potential applications.

The European Commission should provide incentives for formation of sustainable strategic partnerships between universities, industrial labs and research centres, and the European research infrastructure for the advancement nanomaterials science and technology. Raising the profile and intensity of interdisciplinary research in nanomaterials will help to restore the leadership and activity in European research that generated many of the advances in the 21st century that benefit our lives today.

These research and development partnerships should be encouraged in order to:

- Enable cross-disciplinary and cross-sectorial research in key fields;
- Create a new spirit of open innovation;
- Improve academic knowledge on industry priorities and needs;
- Improve industrial knowledge on nanoscience discoveries;
- Exploit the existing European research infrastructure for nanomaterials development
- Assemble teams that can recreate the fertile research environment of the large industrial research labs;
- Develop the commercial exploitation and patenting of new technologies.

These partnerships should be fostered by:

- European and national funding;
- Encouraging university and research labs internships and sabbaticals in industry.

For a future strategic collaboration between industry and the European research infrastructure, it is prerequisite to overcome the following three key barriers:

- Lack of expertise and lack of understanding of complex analytical tools;
- Concerns over commercial confidentiality and intellectual property;
- Non-existent standardised analytical setups.

In turn, there are challenges for the large-scale facilities:

- Standardisation of analytical concepts and set-ups;
- Certification of measurement procedures;
- Faster access to the European Research infrastructure for academics and industrialists;
- Support for non-specialist users of the facilities before, during and after the experiment;
- Close cooperation between instrument scientists and users;
- Predefined sets of standard sample environments.

H. IMPLEMENTING GENNESYS: CHALLENGES AND REQUIREMENTS

The development of nanomaterials and nanotechnology in Europe faces several challenges:

- Nanomaterials science in Europe is severely fragmented into different disciplines, sectors and member states;
- Its critical role not appreciated by the public, because it takes place in the background;
- The European nanomaterials community and the European research infrastructure are largely unaware of each other;
- There is no efficient platform for continuous knowledge transfer between academia and industry.

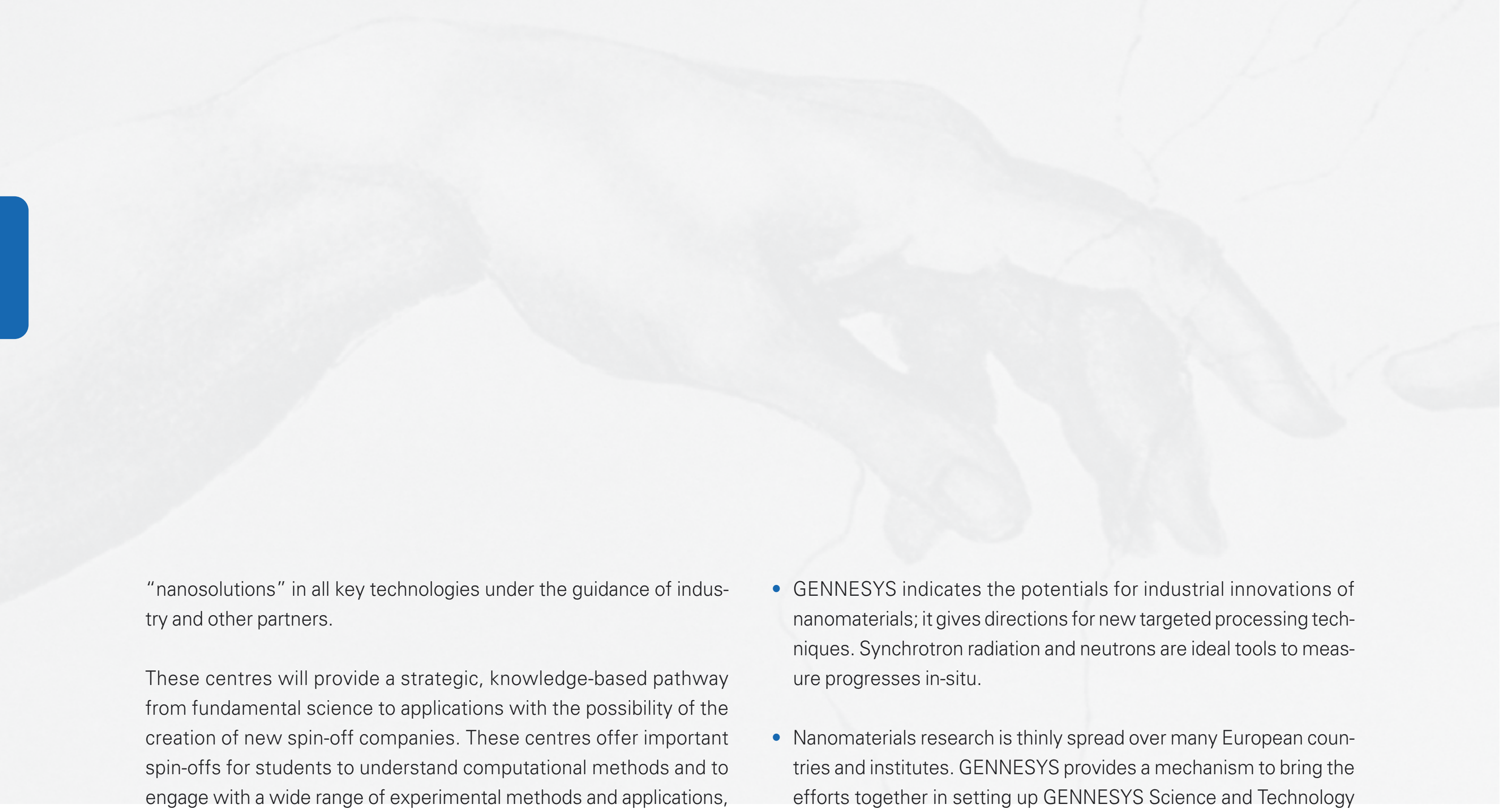
With the implementation of the GENNESYS vision, all these problems could be overcome or at least substantially mitigated. It is hoped that the roadmaps presented in this GENNESYS European Nanomaterials Strategy Study will provide a point of reference for policy-makers, lab directors, university rectors and industry management. It is envisaged that GENNESYS will serve as world-wide platform for scientists to foster future collaborative, cross-disciplinary research and development, and to stimulate growth in the commercial exploitation of nanomaterials science and technology in Europe.

