Lloyd's Register Foundation

Life matters

Lloyd's Register Foundation

Foresight review of nanotechnology

The next industrial revolution

April 2014

Lloyd's Register Foundation
Report Series: No.2014.1

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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Foreword

Is nanotechnology the next industrial revolution? Whatever its revolutionary claims the technology is here now. It heralds the ability to manufacture things – materials, components, systems – with atomically precise control. It is the ultimate in miniaturisation; molecular manufacturing.

Imagine a material orders of magnitude stronger than steel yet a fraction of the weight; materials that can heal themselves and self-repair when damaged; structures made from materials that can 'feel' the forces acting on them and communicate; liquids that can transform into solids and back again at will thus able to absorb shocks; wires and electronics as tiny as molecules; ultra-high density energy storage batteries and capacitors; artificial intelligence; DNA-based computing; nanoelectromechanical actuators and nanorobots. All of these are already existing or foreseeable applications of nanotechnology.

It is convergence of the sciences spanning chemistry, physics, materials science, biology, and computational sciences that is making nanotechnology possible. Its applications will impact almost every industry including energy, transportation, manufacturing, medical, computing and telecommunications.

Nanotechnology and its applications depend on creating the necessary tools to position atoms and molecules and build complex structures and machines with atomically precise control. Underpinning this are the modelling and simulation, imaging, and metrology instruments and methods needed to manipulate matter at the atomic scale.

This report has been commissioned as a foresight exercise to look at the worldwide developments being made in nanotechnology and what the impact of its applications might be in the engineering-related sectors of relevance to the Lloyd's Register Foundation. Based on its findings, the Foundation is looking to identify the gaps or 'white space' in nanotechnology research where it could make a distinctive contribution, which would lead to enhancements in safety. This would be through accelerating targeted technology applications or contributing to the body of knowledge addressing any uncertainties about potential risks to human health, property or the environment. As the Lloyd's Register Foundation we do this in pursuit of our charitable objectives, because… life matters.

Professor Richard Clegg
Managing Director
Lloyd's Register Foundation

Professor Sir Mark Welland
Director of the Nanoscience Centre
University of Cambridge

Nano flower bouquet, three-dimensional nanostructure grown by controlled nucleation of silicon carbide nanowires

Image courtesy of the Nanoscience Centre, University of Cambridge

Background

This report has been commissioned by the Lloyd's Register Foundation as part of its emerging technologies research theme. It aims to try and look into the future at what potential impacts developments in nanotechnology might have on the safety and performance of engineering assets and the infrastructure on which modern society relies.

The Lloyd's Register Foundation is a charity and owner of Lloyd's Register Group Limited, a 254-year old professional services company providing independent assurance and expert advice to companies operating high-risk, capitally-intensive assets in the energy and transportation sectors. This includes ships, oil rigs, power plants, industrial facilities and railways.

This report has been commissioned by the Lloyd's Register Foundation as part of its emerging technologies research theme

Based on the findings of this review, the Foundation will be looking to identify those areas of nanotechnology that could have a significant impact (positive and negative) in the areas covered by its charitable objects, and then to focus on where the Foundation could consider funding fundamental research that could make a distinctive contribution and make a real impact.

Fundamental to an informed analysis of the potential impact of nanotechnology was the establishment of an expert advisory panel with extensive experience at both the scientific and safety / regulatory levels. In addition, reflecting the Foundation's global presence, an international cross-section of experts was assembled with representation from the USA, Asia and Europe. The panel met in Lloyd's Register's offices in London towards the end of 2013. This report contains the output and findings from that panel.

Expert Panel membership

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Introduction to nanotechnology

In 1998, Neil Lane, then Assistant to the President of the USA for Science and Technology said:

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

This statement epitomises the view of governments worldwide and indicates precisely why so much financial investment in both nanoscience and nanotechnology is being made. To understand this more fully it is important to understand what nanoscience is, what nanotechnology offers in terms of commercial opportunities and what role nanotechnology will have amidst all the other technologies that shape our lives.

The prefix nano- has two meanings. In an exact sense it means a factor of one thousandth of a millionth, 10^{-9}, and hence a nanometre (5 atom diameters) as a length measurement and a nanosecond as a time measurement. In its popular use, the nano- prefix normally refers to the length scale. The more imprecise definition of nano is 'extremely small'. Hence a nanosatellite is simply a satellite that is extremely small compared to a conventional one, and not a satellite that is a few atoms in size – in fact it is more likely to be the size of a football. The interest surrounding nanoscience and nanotechnology is associated with the exact definition and the fact that both science and engineering are now possible on the nanometre length scale.

The prefix nano- has two meanings. In an exact sense it means a factor of one thousandth of a millionth. The more imprecise definition of nano is 'extremely small'

To put this into perspective, engineering at the nanometre scale with respect to a metre length is the equivalent of being able to position a single eye of a common house fly to an accuracy of less than 1/10th of its diameter in the distance between Paris and Rome.

