16 May 2006

MARKET INTELLIGENCE REPORT
NANOTECHNOLOGY

An initial study of the market for Nanotechnology technologies, defined as “The science of manipulating materials at the atomic and molecular level to develop new or enhanced materials and products”

 Version 1.0

CONTENTS

EXECUTIVE SUMMARY

This document provides market intelligence into the sector defined as Nanotechnology by the Intermediary Technology Institute (ITI) in Techmedia. For the purposes of this report, Nanotechnology is defined as:

"The science of manipulating materials at the atomic and molecular level to develop new or enhanced materials and products"

Using the acquired knowledge as a base input, ITI Techmedia will select those applications and functional needs that have strongest potential and 'market fit'. The functional needs will be used to identify potential technology platforms which will then be used as input to ITI Techmedia's programme selection process.

During this process, ITI Techmedia will continue to report to its Membership on progress and results. Members are encouraged to provide comment and input to this process, and to become actively involved in programmes.

Global interest in Nanotechnology is huge…

Significant activity is occurring in the Nanotechnology area:

- in 2001, the National Science Foundation in the USA projected that 'USD1 trillion in products worldwide would be affected by Nanotechnology in 2015'. This forecast has recently been brought forward by five years to 2010
- investment in nanoscale research has grown from around EUR1 billion per annum in 2000 and is expected to reach Some EUR10 billion per annum worldwide by 2006 according to the Institute of Nanotechnology
- according to Lux Research, corporations spent some USD4 billion globally on Nanotechnology R&D in 2004.

This interest is being sparked by a number of factors but is, in the main a result of the promise of Nanotechnology to offer new and cost-effective methods of making things. Despite the degree of interest and investment, the market for Nanotechnology products remains immature.

…and it is important to distinguish hype and reality

Advances in tools over the past 25 years allow us to observe, measure and manipulate the nanoscale. This new found knowledge of material properties has created new understandings and discoveries of how materials behave and perform on the atomic scale. Some of these discoveries have been theorized about in the past and can now be put into practice, while some are new and novel discoveries.

Nanotechnology is surrounded by hyperbole, and for good reason. It arguably shows as much promise in both science and business as any other major technology of the past century, including nuclear energy in the 1950s or genetics in the 1990s.

Many researchers involved in nanoscience are sceptical about the hype related to Nanotechnology and its implications. To a large degree many researchers feel there is nothing new in Nanotechnology. However, even the most sceptical researcher/investor has expectations of nanoscience leading to a significant change in technology development and for some even expectations of significant industrial change.

Nanotechnology has potential application across a wide range of industry sectors…

Nanotechnology is not a market per se. Rather, it is an enabling technology for the development of both:

- new opportunities within existing markets
- entirely new markets.

The application of Nanotechnology in a number of industry sectors has been assessed, and the industrial sectors examined are identified below.

Advanced materials and chemicals	IT, telecoms and leisure
Aerospace and defence	Security
Environment and Water	Textiles
Mining	Transport and automotive
Food and household products	

In this report we find that a plethora of opportunities exist for the application of Nanotechnology in these various sectors. However, successful adoption of any particular application will be dependent on a Nanotechnology solution being able to demonstrate:

- significant functional benefits over existing products
- an appropriate price point, implying that nanomaterials must be produced in sufficient quantity volume at the appropriate quality, price and yield.

…underpinned by a variety of key technologies

Nanomaterials, and their associated manufacturing and processing technologies, are the key enablers of the Nanotechnology industry and encompass a wide range of materials.

The common link across these materials is that they all exhibit features only present at the nanoscale that potentially offer performance enhancements over existing materials. Nanomaterials typically measure in the range of 1 to 100 nanometres (nm).

In this report, a brief overview of the following core nanotechnologies is provided:

- nanoparticles
- nanoparticulate coatings, thin films and surface layers
- nanocomposites
- carbon nanotubes
- nanoporous materials
- quantum dots
- nanofibres
- fullerenes
- nanowires
- nanocapsules.

A vast array of applications based upon these core technologies are identified in this report.

Nanotechnology is a component within an overall end-product value chain…

Nanotechnology provides building blocks upon which end-user products can be developed. A generic view of the Nanotechnology value chain, and example players, is presented below.

	Research	Tools and instrum-entation	Materials production	Product developer	End producer
Actors	Academia, industry labs	Mainly SMEs	Large chemical co's, SME's	Large chemical co's, SME's	Large corporates
Examples	Cambridge Nanoscience Centre	Digital Instruments Physike Obducat	BASF Degussa Nanophase	Oxonica Nanoco Nanogate	Pilkington Boots L'Oreal

A significant body of research is being undertaken in relation to the identification and characterisation of materials that may be suitable for use in identified applications. Likewise, the areas of tools and instrumentation would appear to have attracted significant interest and funding.

However, the productisation of these materials would appear to be relatively undeveloped, and end product functions are even more immature.

…and a number of key trends are affecting the sector

Trends in Nanotechnology are generally market/application specific. However, some generic trends and drivers are influencing the Nanotechnology sector. Nanotechnology is now being applied in an increasingly diverse number of areas. Factors that have led to this increase in commercial exploitation include:

- greater interaction between academia and industry to more readily enable technology transfer and innovation along the value chain
- increasingly coherent technical and funding strategies emerging at the national and international level
- evolving industry focus away from a technology-orientation towards a more market-oriented focus
- the recruitment of highly-skilled professionals worldwide into the Nanotechnology sector

A number of drivers and inhibitors are affecting the sector, and are summarised in below.