I. GENNESYS SCIENCE CENTRES

To be able to take the world lead in nanomaterials – discovery, scientific understanding and industrial innovation – Europe must concentrate its best researchers, research facilities, research equipment, research expertise and research infrastructures to tackle the key challenges in nanomaterials research. While similar efforts have already been made in the US, the GENNESYS recommendation goes a step further.

Successful nanomaterials research for solving a given urgent problem of our society will require a multi-disciplinary approach across all sectors, incorporating expertise in physics, chemistry, biology and engineering as well as computational and theoretical tools; and a broad spectrum of advanced and dedicated analytical methods which interrogate the nanomaterials and nano-architectures in-situ, non-destructively, at all relevant length scales and under a range of environmental and operating conditions. GENNESYS taskforces strongly recommend that synchrotron radiation, laser and neutron facilities must play a strategic role in this research effort.

GENNESYS recommends creating European Centres of Excellence in nanomaterials research with a clear mission to solve an urgent problem. In order to capitalise on the existing unique analytical potential of the European research infrastructure, those Centres should be built at large-scale facilities for the fine analysis of matter. Science Centres will focus onto fundamental research in nanomaterials science under guidance of an academic research lab consortium and provide the molecular database for robust technology development, Technology Centres will focus onto the development of working



"nanosolutions" in all key technologies under the guidance of industry and other partners.

These centres will provide a strategic, knowledge-based pathway from fundamental science to applications with the possibility of the creation of new spin-off companies. These centres offer important spin-offs for students to understand computational methods and to engage with a wide range of experimental methods and applications, providing a basis for them to become successful researchers and industrial innovators. Such centres will also attract, train and develop the next generation of leading young scientists who are vitally-important for a growing, modern economy.

Conclusions and recommendations

Nanomaterials science and technology will provide breakthroughs for many technologies in the future, and solutions for urgent problem in our society. In order to leverage the fragmented knowledge in Europe for a strategic pan-European nanomaterials programme, a joint effort of all sectors of research and innovation is necessary, including the existing highly developed European research infrastructure.

A close collaboration between scientists, industrialists and the government is needed to safeguard this new nanomaterials research field. To stay competitive in a global market, to secure energy supply, and to meet the environmental challenges of our industrial society are the main socio-economic driving forces for the future development of the European economy, and the potential impact and benefits of nanomaterials simply cannot be ignored.