Nanometre length scale

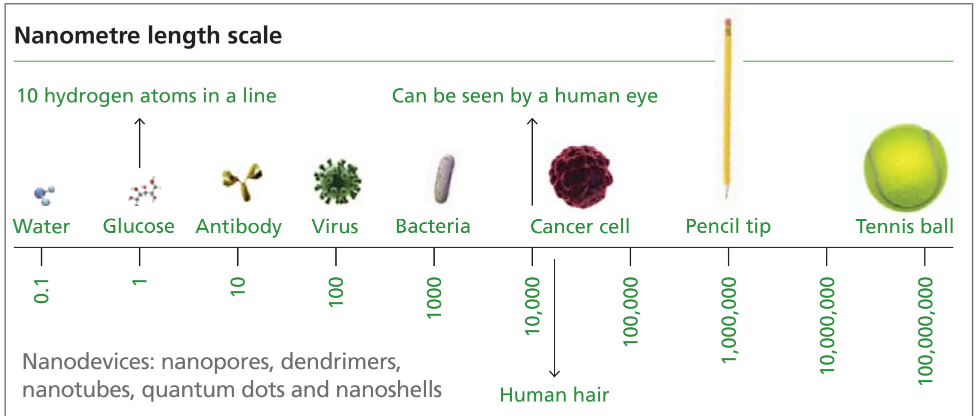


Figure 1

The fact that science and engineering on the nanometre scale is now ubiquitous is predominantly a natural consequence of miniaturisation that has been constantly evolving over the last few centuries: we are simply used to having smaller and more complex machines. Two obvious examples of this are how the sizes of watches and clocks have decreased in the past 500 years and how, in the past 15 years, the size of mobile phones has shrunk even though their complexity has increased. Miniaturisation by itself does not however explain the nano-boom. There are at least three unique factors that combine to explain the real potential, and ultimately some concerns, around nanoscience and nanotechnology.

1. The end of the road for miniaturisation

The atoms and molecules of everything around us represent the fundamental building blocks of nature that we can currently explore and exploit. In this sense miniaturisation has come to a natural limit. The importance of this is best summed up in a quote from Horst Stormer, a Nobel Laureate who said:

"Nanotechnology has given us the tools…to play with the ultimate toy box of nature – atoms and molecules. Everything is made from it… The possibilities to create new things appear limitless."

2. Nano is different

As an object is shrunk in size there is a length scale beyond which the physical properties of the object itself can start to change. This is not because the laws of physics have changed it is simply because the size and shape of the object now play a role in defining the objects' physical property. Thus, for example, magnetic properties of magnets smaller than a few hundred nanometres in size become increasingly dependent upon size and shape – a fact that will be exploited in future computer hard disk drives. Engineering at the nanometre scale therefore provides an opportunity to make new types of materials and devices with unique properties. Nanoparticles such as carbon nanotubes are good examples of this. As a tool however it is important to recognise that it is not a technology in its own right. It is simply an enabling technology that will allow one or more elements of a material, product or process to be done differently – energy efficiently, uniquely or through the use of fewer raw materials. It is just one of the plethora of technologies that are available and therefore to be used only where appropriate.

3. Nano is ubiquitous

Since atoms and molecules are nanometre size objects it is not surprising that nanoscience has relevance to a range of scientific disciplines and nanotechnology is important across technology sectors. It also explains why nano- can so easily become a catch-all prefix. Since nature is constructed from atoms and molecules a nanometre or so in size, it is possible to claim that nano- is therefore everything. Chemists have been making and measuring molecules for over 100 years, does this mean they are suddenly all nanoscientists? In a sense the nomenclature does not really matter. What is actually important is that the nanometre is a unit of length of fundamental importance to many disciplines so that advances in science and technology in any one area can have an immediate impact on another. A prominent example of this is how an imaging tool, the scanning tunnelling microscope, designed to image single atoms, is now applied to problems in nearly every area of science that range from understanding how crystals grow to watching DNA molecules at work.

The investment in both nanoscience research and commercialisation underlines the expectations that surround nano- in terms of technological and commercial opportunities. Whether these opportunities are new types of materials that are tuned to a specific application – a plastic computer chip that can be manufactured in a developing nation at a tiny fraction of the cost of its silicon counterpart; a medical sensor that can detect disease before symptoms appear; or a solar cell that can provide cheap electricity – nanotechnology will play a key enabling role. But the power of nanotechnology to effect dramatic change, based on the understanding of nature at the fundamental level, in turn means that the potential for it to be misused or generate unexpected consequences needs to be considered; there are both opportunities and risks. In some sense this is no different to any other evolving technologies as, for example, the GM debate, human cloning and even the internet have demonstrated. However, successful commercial exploitation of nanotechnology requires, simultaneously, the addressing of regulatory and safety issues to optimise its impact.

Future prospects of nanotechnology relevant to the Lloyd's Register Foundation

Given the atomic scale of nanotechnology it might appear at first sight that the connection with the scale of the physical infrastructure that represent the Foundation's various interests is tenuous. In determining the focus and modus operandi of the Expert Panel it was therefore crucial to identify technology innovations / enablers that were significantly dependent upon nanotechnology but that were also drivers relevant to the Foundation.

A current example of where nanotechnology has had impact over the past 20 years is in electronics. The current generation of computers, mobile phones, digital cameras, tablets and related technology rely fundamentally on techniques to manufacture and measure on the nanoscale using the tools of nanotechnology. This consumer electronics market is expected to be worth $289 billion in 2014 [1]. The Expert Panel did not consider this sector specifically in its deliberations as it is already integral to all aspects of life, commercial and personal. The panel did however note that the industry will continue to innovate, grow and substantially alter the world around us.