Drivers	*Inhibitors*
Ongoing need for better technological performance	Sub-optimal yield and quality in nanomaterial manufacturing
Improved, cost-efficient, medical treatment	Scalability of nanomaterials from lab-scale pilot plants to industrial-scale commercial plants
Need for enhanced manufacturing and production processes	Identification of profitable commercial end uses/applications
Demand for improved security and defence	The pace of development of effective nanomaterials for such areas as robotics, microfluidics and micromachining lags the pace of applications requirements
	Corporate inertia coupled with competitiveness of established technologies
	Regulatory concerns over the effect of nanomaterials in the wider environment (e.g. toxicity)

It is expected that the nature of the market drivers and inhibitors will evolve over time. For example, it can be expected that the regulatory environment in which the Nanotechnology industry will operate will mature and stabilise as additional research and analysis becomes available.

A number of attractive areas of application have been identified

The list of applications identified in this report was filtered in order to identify those applications areas of greatest interest, specifically:

- that exhibited a large overall market opportunity
- in which nanotechnologies would comprise a significant proportion of the value of end products.

The resulting application areas identified as being worthy of further consideration were:

High density data storage	Semiconductor devices
Anti-bacteria and anti-fouling	Environmental filtration and sensing
Corrosion protection	Shape memory alloys
Food packaging	

1 INTRODUCTION

1.1 Document Purpose

The purpose of this document is to provide a 'snapshot' view of the Nanotechnology sector in order that the Membership:

- have visibility of the market analysis activities undertaken in this sector by ITI Techmedia
- can gain access to market information relevant to the sector
- are provided with an indication of the functional needs that ITI Techmedia will explore further to identify the technology platforms which will form the basis of any ITI Techmedia research and development programme in this area.

This document should not be considered as providing a comprehensive analysis of the competitive environment within the Nanotechnology sector. Such an analysis is beyond the scope of this document. This report aims to provide an understanding of Nanotechnology and its applications. It also aims to give those who wish to act as players in any part of this space with an apprehension of the dynamics and potential scale of this market.

1.2 Structure and Content

This document provides market intelligence into the sector defined by the Intermediary Technology Institute (ITI) in Techmedia as Nanotechnology (see Section 0 for the definition of Nanotechnology). The information captured within the document has been obtained following the principles of market intelligence gathering (otherwise known as foresighting) established by ITI Techmedia.

During the process of developing this market intelligence report, both primary and secondary market data were acquired and collated. Primary data was collected via discussion with industry experts. This was supplemented by discussions with key Scottish experts in the sector. The primary data gathering process was augmented by desk research which was used to obtain secondary data from internationally recognised market analysts with expertise in the area of Nanotechnology. Where possible, the source of any data used in this report has been identified.

Section 1: Introduction. This Section covers the background, aims and scope of the Intermediary Technology Institutes (ITIs). It also provides a high level description of the 'Techmedia' areas of focus. Further background information can be obtained on the website www.ititechmedia.com.

Section 2: Market Overview. This section provides a working definition of the Nanotechnology sector, reviews the possible application of Nanotechnology within a number of industry sectors, introduces a range of key nanotechnologies, identifies the main trends, drivers and barriers affecting the sector and describes a generic value chain representing current industry structure.

Section 3: Market Assessment. This section provides qualitative and quantitative assessment of a number of potential market opportunities identified during the foresighting process, and provides a high-level view of key functional requirements across these areas of application.

Given that Nanotechnology has potentially a very wide area of application, considerable effort has been made throughout the report to provide possible examples of the application of nanotechnologies.

1.3 Background: Intermediary Technology Institutes (ITIs)

1.3.1 Economic Context

A global driver for economic growth is the development and exploitation of technology both for present needs and future requirements. Successful economies are underpinned by a vibrant research base which extends from basic science through to pre-competitive research and development, with a clear focus driven by global market opportunities. Scotland has a reputation for world class research in many fields and already undertakes significant research activity in several areas which have the potential to be strong future market opportunities. In addition to the research base, most developed economies have institutes or organisations that promote knowledge generation and increase commercial exploitation capacity. The establishment of such organisations has had significant economic impact over the long term.

1.3.2 ITIs

The creation of the Scottish ITIs is aimed at increasing the effectiveness of Scottish businesses in the key global market sectors of Communications Technologies and Digital Media ('Techmedia'), Life Sciences and Energy, all targeted to address the particular (research) strengths and (company) weaknesses of the local economy. The ITIs will also interact with each other to identify potential overlap or "white space" market opportunities between Techmedia, Life Sciences and Energy. The creation and development of the Scottish ITIs is a long-term initiative, and will be supported for a significant period of time.

The ITIs are, in essence, a centre or "hub" for:

- identifying, commissioning and diffusing pre-competitive research that is driven by an analysis of emerging markets
- managing intellectual assets to maximise commercial and economic value.

An active membership is core to the proposed Institutes. The ITIs are open for membership to all companies and research institutions, and all members will be encouraged to actively participate in its activities. ITI strategy and operation will be actively guided and supported by its members. It is essential to attract members with a broad global perspective on markets and new technology directions, as well as a local focus, to ensure that propositions will be transferred effectively into the Scottish economy.

1.4 Definition of the Techmedia Sector

ITI Techmedia is centred on the development and creation of commercial opportunities encompassing the communications technologies and digital media sectors. The activities of the ITI will bring Scotland's economy to the cutting edge of emerging markets by allowing local companies to access and build upon pre-competitive technology platforms developed by the ITI.