GENNESYS is a foresight and strategy document compiled by using expert input from the education, science, technology, policy-maker and governmental authorities. It has demonstrated that a stepwise improvement in Europe is needed in order to take a leading position in the world of nanomaterials science, technology and industrial exploitation. A strategy must be developed and delivered to ensure future impact on economy and society, and success in this grand challenging new world.

The conclusions of GENNESYS can be summarised as follows:

- The study gives an overall picture of the future research needs in the large spectrum of nanomaterials and highlights the important roles of advanced analytical equipment in reaching breakthroughs, especially the synchrotron radiation and neutrons facilities. The study is a reference work for scientists, research managers, industrialists and policy-makers to design new programmes and guide future research in nanomaterials.

- GENNESYS indicates the potentials for industrial innovations of nanomaterials; it gives directions for new targeted processing techniques. Synchrotron radiation and neutrons are ideal tools to measure progresses in-situ.

- Nanomaterials research is thinly spread over many European countries and institutes. GENNESYS provides a mechanism to bring the efforts together in setting up GENNESYS Science and Technology Centres throughout European at large-scale facilities. This is a necessity to keep Europe a forerunner in this field.

- The European GENNESYS Centres of Excellence bring the European talent together – scientifically, industrially, socially and economically. They are multi-disciplinary centres where nanoscientists from all European countries are welcome. They offer opportunities to research institutes and universities of central- and Eastern Europe to participate actively. The centres should have the theme of "Science" or "Technology" orientation. They could be compared to the CERN organisation in high energy physics in Geneva.

- GENNESYS highlights the importance of creating a European/international institution for nanomaterials where talented students could prepare for a brilliant career. This institution, with satellites around various large-scale facilities, recognised universities and industries, will become competitive with the best US and Japanese school in nanomaterials. The institute should also deliver qualifications that are recognised throughout Europe.

- The GENNESYS study analyses a wide spectrum of nanotechnologies. It hints towards solutions in the complex energy question, particularly related to new energy sources or to the improvement of existing sources. It also studied completely new topics such as nanomaterials for security and safety, nanopharmaceuticals and nanofoods, the role of "nano's" in global climate change, etc.

- The study pinpoints the advantages of nanomaterials but analyses in depth the research needs to combat the toxicology and nanoprotection problems and tries to delaminate the borders/boundaries between danger and no risks. Synchrotron radiation and neutrons are of great importance in studying the mechanisms of dangerous nanospecies in the body.

- In order to cope with the challenges and needs of nanoscience and technology, considerable improvements are needed also with large-scale facilities such as synchrotrons and neutron sources.

This has technical aspects as well as organisation aspects (availability, ease of access) and educational ones: e.g. extreme focusing nanobeam stations, small neutron beams, transferring scientific results from laboratory conditions to realistic industrial ones, etc.

- To achieve efficient work and collaborations between large-scale analytical facilities and nanoscience and technology, the creation of GENNESYS type analytical centres is essential.

Europe will need to invest in the next generation of synchrotron radiation, laser and neutron facilities, offering higher fluxes and more brilliant probes, and providing significant and necessary advances with regard to resolution, sensitivity, and data acquisition. A continuous investment is needed in the upgrading of Europe's synchrotron x-ray sources, with improvements in equipment and instrumentation, new ancillary equipment to support new experimental methodologies, and a rolling programme of upgrades to ensure that Europe's synchrotron sources remain at the forefront of research in nanomaterials science and technology.

- It is suggested that the European Commission, in collaboration with the European Science Foundation and other European authorities and national funding agencies, should establish a European body with the mandate to coordinate all nanomaterials activities and large-scale facilities in Europe.

- GENNESYS recommends creating a European College for Nanomaterials Science, Science Centres and Technology Centres of Excellence for research, development and exploitation of nanomaterials in closest interaction with the European research infrastructure. The European synchrotron radiation, laser and neutron facilities have the most advanced analytical equipment and a solid and proven infrastructure of scientists and equipment.

Governments should promote the creation of new European Centres of Excellence and an International Institute for Nanomaterials Education, to be coordinated by the European Commission and/or relevant agencies.

Helmut Dosch
Marcel H. Van de Voorde

Max-Planck-Institut für Metallforschung