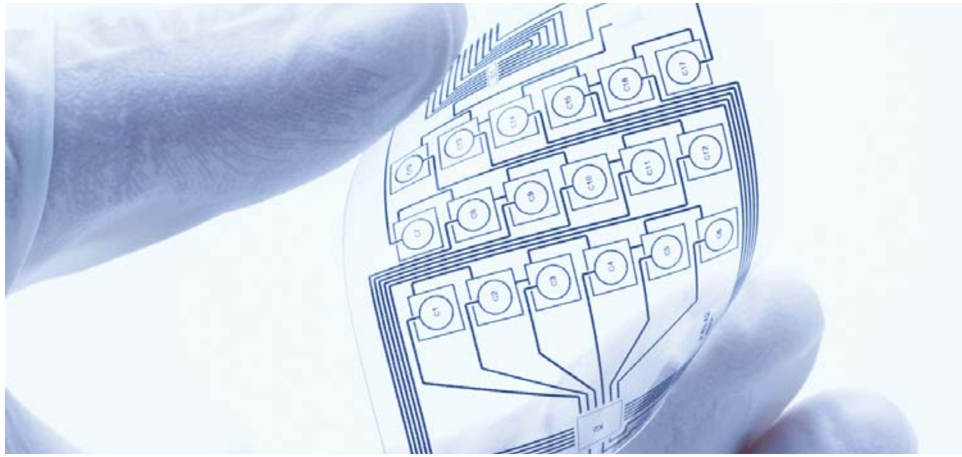
The current generation of consumer electronics rely fundamentally on techniques to manufacture and measure on the nanoscale using the tools of nanotechnology

The four technology enablers the Expert Panel identified where nanotechnology would be a significant innovator relevant to the Foundation's future business are:

- pervasive sensing
- smart materials
- energy storage and generation
- big data.

Finally, the Expert Panel also considered:

- nanotechnology and risk - the potential of human exposure to nanoparticles
- quality assurance, certification and traceability of manufactured nanoparticles.



Pervasive sensing

A direct consequence of miniaturisation that nanotechnology affords is the ability to manufacture ever smaller sensors. Such sensors range from those that would be incorporated into concrete and interrogated in order to determine the chemical state of the concrete and the local stresses within the material, to sensors incorporated into the human body to monitor key physiological or biochemical indicators. Sensors could be hardwired into a system architecture, could be wireless but powered, or could only be activated during interrogation so that both power and data readout were effected externally.

This ability to incorporate sensors into even very basic materials such as concrete, has engendered the concept of pervasive or ubiquitous sensing. This concept allows for, at one extreme, the monitoring of long-term stability and behaviour of construction materials to, at the other extreme, the ability to control a complex system with optimal efficiency by continuously monitoring all aspects of the system's state. A simple example of how sensing can significantly enhance system efficiency is the degree to which automotive engines are now equipped with sensors to optimise performance. Such proliferation of sensors fundamentally relies on the ability to miniaturise components to reduce the physical footprint, increase complexity / intelligence and reduce energy requirement; all a direct consequence of the ability to manufacture using nanotechnology.

If one assumes, as is already happening [2], that sensors will be routinely incorporated into structural components then there is an obvious opportunity to enhance and extend the ability to monitor structures' components and assemblies at all stages in the supply chain and lifecycle through manufacture, distribution, operation and disposal.

This real-time asset monitoring has implications not simply for monitoring the integrity of a supply chain, but will enhance the ability to predict and manage component failure, wear and performance. It is unlikely that all materials and components would be provisioned with sensors; mostly those components that are critical either in terms of cost or function would be augmented with some sensing capability.

Sensors in control loops or even in extended systems will enhance efficiency at all levels. At a local level this could be, as in the automotive example, increasing the efficiency of a powertrain in a ship or train. At an intermediate level this might be enhancing the operation of a power station by monitoring all aspects of the power stations' function. At a much higher level sensing may allow for more active control of an entire system such as the shipping of commodities from factory to user at a global level. The addition of environmental sensing, allowing the system to adapt to changing conditions, will also have an impact. Once again, using the automotive analogy, monitoring the temperature and oxygen content of inlet gases to an engine allows for increased engine efficiency. At a larger scale, the ability to adapt to changes in environmental conditions and to avoid environmental hazards could be advantageous.

Finally, we are already seeing the consequences of pervasive sensing and increased control loop intelligence in the appearance of autonomous vehicles. There is no doubt that this technology revolution will continue so that it may be routine for there to be no provision for a human as the main controller of a vehicle, ship or even perhaps aircraft. There are difficult questions here as to how one underwrites the safety case for such autonomous systems, how one demonstrates failsafe mechanisms and, given that such systems require electronic communication, robustness against external interference.

Figure 2 indicates how pervasive sensing may impact the Foundation.

The findings of the Expert Panel show that pervasive sensing has the potential to make a significant impact on the types of high-hazard, capitally-intensive assets of relevance to the Lloyd's Register Foundation. In many respects, the impact could be paradigm shifting.

Today, engineered assets – ships, oil rigs, power plants, industrial facilities, railways etc – require manual safety inspections of their structural integrity and performance. Robotics and remote non-destructive examination and assay techniques are also used in harsh or inaccessible environments. Pervasive sensing takes this to another level, with the ability to incorporate into materials, components and structures, cheap, intelligent sensors that will monitor asset performance, ageing and degradation in real time. Such sensors may be embedded at the manufacturing stage, the construction stage or retrofitted later.

All of this, combined with other advances and applications of nanotechnology – such as in robotics, artificial intelligence, telecommunication – creates a realistic vision of the future entailing 'man out of the loop', with assets being monitored, surveyed, and inspected remotely and in real time.

Pervasive sensing

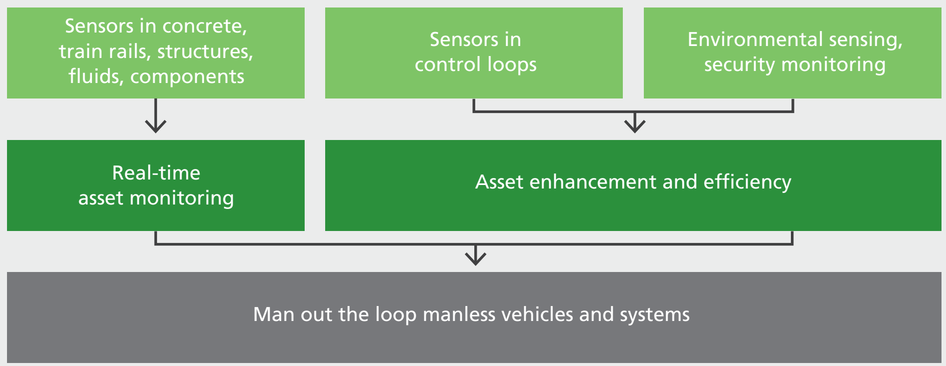


Figure 2

Smart materials

We are already seeing a revolution in the types of materials now available for critical engineering tasks. The Boeing 787 Dreamliner, being made substantially from carbon fibre composite and plastic, being a case in point. Composites based on nanotechnology where one component is a nanoparticle are already in use in niche applications. There are a number of potential advantages from using materials with a nano component.