The term 'Techmedia' arose out of the need to reflect the market evolution of communications technologies and digital media. The overall trend in the marketplace is one governed by a value chain ranging from content/application generation through delivery to consumption. Content is no longer considered in isolation from service provision, service provision in isolation from delivery channels, or delivery channels in isolation from enabling and managing technologies.

The following elements are examples of the areas which fall within the Techmedia remit. These elements are best viewed as illustrations and represent some of the over-arching philosophies. Nevertheless, these are global drivers which help to place the output of the ITI in context:

- broadcast content: ultimately the product for which the customer is paying, either directly or indirectly
- service provision: the mechanisms for providing customer-driven content and applications
- delivery: technologies and infrastructure required to transport the digital content service to the end-user, as well as providing the feedback channels for interactivity
- enabling software and systems integration: technologies and infrastructure required to condition, control and manage the delivery of content/service to the end-customer.

One globally accepted trend is the delivery of content and services over multiple channels e.g. the provision of same (or modified) content to be received over mobile devices, through TVs or via PCs. Content consumption is the key revenue generating stream in many of the markets, and is thus central to many of the drivers that affect future market evolution in the Techmedia sector.

The Techmedia sector is potentially very broad and hence a phased approach to market foresighting has been adopted. Previous foresighting concentrated upon six major market areas:

- Health
- Commerce and Finance
- Learning and Education
- Communication Services
- Entertainment and Leisure
- Digital Cinema

Based on member feedback on these topics, Nanotechnology was chosen as a desirable area for a more detailed analysis given the perceived importance of this area to future economic growth.

1.5 Next Steps

This report describes the results of the market analysis activities undertaken by ITI Techmedia in the Nanotechnology sector. As such, the report describes the future market opportunities, challenges, key drivers and functional needs in the Nanotechnology sector.

Using this acquired knowledge as its base input, the ITI will select those functional needs with the strongest potential market ‘fit’, and the greatest potential to be a success when utilised within the identified target markets. The selected functional needs will be used as input to define potential technology platforms, and these platforms will then be used as input to the ITI Techmedia programme selection process.

During this process, ITI Techmedia will continue to report to its Membership on results and progress. Members are encouraged to provide comment and input to this process, and to become actively involved in programmes.

ITI Techmedia intends to further develop its knowledge base in this sector. In order that the Membership gain visibility to ongoing developments identified by ITI Techmedia, this report will be subject to periodic review and re-issue.

2 MARKET OVERVIEW

The purpose of this section is to provide an overview of the Nanotechnology sector. To achieve this, the section has been divided as follows:

- Section 2.1 provides a definition for Nanotechnology, including a distinction of nanotechnology hype and reality
- Section 2.2 characterises the Nanotechnology opportunity within a number of distinct and diverse vertical markets
- Section 2.3 provides an overview of a number key technologies within the sector
- Section 2.4 summarises the structure of the Nanotechnology sector
- Section 2.5 summarises the major trends and drivers affecting the sector.

2.1 Definition

For the purposes of this report, Nanotechnology is defined as:

"The science of manipulating materials at the atomic and molecular level to develop new or enhanced materials and products"

Global interest in Nanotechnology is huge:

- in 2001, the National Science Foundation in the USA projected that 'USD1 trillion in products worldwide would be affected by Nanotechnology in 2015'. This forecast has recently been brought forward by five years to 2010
- investment in nanoscale research has grown from around EUR1 billion per annum in 2000 and is expected to reach some EUR10 billion per annum worldwide by 2006, according to the Institute of Nanotechnology
- according to Lux Research, corporations spent some USD4 billion globally on Nanotechnology R&D in 2004.

This interest is being sparked by a number of factors but is, in the main, a result of the promise of Nanotechnology to offer new methods of making things. Nanotechnology promises to deliver more for less – smaller, cheaper and faster materials with in-built 'intelligence' – by altering the basic nature of raw materials.

Despite the degree of interest and investment, the market for Nanotechnology products remains immature. The opportunity it creates has not yet been adopted across the various areas of the economy, and it is not yet clear precisely which of the possible uses that might fall under this definition will take off and become widely established.

2.1.1 Nanotechnology hype versus reality

Synthetic chemists and materials scientists have been working at the nanoscale for decades. For example, customising polymers to specific properties and computers also routinely use components which are of this scale. Computer hard drives contain giant magnetoresistance effect (GMR) heads, with nanoscale thin layers of magnetic materials that allow a significant increase in storage capacity.

However, advances in tools over the past 25 years allow us to observe, measure and manipulate the nanoscale. This new found knowledge of material properties has created new understandings and discoveries of how materials behave and perform on the atomic scale. Some of these discoveries have been theorised about in the past and can now be put into practice, while some are new and novel discoveries.

Nanotechnology is surrounded by hyperbole, and for good reason. It arguably shows as much promise in both science and business as any other major technology of the past century, including nuclear energy in the 1950s or genetics in the 1990s.

Many researchers involved in nanoscience are sceptical about the hype related to Nanotechnology and its implications. To a large degree, many researchers feel there is nothing new in Nanotechnology. There are notable scientists, such as Sir Harry Kroto, who insist Nanotechnology is nothing new, and is merely chemistry re-badged. However, other figures, such as Mark Welland, insist this is wrong. Although there has been a lot of hype regarding the medium- to long-term applications of Nanotechnology, it can be argued that there have been enough incremental improvements witnessed to date which, at least, partially justify these expectations.