First, a little like carbon fibre composite, one can design stiffer, lighter material components. The current cost of producing such materials is significantly higher than more conventional materials so that they tend to be used in more critical applications, such as the Dreamliner where energy efficiency is paramount. As manufacturing techniques improve there will be an inevitable increase in applicability of nanotechnology-based materials away from niche applications towards more mainstream and larger scale use.

A second advantage of nanomaterials is that one can enhance existing material properties with further function. A simple example is the use of super hydrophobic coatings to prevent water attaching to surfaces. There is already an antifouling paint available for marine applications [3] based on nanomaterial incorporation. It is also possible to nanostructure the surface of a material, much like a butterfly's wing, where the colour comes not from the use of a dye or paint but from how the light interacts with the nanostructured surface. Coatings or additives also have the potential for materials to 'heal' when damaged or abraded [4].

The Boeing 787 Dreamliner, made substantially from carbon fibre composite and plastic, is an example of smart materials for critical engineering tasks

A further potential application for nanomaterials is where the material properties can be changed by the application of an external stimulus. There are already examples of materials in armour applications where in normal use the material is soft and pliant but when impacted by a projectile becomes hard and protects the wearer. But it is also possible to change properties by the application of a magnetic or electric field. It may be possible to control whether a material component is soft or hard simply by the application of a voltage. Although such applications are currently at the research phase, it is likely that this type of technology will start to appear in commercial applications.

In addition to the ability to produce lighter, stiffer and adaptive materials that will have application in a broad context, there is the prospect of mimicking biology to produce materials like spider's silk or coatings which behave like a gecko's foot and 'stick' to surfaces [5]. Both materials rely on controlling structure at the nanoscale. Irrespective of the type of nanomaterial, we should anticipate impact across all industrial sectors.

The findings of the Expert Panel indicate that smart materials have the potential to significantly impact on the sectors and sorts of engineered structures relevant to the Lloyd's Register Foundation (see figure 3). The world will move on from being based on metallurgy to nanocomposites and biomimetics with designer properties. Such new materials will require new joining techniques, together with new safety skills and methods to assess their operational integrity and safety performance.

One particular area the Expert Panel highlights is the potential application of nanotechnology in the area of RFID (radio-frequency identification). RFID is used in tags containing electronically stored information which can be read wirelessly for the purpose of automatically identifying and tracking tags attached to objects. They are however bulky and relatively expensive to produce. A new generation of RFID-like tags based on nanotechnology are already being explored. These tags, that are essentially invisible, can be interrogated with a simple optical scanner. Each tag has an optical barcode comprised of nanodots, activated when illuminated by the scanner. These will be significantly cheaper and therefore able to be deployed more readily allowing for accurate labelling, tracking and traceability of components and assemblies.

Smart materials

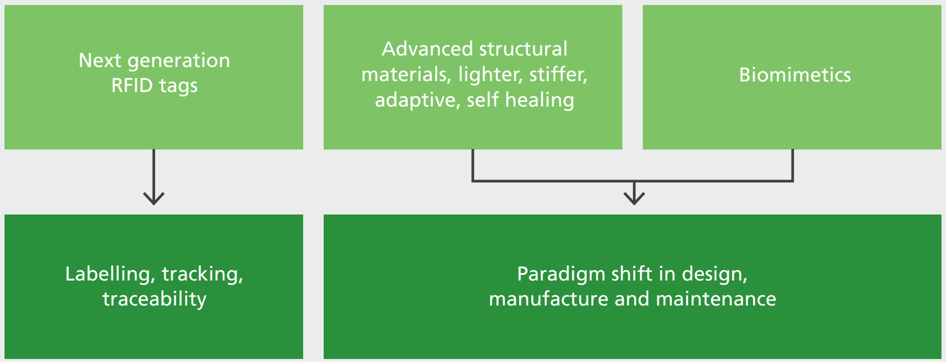
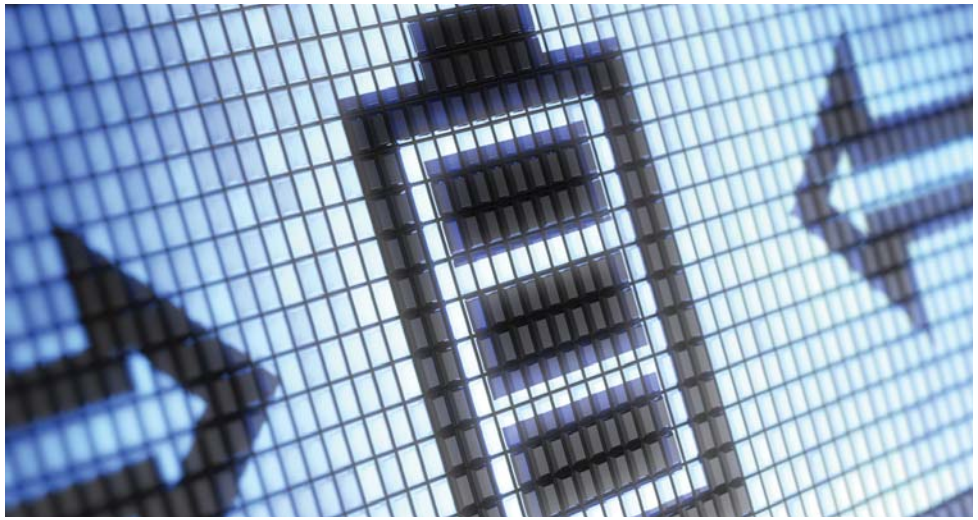