Many areas of nanoscience research are, indeed, too early to accurately predict progress and benefits e.g. Quantum computing, molecular electronics and nanodevices for targeted drug delivery. Yet there are many areas where Nanotechnology is producing revenues today, or will do so in the short term, such as coatings for scratch resistant glasses, smart fabrics, advanced thin film photovoltaics on polymer substrates and low power, organic silicon displays. Investors who lack the knowledge, resources or time to differentiate the various areas or stages of Nanotechnology and separate the attractive from the unattractive investments, perpetrate this myth that Nanotechnology is more hype than reality.

However, even the most sceptical researcher/investor has expectations of nanoscience leading to a significant change in technology development and, for some, even expectations of significant industrial change. In other words, there is a widespread sense of novelty and expectation of new industrial opportunities springing from nanoscience. A number, however, express scepticism about the scope of industrial effects, and warn that the hype may lead to unreasonably high expectations for Nanotechnology and a backlash, especially in the short term.

2.2 Market Segmentation

Nanotechnology is not a market per se. Rather, it is an enabling technology for the development of both:

- new opportunities within existing markets
- entirely new markets.

In order to understand the potential of Nanotechnology, a number of distinct areas of the economy have been assessed for this report as follows:

- an overview of the economic area
- a description of some of the key factors driving the demand for Nanotechnology applications within that area of the economy
- examples of the type of Nanotechnology applications, and possible impact, within that economic area.

The application of Nanotechnology in a number of industry sectors has been assessed, and the industrial sectors examined are identified in Figure 1 below. The Nanotechnology applications in these sectors are described further in the following sections.

Advanced materials and chemicals	IT, telecoms and leisure
Aerospace and defence	Security
Environment and Water	Textiles
Mining	Transport and automotive
Food and household products	

Figure 1: Areas of the economy assessed [Source: ITI Techmedia]

It should be noted that, due to the sheer scale of opportunity, a specific consideration of application of Nanotechnology within the health and life sciences field is outside the scope of this report.

2.2.1 Advanced materials and chemicals

Advanced materials and chemicals are building blocks of and components in, a huge array of products. To provide some indication of the breadth of market addressed by these industries, the chemicals market alone comprises a number of distinct segments including:

- basic chemicals (e.g. petrochemicals, plastics, gases)
- pharmaceuticals
- consumer chemicals (e.g. cosmetics, detergents)
- speciality and fine chemicals (e.g. paints, inks).

The scale of the chemicals market is immense. According to Frost & Sullivan, the chemicals market in the European Union alone was worth over EUR490 billion in 2004.

Industry giants such as DuPont, Degussa, Bayer, Dow Chemical and Eastman Chemical are turning to innovation to meet rising expectations of revenue growth from products introduced in the last five years. Nanotechnology is seen by such companies as the future source of novel material properties which will be applicable to a multitude of end-user applications.

Such applications are identified in Figure 2 below, and the Advanced Materials and Chemicals market opportunities are discussed further in the sections which follow.

Areas of use	*Application*
Catalytic converter	Novel membranes to improve environmental performance
Material durability and weight	Novel materials to increase barrier resistance, weight and thickness
Paints	Improve reflecting properties of materials and introduce ability to self-heal
Coatings	Improve properties of coatings in a variety of areas including flame retardence, oxygen and light resistance, scratch resistance

Figure 2: Potential areas of application of Nanotechnology in the Advanced Materials and Chemicals sector [Source: ITI Techmedia]

Advanced Materials

A key driver for the adoption of Nanotechnology in the Advanced Materials sector is performance improvement, allowing suppliers to improve the benefit of their products and thereby sustaining, or possibly increasing, operating margins.

Nanotechnology has the potential to fundamentally change or exploit certain features of materials at the nanoscale to provide improved product performance. The ability to synthesise nanoscale building blocks with precisely controlled size and composition, and then to assemble them into larger structures with unique properties and functions, could revolutionise segments of the materials manufacturing industry. For example, the use of nanostructures is expected to yield materials with new and improved properties for use in such diverse applications as:

- organic solar cells
- anti-corrosion coatings
- cutting tools
- photocatalytic air purifiers
- medical implants

The key enabling factor for industrial exploitation of these materials is the development of cost-effective (not necessarily lower cost), large-scale manufacturing processes. There is no single large hurdle which needs to be overcome; rather, there are many hurdles in each individual development effort, since each material has its own chemistry and its own set of problems to be solved.

Such hurdles include:

- broadening the range of available materials
- driving down the costs of material development and production
- improving quality and purity of materials

Chemicals

The chemical industry is closely linked to the development of Nanotechnology, as it:

- supplies crucial base materials
- is expected to use Nanotechnology-based innovations in process technology

Many chemical industry products classified today as Nanotechnology have been around for decades. Despite this, Nanotechnology could enable the chemical industry to generate a new wave of innovation, and there are signs of new products emerging, which have strong commercial potential due to the sheer size of the chemicals market. The main areas of application of Nanotechnology in the chemical industry are expected to include:

- catalysis
- pigments
- coatings
- lubricants
- micro/nanoreaction technology
- membranes and filters
- pharmaceuticals
- cosmetics.

2.2.2 Aerospace and defence

The aerospace and defence industry is large and diverse, and encompasses a wide variety of activities including:

- aircraft
- aircraft engines and parts
- guided missiles and space vehicles
- propulsion units
- search, detection, navigation and guidance systems
- command and control systems

Frost & Sullivan estimate that, in 2003, the United States aerospace and defence industry alone generated some USD150 billion in sales. In 2003, the United States Department of Defence budget was increased to USD45 billion.