Figure 3

Energy storage and generation

Energy storage, generation and efficiency are topics of enormous current interest on a global scale. The global investments into these areas are manifest. Whether smaller but more energy dense batteries for mobile phones, compact fuel cells to burn hydrocarbons, photovoltaic cells, or super capacitors to store electrical energy, nanotechnology is already playing a substantive role. For batteries and capacitors nanostructuring allows for the more efficient storage of electrical energy, in photovoltaic cells it allows for efficient conversion of light to electricity, and in fuel cells it provides a large surface area to convert heat to electricity.

At the same time as energy storage technologies develop there will be a significant change in the way energy is managed in its entirety. The process of generation, storage, use and recycling will become more integrated, as seen already in the introduction of 'smart grids' [6]. Such systems draw on the ability both to sense all aspects of the energy chain alongside using computer-based modelling and control to optimise the entire process thereby maximising energy efficiency. This is a very significant change to the more binary approach, a source of energy on one side and a consumer on the other side, that we have seen historically. Such an approach goes beyond simply optimising a system; it will also drive changes in generation, storage and transmission technologies.



Referring to figure 4 below, for the Lloyds Register Foundation there will be an increasing reduction of fossil fuel use and the prospect for high density battery technologies to be used to power large power plants and for propulsion; the developments in battery technology for electric and hybrid cars will increasingly impact on the road, rail and maritime transport sectors.

Energy storage and generation

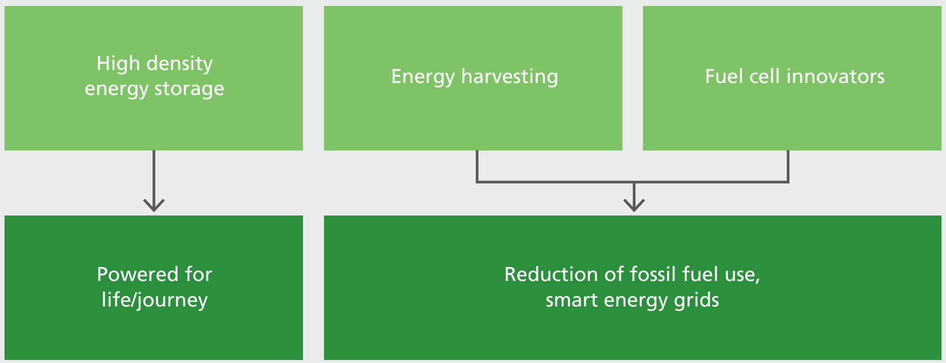


Figure 4

Big data

Although not explicitly driven by nanotechnology, one characteristic of the future will be the plethora of sources of data constantly providing streams of information on all aspects of our lives. In some cases this data explosion is a consequence of the information revolution, in turn driven by nanotechnology and miniaturisation, but is also a consequence of the pervasive sensing described above. At the simplest level the quantities of information available will require further advances in storage and transmission that nanotechnology will play a critical role in developing. But there are further opportunities and challenges.

The quantities of information available will require further advances in storage and transmission that nanotechnology will play a critical role in developing

Beyond the immediate use of data to, for example, control a system, there is scope to further analyse the data to provide significant information on the behaviour of systems, the identification of faulty or inefficient components and sub-processes and predictive algorithms that will allow for system failure and fault analysis.

The data itself also becomes a powerful commercial tool that will almost certainly require standards for storage and use to ensure that such data can be meaningfully used and interpreted. For example, data streams from sensors would be an almost useless commodity in a post-processing sense if the characteristics of the sensor itself were not included. Similarly, data would almost certainly require a time / date and spatial location stamp to make the data viable.

The importance of big data to the Lloyd's Register Foundation is clear. Recognising this the Foundation has commissioned an international academic expert panel, chaired by Professor Sir Nigel Shadbolt, to provide a detailed assessment of technology trends in the field of big data, particularly relating to 'machine data', and the impact these are having on society. The panel's report will be published as the second in this Report Series.

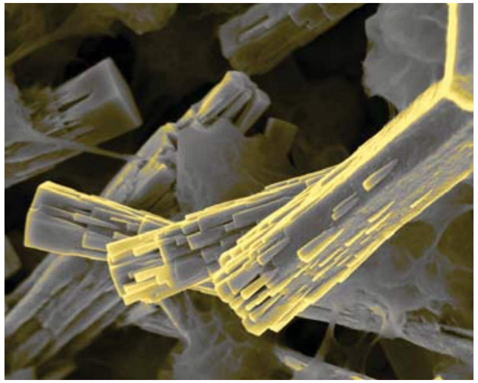
Nanotechnology and risk

As with all new technologies there is a potential for nanotechnology to impact human health, the environment and safety. There are however a number of specific factors that make nanotechnology challenging when trying to determine regulation and best practice in respect of health and safety.

The first factor is simply the size of a nanoparticle that is typically defined as being a particle with dimensions less than 100 nm. For such particles, their size means that they can generally move fairly freely through a living organism and indeed the environment itself; the size range is not much different to a chemical. An approach is therefore required that, similar to chemical regulation, takes into account the mobility and long-term fate of free nanoparticles in the environment as well as the potential toxicological consequences on living organisms.

A second complicating factor is that the properties of a nanoparticle can change with shape and size. Unlike larger particles whose physical properties are independent of shape and size, nanoparticles can exhibit quite dramatic changes in property. Thus, for example, a gold nanoparticle can appear to have a range of colours from blue to red purely dependent upon the particle size. Although this size- and shape-dependent behaviour is one of the defining characteristics of nanotechnology, it complicates the issues around health, safety and regulation. This complication arises because if one has assessed a nanoparticle of particular shape and size range in terms of its hazard and risk, then a new assessment might be required for a case with a different shape and size range even though the chemical structure might be the same. This places a specific onus on regulatory bodies to define metrics for size and shape as well as chemical composition of nanoparticles.

There are also issues around whether the nanoparticle is free or bound into another larger structure. For nearly all applications nanoparticles tend to be incorporated into other materials, whether a computer chip, a composite material or a paint. Once so incorporated their bioavailability needs to be assessed to determine if there is any route for free nanoparticle release into the environment which would create a potential hazard. This approach needs to be considered over the full life time of a product or material with the probability of human exposure to free nanoparticles being determined at every stage. Typically, the greatest risk of human exposure is where the particles are synthesised at the start of a manufacturing process since they are then very likely to be free. There will also be a risk of release at the end-of-life stage where the component breaks down or is recycled.



Zinc oxide nanorods

Carbon nanocones

Images courtesy of the Nanoscience Centre, University of Cambridge

A few final factors. First that nanoparticles are already common in the environment; pollution such as city smog is made up of carbon-based particles from burning fossil fuel. And at the lower end of their size nanoparticles are the same size as chemical and biochemical molecules and associated cellular structures. So it is important to differentiate between manufactured (new) nanoparticles and those already in the environment. Second, the size makes the research into toxicology very challenging as identifying individual particles is only possible by very sophisticated and expensive experimental techniques. Finally, the public attitude to the introduction of new technologies has been sensitised by some high profile cases, such as GM, placing a greater onus upon the responsible introduction of nanotechnology with as much scientific rigour as possible in support of risk analysis and regulation.

All of the above issues were recognised at a very early stage by governments around the world and there has been considerable investment in research to support risk analysis and regulation. A seminal report by the Royal Society of London in 2004 [7] looked explicitly at the balance between opportunity and risk for nanotechnology. The European Union has sponsored a number of projects to improve understanding and quantification of risk, including ITS-NANO [8], and finally international standards are being developed for nanotechnology through ISO [9]. An example of a flow diagram for the risk process of nanoparticles is shown in figure 5.

Nanoparticles risk process

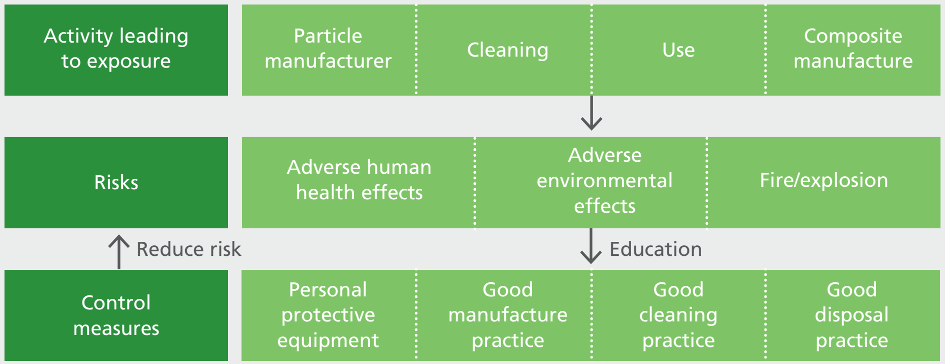


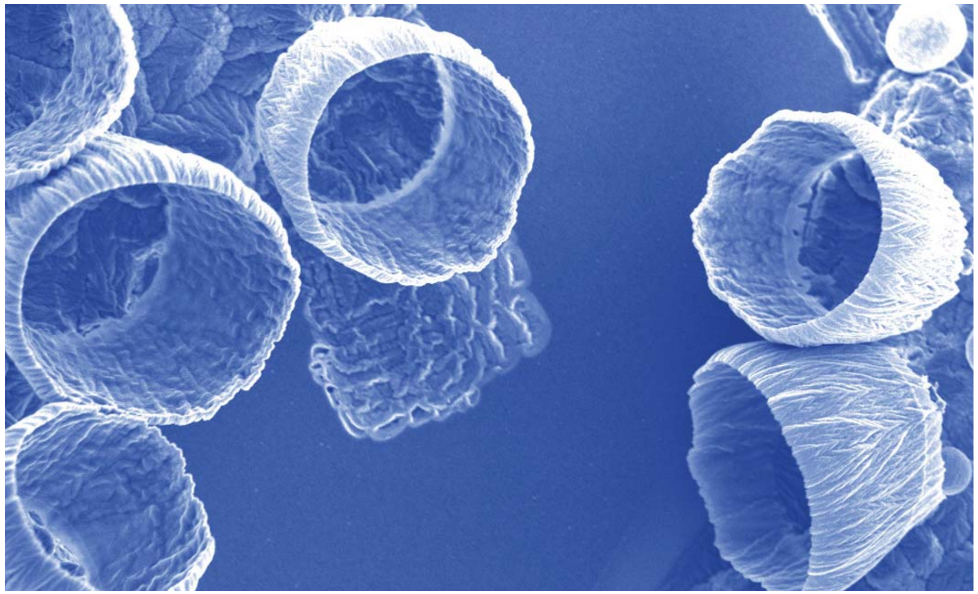
Figure 5

Although significant progress in risk analysis and regulation is being made there are still research challenges in providing both tools and protocols for analysis, but also in developing standards that can be meaningfully applied. The Lloyd's Register Foundation will certainly be affected by any regulatory standards but there is also perhaps the opportunity to support research into areas where nanotechnology products may specifically impact business and where either standards or risks are particularly relevant.