It is no surprise that, in such a varied and technologically advanced market, the Nanotechnology opportunity is wide and diverse. Drivers and opportunities in the aerospace and defence markets are separately considered in the following sections.

Defence

The defence sector is a prime developer and market for Nanotechnology. The use of Nanotechnology in defence opens up opportunities for improved weapons, innovative materials and new application areas.

Key drivers for the exploitation of Nanotechnology for defence purposes include:

- biological and chemical threat detection
- high performance information technology/remote control
- military uniforms with enhanced features including protection and self-healing
- new vaccines and medical treatments
- minimising civilian casualties through the use of smart munitions

The United States, even more so since September 11, is the dominant global powerhouse of world defence and aerospace. The United States regards technological advancement as critical to maintaining its edge in national defence, especially with regard to aerospace capabilities. For example, at MIT, the US Department of Defence funds the Institute of Soldier Nanotechnologies, whose major research areas include:

- energy absorbing materials
- mechanically active materials and devices
- sensing and counteraction
- biomaterials and nanodevices for soldier medical technology
- processing and characterisation
- modelling and simulation of materials and processes
- systems design, hardening and integration

In land and air vehicles, conventional structural materials could be replaced by more rigid and lighter materials. Improvements could also be achieved in direct (armour) and indirect protection for military vehicles (camouflage and mislead, e.g. through colour changes with "intelligent" surface coatings). Important impacts of Nanotechnology on the operation of military platforms can also be expected in the conversion and storage of energy (e.g. more efficient solar cells, suitable membranes and catalysts for operating fuel cells, and enhanced performance batteries).

Nanoscale electronic, sensor and electromechanical components could make control and steering of vehicles more effective and robust. The current trend towards unmanned and autonomous systems in air, sea and space could be further reinforced by this.

Nanotechnological developments will also have significant impacts for military personnel, including at the level of personal equipment. The focus is on the effort to equip soldiers with additional functionalities, without significantly increasing the weight of their equipment. Typical areas of application are listed in Figure 3 below.

Areas of use	*Applications*
Smart planes	Minimising the weight and maximising strength of the planes; changing wing shape
Threat detection	Synthetic and analytical chemical devices
High strength, multifunctional materials	Self-repairing structures
Soldier protection	Sensors for wound detection and treatment systems within uniforms.

Figure 3: Potential areas of application of Nanotechnology in the Defence sector [Source: ITI Techmedia]

Aerospace

There are extensive possibilities for applications of Nanotechnology in the aerospace industry. The aerospace industry in general is characterised by very high investments in R&D. For example, the German aerospace industry invested about 17% of its revenues in R&D in 2003[1].

Important drivers for the future use of Nanotechnology, especially in space applications, are:

- cost reduction
- improved capabilities
- lowering of mission risks
- higher mission flexibility
- new system concepts

Advanced technologies are evaluated constantly and Nanotechnology is an area of great interest in this sector. These are particularly numerous and varied in the space industry, where demands on the technological capability of components are often extremely high. Potential areas for the application of Nanotechnology within the aerospace sector are listed in Figure 4 below.

[1] Source: European Commission

Areas of use	*Applications*
Structural materials	Saving weight and energy by using light-weight, ultra-rigid materials based on Nanotechnology
Information and Communications	More efficient design of data transfer between space vehicles and terrestrial information networks using electronic and optoelectronic Nanotechnology components
Sensors	Improving medical monitoring of aircrew with sensors based on nanostructured materials
Thermal protection and control	Improving thermal control systems through nanostructured diamond-like carbon coatings

Figure 4: Potential areas of application of Nanotechnology in the Aerospace sector [Source: ITI Techmedia]

2.2.3 Environment and Water

The environment and water sector encompasses a very broad range of activities, including:

- waste and water treatment
- hazardous materials treatment and disposal
- air pollution management
- in-building environment management
- remediation of polluted areas

As a revolutionary science and engineering approach which affects the existing infrastructure of consumer goods, manufacturing methods and materials usage, Nanotechnology has the potential to have major consequences - positive and negative - on the environment.

A number of drivers will affect the take-up of Nanotechnology within this sector, including:

- reduced harmful emissions into the environment
- improved detection and monitoring
- increased energy efficiency
- improved filtration
- access to clean, affordable, water

Nanotechnology has the potential to substantially benefit environmental quality and sustainability, through pollution prevention, treatment and remediation. Such benefits include improved detection and sensing, removal of the finest contaminants from air, water and soil, and the creation of new industrial processes which reduce waste products and are themselves "green". Nanotechnology can be of benefit to environmental protection in applications such as reducing use of raw and manufactured materials (dematerialisation), minimising or eliminating the generation of wastes and effluents and reducing toxics. The environment is also protected in applications which treat waste streams more effectively and remediate existing polluted sites.

Possible applications in the Environment and Water sector are listed in Figure 5.

Areas of use	*Applications*
Remediation	Nanoscale bimetallic particles for In Situ Remediation
End of pipe treatments	Nanoporous membranes for filtration
Water treatment	Nanoparticles for photocatalytic water purification
Biosensing	Nanosensors capable of detecting minute traces of chemicals or organic compounds
Environmental absorbents	Nanoparticulate soils for to absorb material such as chloride, sulphate and phosphate,
Biodegradable plastics	Environmentally-friendly, cornstarch-based nano-polymer

Figure 5: Potential areas of application of Nanotechnology in the Environment and Water sector [Source: ITI Techmedia]

Nanotechnology could also lead, possibly, to environmental problems. It is largely unknown how nanostructured materials, nanoparticles and other related nanotechnologies will interact in the environment. Such interactions may be a function of the nature of nanoparticles themselves, the characteristics of the products made from them, or aspects of the manufacturing process involved.