Quality assurance of nanoparticles

The manufacturing supply chain of nanoparticles is an area of focus that the Expert Panel also highlights. The manufacture of nanoparticles is a sophisticated process with many end users buying such materials from specialist suppliers. The quality assurance, traceability and certification of nanomaterials is therefore an issue of concern for users, particularly as analysis and assay techniques are expensive, and with universities normally being the only organisations with the right sort of equipment and expertise able to perform such analysis. Standardised analytical protocols also do not exist.

A further complexity is that the properties of certain nanoparticles can vary dependent on how they have been manufactured or the conditions under which they have been grown. For example, the properties of carbon nanotubes can be modified with small changes in diameter and chirality.



Nanorings, small ringformed crystals

Images courtesy of the Nanoscience Centre, University of Cambridge

Smart materials: There is the prospect of mimicking biology to produce materials like spider's silk or coatings which behave like a gecko's foot and 'stick' to surfaces

Nanotechnology timeline

In order to quantify how nanotechnology may impact the industry sectors of strategic relevance to the Lloyd's Register Foundation, the tables in the appendix (page 29) set out future prospects in the areas of energy, transport and marine, and management systems. The underpinning science, the broad applications and the potential impact on these specific business sectors are mapped out on a short- (0 to 5 years), medium- (5 to 10 years) and long-term (10 to 20 years) timescale.

The figures in this report together with the tables in the appendix have also been summarised into a single roadmap shown overleaf in table 1. This illustrates how nanoscience development will translate into future technology applications and the forecasted timeline of their impact.

The roadmap overleaf shows how nanoscience development will translate into future technology applications and the forecasted timeline of their impact

Table 1
Timeline of future technology applications relevant to the Lloyd's Register Foundation

Science area	Future prospects	Application timeline		
		0-5 years	5-10 years	10-20 years
Stimulus responsive materials Intelligent materials that can change their properties upon external stimulus such as light, temperature, pressure **Nanocomposites** Incorporation of nanoparticles into a bulk matrix like ceramics, metals, polymers, creating smart materials **Biomimetics** New materials, devices and systems created by mimicking nature, like nanotubes, nanodots	Man out of the loop, UAV's, advanced robotics Pervasive sensing Paradigm shift in design, manufacture and maintenance Powered for life / journey components, systems, infrastructure Smart energy grids. Overall better usage and efficiency from local energy generation High density energy storage devices Advanced structural materials that can be lighter, stiffer, stronger Smart materials with unique mechanical, electrical, thermal, optical, friction, catalytic properties Big data and metadata	Nanocatalysts and nanostructured catalysts replacing precious metals, used in variety of chemical and industrial processes from water purification to emissions Milli-micro power generation systems, such as for emergency backup Safety, semi-autonomous systems, anti-collision, guidance systems Invisible labelling based on low-cost spray inkjet Complex nanoscale electronics, nano-enabled devices, sensors, electro-mechanical systems	Real-time supply chain interrogation, monitoring and tracking, smart labelling, supply chain tracking, traceability Real-time asset monitoring Enhanced data management and communication systems through integration of satellite systems (GPS), optical systems (Glas) and broadband systems. Feedback systems for optimal human interface Active integrated control systems, such as driver constrained systems for transportation and automotive safety 3D printing – cheaper, just in time, critical component manufacture High-density energy storage. Energy harvesting (ie artificial photosynthesis) Fuel cell-based transportation systems New batteries, supercapacitors for energy storage and conversion New batteries and supercapacitors for transportation etc, including energy recovery from braking, short-term energy storage and burst-mode power delivery Setting standards for nanomaterials Nanomaterials contained in the fabric of textiles transforming the fabric as needed from flexible, comfortable material to rigid, impact proof, or sealed from chemical or bacterial agents	Quantum computers, DNA-based computing, artifical intelligence, data management Active integrated control / safety systems Self-diagnostic, self-healing, self-repair materials, coatings, structures Energy conversion and transfer – eg tidal generators with piezoelectic elements. Piezoelectric roads converting vibrations into electricity Smart integrated transport networks Nanorobots perform cellular repairs that could cure almost any disease. Carbon nanotube cables enabling inexpensive space travel, such as the space elevator Molecular manufacturing enabling building of almost anything inexpensively atom by atom. Diamonoid materials with a strength-to-weight ratio of about 50 times that of steel could make very lightweight cars, planes, and spacecraft available Setting standards for nanomaterials traceability

Recommendations

The Expert Panel made the following recommendations to the Lloyd's Register Foundation which they felt would properly ensure that the charity could take account of the changes and opportunities that nanotechnology would bring in deciding its research priorities, and which would also ensure that they retained an expertly informed position for the future.

1. Horizon scanning: anticipation, adaptation and innovation

The Expert Panel provided a snapshot of where nanotechnology is and the potential prospects for the future. There would be sense in ensuring that the scope of nanotechnology is constantly refreshed in respect of the Foundation through a horizon-scanning exercise that would identify technology opportunities, impact on industry and the regulatory environment. Assembling ad hoc expert panels along the lines of the nanotechnology review is an excellent way of informing the Foundation as to where research opportunities might lie that help deliver its public service mandate.

2. Business road-mapping

Being aware of the technology and its implications is not enough. To properly exploit this information the wider effect on future and current industry needs to be regularly explored. In this sense we recommend that an annual road-mapping exercise is undertaken to identify where a particular technology, and nanotechnology is one of those, would impact the sectors of strategic relevance to the Lloyd's Register Foundation. Such a road mapping would build upon the horizon scanning of 1 above but place it into a business context.