As the use of Nanotechnology is scaled up, emissions to the environment may also increase, and perhaps a whole new class of toxins or other environmental problems may be created. In consequence, the potentially harmful effects of Nanotechnology applications need to be anticipated and prevented, or minimised, in order to increase the attractiveness of the technology.

2.2.4 Mining

Mining industries relate to the extraction of resources stored within the earth. As such, they comprise a variety of applications, including:

- hydrocarbons
- metals
- minerals

The extractive industry has adopted a watch-and-wait policy with Nanotechnology, continuing to view nanomaterials as something for the future. While nanomaterials are associated frequently with alternative energy sources, such as solar, fuel cells and the hydrogen economy, their application in extraction industries is less frequently discussed.

Considering the hydrocarbon extraction sector, over the next five years it is expected that some 15,000 offshore wells will be drilled worldwide[2], at a total cost of some USD189 billion. Of these wells, around 4,500 will be exploratory (costing USD75 billion) and around 10,500 will be development wells (costing USD114 billion). The proportion of wells drilled in deepwater is expected to increase to around 17% of all wells drilled by 2008, with USD56 billion (30%) of the total forecast expenditure on drilling and completion being directed toward deepwater wells.

In meeting these forecasts, the oil and gas sector faces a range of materials-related challenges, which lead to increased costs and limit the operating envelope of drilling and production technologies. The material properties necessary to deliver the required drilling, well-bore and production capabilities in increasingly difficult environments include:

- abrasion and corrosion resistance
- high strength-to-weight ratio
- increased thermal conductivity
- thermal and chemical stability

Since these properties are familiar in the Nanotechnology context, Nanotechnology is an area of great interest to the oil and gas sector. However, barriers to entry and adoption are high, and collaboration between the oil industry and nanomaterial developers has been limited to date.

As a result, very few nanomaterial-based products have yet to appear in this sector. This can be attributed to a number of factors:

- lack of innovation in the oil and gas sector
- perceived cost and risk
- lack of awareness of oil and gas challenges within the Nanotechnology sector

[2] Source: Shell

This risk-averse attitude within the oil and gas sector results, in large part, from the considerable cost of failure. With a cost to drill a well ranging anywhere from USD0.5 million to USD100 million, and fully loaded rig costs running up to USD500 000 per day, any delay or upset requiring remedial action can lead rapidly to considerable cost overrun.

In spite of a risk-averse view towards the adoption of new technologies, the extractive industries remain interested in innovations which will save considerable time and money on processes and materials. Nanotechnology has appeared on the radar of companies such as Shell and BP and continues to be monitored, including the opportunities it affords for alternative energy sources. Possible applications of Nanotechnology in the extractive industries sector are identified in Figure 6.

Areas of use	*Applications*
Heat transfer	Nanofluids with enhanced heat-transfer characteristics
Emission controls	Selective gas adsorption/conversion/separation nanoparticle technology, with the resultant increase in active surface area
Coatings to prevent fouling and corrosion	Self-cleaning/healing, scratch resistant, anti corrosive nanocoatings

Figure 6: Potential areas of application of Nanotechnology in the Mining sector [Source: ITI Techmedia]

2.2.5 Food and Household Products

This section considers two major areas of end-consumer consumption – food and household products. These goods account for a very significant proportion of average household expenditure. For example, in the United Kingdom, such goods accounted for some 21% of total household expenditure in 2004-05[3].

[3] Source: United Kingdom Office for National statistics

Food production and supply

Across the agri-food chain, from farm to fork, there is a major potential market for future applications and developments in nanomaterials. Research in agriculture has always dealt with improving the efficiency of crop production, food processing, food safety and environmental consequences of food production, storage and distribution. Nanotechnology provides a new tool to pursue these goals.

The application of Nanotechnology in food and agriculture is in its nascent stage. However, over the next decade, the use of Nanotechnology may increase to encompass such applications as the detection of carcinogenic pathogens and biosensors to enable contamination-free food and agricultural products. Some potential applications in the food production and supply sector are identified in Figure 7 below.

Areas of use	*Applications*
Production, processing and shipment of food products	Nanosensors for pathogen and contaminant detection
Increase efficiency and security	Integration of “Smart Systems” into sensing, localisation, reporting and remote control
Bioprocessing	The use of molecular probes or the development of devices that allow rapid identification of microbes present in feedstock are examples of research at the nanoscale that can increase the efficiency of bioprocessing
Bioanalytical Nanosensors	Detection of very small amounts of a chemical contaminant, virus or bacteria in agricultural and food systems is envisioned from the integration of chemical, physical and biological devices, working together as an integrated sensor at the nanoscale. The bioanalytical nanosensors either use biology as a part of the sensor, or are used for biological samples

Figure 7: Potential areas of application of Nanotechnology in the Agriculture sector [Source: ITI Techmedia]

Household Products

Nanotechnology is viewed as a potentially discontinuous technology in the area of household products. For example, the CEO of one household product multinational indicated that self-cleaning coatings were potentially the greatest technological threat to its existing market position. As such, Nanotechnology promises to represent both a commercial opportunity and a threat.