3. Database: materials, technologies

Establishing a bespoke database which defines materials, technologies and processes relevant to nanotechnology would ensure that the Lloyd's Register Foundation could draw upon its own set of definitions, ensuring both consistency and relevance where such definitions are used by the Foundation or its associates. The establishment of such a database could be a part of the responsibilities of the horizon scanning team described in 1 above.

4. Safety, regulation and standards

As standards and regulation around nanotechnology continue to be implemented it is important there is an opportunity for an independent and authoritative organisation such as the Lloyd's Register Foundation, to contribute to the body of science that informs standards' setting and to ensure that the advice given is interpreted properly and that the resultant regulations are meaningful and relevant.

5. Research: system level modelling, intelligent customer

In terms of the role of the Lloyd's Register Foundation in supporting research, the most significant opportunities are probably in system level modelling. In respect of research it is highly unlikely that the Foundation will be able to impact on nanotechnology research given the massive worldwide investment at the more fundamental level. There are however possibilities for modelling the complex systems such as those relating to pervasive sensing which are less well supported externally and would be more relevant to the objectives of the Foundation.

The ability to incorporate sensors into even very basic materials such as concrete, has engendered the concept of pervasive or ubiquitous sensing.

Appendix

Quantification of how nanotechnology advances could impact the sectors of relevance to the Lloyd's Register Foundation

Table 2
Future prospects – energy sector

Energy	Short term	Medium term	Long term
	0-5 years	5-10 years	10-20 years
Impact	• Energy storage, facilities and generation • Emergency back up • Milli-micro power generation systems	• Fuel cell-based transportation systems	• Overall better usage and efficiency from local energy generation
Broad applications	• Energy storage • Improved efficiency • Charge-up vehicles • Photovoltaics / solar thermal • Nanocatalysts • Hybrid systems • Emission reduction, coal liquefying	• New batteries • Supercapacitors • Fuel cells • Geothermal energy conversion • Biomass and microbial decontamination • Artificial photosynthesis	• Energy conversion and transfer • Tidal generators with piezoelectric elements • 50+ years: fusion
Underpinning scientific advances	• Hydrogen fuel cells • Batteries and super capacitors • Photovoltaics • H2O +light photoelectrochemical cells • Broad spectral sensitivity (efficiency, capture, nanocatalyst) • Water and tidal turbines (hydroelectric) • Bearings, composites (wind turbines) • Energy transport (cables, turbines) • Sensors • Nanomaterials: ion transport	• Antifouling and anticorrosion glass • Heat exchange systems • Sensors • Efficient LED and OLED materials • Energy harvesting	• Piezoelectric pavements and related systems • Nuclear waste cooling • Isotope conversion • Nanomaterial design for energy utilisation

Table 3
Future prospects – transport and marine sectors

Transport and marine	Short term	Medium term	Long term
	0-5 years	5-10 years	10-20 years
Impact	• Fuel efficiencies • Material safety • Improved durability • Extended maintenance cycle • Secondary less critical component production improved	• Shipping security • Aircraft efficiencies in components • Cheaper critical component production	• Multifunction eg water resistance, fouling, self-cleaning, colour change • Setting standards for nanomaterials traceability
Broad applications	• Safety improvements • Lighter, cheaper, sustainable components, fire-retardant • Light ships and airframes (balloons) • Offshore oil rigs • Guidance systems • Sensors	• Antifouling / corrosion / friction • Bespoke design - multifunctional products • E-cars, new components for wings, engines, fuel efficiency, anti-friction/biometrics • Setting standards for nanomaterials • Traceability • Integrated sensor platform	• Magnetic suspension • Self-healing coatings • Smart transport • Automated (man out of loop)
Underpinning scientific advances	• Sensor communication • Composite / foamy structured materials • Nanoparticle coatings - paints, antifouling • Fuel additives CeO_2 • Lubricant additives • Composite structural materials • Complex nanoscale electronics	• Low friction concepts • Cellular adhesion / detachment coating • Nanosensors for security • Safety • Ubiquitous sensing • 3D printing • Control, integration of power and connectivity	• New structure components • Data management, artificial intelligence

Table 4
Future prospects – wider quality and safety implications

Management systems	Short term	Medium term	Long term
	0-5 years	5-10 years	10-20 years
Impact	• Inspection and tracking • Semi-autonomous systems • Advances in safety and fault tolerance	• Real-time supply chain interrogation and monitoring	• Fundamental changes to regulatory regime • Licensing and safety assessment of assets based on continuous in-service monitoring rather than routine scheduled inspections or maintenance intervals
Broad applications	• Invisible labelling based on low cost spray inkjet • Safety – semi-autonomous systems, anti-collision • Large databases, big data and metadata • Alarm systems	• Smart labels • Integration of satellite systems (GPS), optical systems (Glas) and broad band systems • Feedback systems for optimal human interface • Ground / ship / air cargo transport • Automotive safety (driver constrained systems)	• Automatic home and security • Quantum computers • Active integrated control system
Underpinning scientific advances	• Quantum dot nanoparticle optically tuned • Communications • Ultra low-power wireless sensors	• MEMS development to nanoscale including lasers • Data management and communication system • Data mining • Energy harvesting	• Maintenance and interrogation • DNA-based computing • Self-repairing • Nanoenabled sensor systems, low power, control / feedback • Nanomaterials that can heal, self-repair

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Engineering at the nanometre scale with respect to a metre length is the equivalent of being able to position a single eye of a common house fly to an accuracy of less than 1/10th of its diameter in the distance between Paris and Rome