The household products sector is large, and exhibits an ongoing battle for market share between the major players. The potential impact of Nanotechnology is being carefully considered by market players as a tool for creating differentiated products, and companies such as Unilever, Henkel and Procter and Gamble are already active in this area.

Examples of areas in which Nanotechnology may play a role in the household products sector are identified in Figure 8 below.

Areas of use	*Application*
Personal health care	Antiseptic ointments, mouthwash against paradentosis (extremely efficient!), deodorant sprays, antifungi sprays and ointments; nano-silver based antimicrobial wound dressings; silver-based toothpaste, hydrogel for acne treatment, mask pad for acne treatment, hydrogel for athletic foot treatment
Beauty care	Ointments containing nanosilver and nanogold, and/or their alloys; nanocapsules for delivery of vitamins to the skin
Baby care	Antiseptic cotton products
Household care	Antiseptic and antifungal paints, washing powders, floor cleaning/wash products, drinking water cleaning with nanosilver (desperately needed in poor countries), incorporation of controlled release technology and antimicrobial mechanisms.
Consumer products	Stable nanocolloids of noble metals and their alloys, in the concentration of 50 parts per million in ultra-pure water. Such materials can be used in the production of antimicrobial plastics, cups, containers, packaging materials for foodstuffs and wrap-up foils. Platinum group metals as nanocolloids can be used in the range of catalytic processes.
Feminine care product	Medical devices consisting of nanosilver contained pill/hydrogel and adaptor for vaginitis/cervitis treatment. Silver-based products for wet tissue paper, douche and spray for female use.
Packaging	Responsive packaging based on flexible displays; oxygen resistant coatings and films

Figure 8: Potential areas of application of Nanotechnology in the Household Products and Packaging sector [Source: ITI Techmedia]

2.2.6 IT and Telecoms

Information and communication technology (ICT) is a very significant industrial sector with a high rate of innovation, and the next stage is likely to see the transition from micro- to nano-electronics. The impact of the sector on the global economy is very significant[4]:

- in 2005, the European ICT market revenues represented 6.5% of GDP and 34% of the worldwide ICT market
- in the past 10 years, the ICT sector has contributed more than one quarter of labour productivity growth in the EU
- the sector is responsible for 25% of commercial research and development

A key aspect which has served to underpin the information technology revolution has been increasing computer power in a smaller space at a lower cost. Historically, the industry has been able to deliver improved year-on-year computing performance and greater storage capability whilst driving down costs to the consumer.

However, the industry is now approaching the limits of what is possible using existing materials and processes and it will need to develop new technology approaches if ongoing performance improvements are to be attained. Microelectronics companies have been working on bringing their technology down to the nanoscale for many years. In the next 10 to 15 years, silicon technology will enter a near-molecular regime as feature sizes approach 25 nano-metres.

The leading companies in information technology are heavily involved in the exploration of Nanotechnology applications, and include Hewlett Packard, IBM, Infineon, ST Microelectronics, Nokia and Philips. Some potential applications of Nanotechnology are identified in Figure 9 below.

Areas of use	*Application*
Data Storage	Extended RAM via magnetic nanoparticles
Advanced Display Technologies	Ultra-thin, light weight flexible displays with low power consumption and operating voltage
Quantum Computing	Components functioning through quantum effects, rather than in despite of them
Heat Management	Nanocomposites for heat management in computer and advanced electronic systems

Figure 9: Potential areas of application of Nanotechnology in the ICT sector [Source: ITI Techmedia]

[4] Source: European Commission

2.2.7 Security

The counterfeiting of branded products is estimated to be worth some USD600 billion worldwide[5], and affects a whole plethora of industries:

- the World Health Organisation estimates that 7% (USD30 billion) of the world's pharmaceuticals are counterfeits, raising significant health and safety implications
- according to the Automobile Manufacturers' Association, counterfeit auto parts, and even whole vehicles, amount to a $12bn global problem
- in 1989, a Norwegian charter airline crashed when its tail assembly fell off because of substandard counterfeit bolts, resulting in 55 deaths
- unapproved or counterfeit parts have also been reported on Air Force One and the Space Shuttle.

The latest developments in brand security and packaging are designed to provide what is referred to as "smart protection", by which new applications for in-print or coating taggants (covert chemical markers) provide not only yes/no authentication of valid products, but also tools to assist companies and organisations in effectively managing product or item integrity in a complex environment.

Nanoscale taggants containing unique magnetic "fingerprints" can be used in a wide range of articles, including pharmaceutical packaging, luxury goods (such as watches and handbags), and automotive and aviation spare parts. It is hoped that such "fingerprints" will stem the tide of counterfeit goods by enabling genuine merchandise to be individually identified.

Multinationals such as Procter and Gamble are active in this area, but mainly use tools and instrumentation to differentiate their products from high level counterfeits. Companies introducing innovative products in this area include Evident Technologies, Nanoinventions and Ingenia Technologies. Possible areas of application of Nanotechnology within this sector are identified in Figure 10 below.

[5] CSIRO

Areas of use	*Application*
Brand security	Covert nanoparticulate chemical markers; Optical Lock and Key Techniques
Product Security	Colour changing inks when packaging breached; oxygen sensors
Anti-Counterfeiting	Magnetic nanoparticle bar coding and tagging
Supply Chain Tracking	Nanoparticles which are encodeable, machine-readable, durable, sub-micron sized taggants; molecules with unique, spectrally distinct signature, allowing for a large number of codes

Figure 10: Potential areas of application of Nanotechnology in the Security sector [Source: ITI Techmedia]

2.2.8 Textiles

The textiles market is very significant. The European Commission estimated that the market for textiles was worth some EUR395 billion in 2003, and the EU was:

- the world's largest exporter of textile products, accounting for some 15% share of the world market
- the world's second largest importer of textiles, accounting for some 20% of the world market

Nanotechnology is already having an impact the textile sector, due to the added functionality it enables: crease resistance, improved breathing properties, wear resistance, spot and water repellence, anti-static properties, active ingredient storage or fire protection. Nanotechnology offers solutions for keeping the textile industry in competition with the rest of the world by:

- lowering costs
- improving margins
- creating access to new markets

Possible areas for the application of Nanotechnology in the textiles sector are listed in Figure 11 below.

Areas of use	*Application*
Anti-bacterial clothing	Nanosilver coated fibres
Wearable electronics	Conductive polymer nanocoating on textile materials
Protective monitoring(military)	Smart clothing; self-healing materials; bio-responsiveness
Functional fabrics	Smart clothes; photocatalytically active coatings; self-cleaning
Healing textiles	Nanosilver wound dressings; antibacterial socks

Figure 11: Potential areas of application of Nanotechnology in the Textiles sector [Source: ITI Techmedia]

Future developments of Nanotechnology in textiles will have a twofold focus:

- upgrading the existing functions and performances of textile materials
- developing smart and intelligent textiles with unprecedented functions

The latter development is more urgent from the standpoint of homeland security and advancement of technology. The new functionality which can be expected to be developed includes:

- wearable solar cell and energy storage
- sensors and information acquisition and transfer
- multiple and sophisticated protection and detection
- healthcare and wound healing functions
- self-cleaning and repairing functions

Combining textiles with electronics is promising to be a significant commercial area and has led to many different new terms, such as 'wearable computers', 'smart garments', 'textile circuits' and 'intelligent garments'.

2.2.9 Transport and Automotive

In 2001, the EU indicated that the European automotive industry, including vehicles and components, achieved a total turnover in excess of EUR450 billion, providing direct employment to some 1.1 million people.

The automotive industry is torn between trying to reduce costs on the one hand, and, on the other, dealing with the high price of performance-enhancing technology and environmental compliance. Key drivers in the automotive industry are:

- reduced air pollution
- reduction of weight
- recyclability
- safety
- better performance and engine efficiency (fuel saving)
- aesthetics
- longer service life

Automotive manufacturers are hungry users of technologies which offer cost-effective improvements in vehicle performance, convenience and safety. Better performance is related to improved engine efficiency and the use of lightweight, high strength materials, all of which will be affected by Nanotechnology. This, coupled with stricter legislation regarding emissions and safety, has underlined the importance of Nanotechnology in the global automotive sector.

The transport and automotive industry can benefit from nanomaterials in several domains:

- frames and body parts
- engines and powertrain
- paints and coatings
- suspension and breaking systems
- lubrication
- tyres
- exhaust systems and catalytic converters
- electric and electronic equipment

Areas where Nanotechnology currently has an impact within the sector include:

- avoidance of lubricants by using thin layers on bearings and gliding elements
- electrostatic filters
- high power switches in ignition devices via field emission principles at sharp tips
- new catalysts using highly porous and chemically-selective surfaces

Nissan have incorporated carbon nanotubes as a filler material in the bumper for the X-TRAIL SUV. General Motors and Montell have successfully produced thermoplastic olefin (TPO) nanocomposites which promise a number of benefits for interior and exterior automotive applications, including reduced weight, improved dimensional stability, high stiffness and good low temperature impact performance.

Nanoparticles are being used in paint additives to produce new colour effects, better hardness and durability. One such area under development is the use of electrically-conductive, vapour-grown, graphitic carbon nanotubes in paints for the creation of conductive paints. Such paints are used by the automotive industry to make parts that are coated with electrically-charged droplets of paint.

In addition, modification of paints by nanostructural inclusions will improve the physical and chemical properties of paints, increasing corrosion resistance properties and scratch and impact resistance. Mercedes-Benz utilises nanoscale ceramic particles in scratch-resistant coatings for their E, S, CL, SL and SLK-Class model series.

Another interesting area is that of the exploitation of Nanotechnology for car interiors, with self-cleaning surfaces under investigation, as are other applications developed in the textiles industry. Much effort is also being put into reducing the number of different plastic species employed by the car industry: polypropylene and polypropylene fibres are more and more used in car interiors, as well as in the car structure. Nanotechnologies in many cases can help in having different grades of functionalised polymers, adding just a small amount of nanoparticles without sacrificing the material recyclability that represents an important goal for a large-scale application of these new materials in the automotive industry.

Potential future applications in the automotive industry could include: motor parts made from new ceramics (particular interest will be the replacement of many metal components that are subjected to high temperatures and stresses); plastics with a higher strength; and better vibration dampers based on magnetic nanofluids.

Some example areas of application are identified in Figure 12 below.

Areas of use	*Applications*
Coatings	Scratch resistant, self healing coatings
Car body	Nanocomposites for high strength, light weight materials
Windscreens	Anti-glare, anti-fogging nano coatings
Engine	Thermal barrier materials for high temperature engines; nanoparticles as diesel additives for greater fuel efficiency

Figure 12: Potential areas of application of Transport and Automotive sectors [Source: ITI Techmedia]

2.3 Overview of Key Nanotechnologies

Nanomaterials, and their associated manufacturing and processing technologies, are the key enablers of the Nanotechnology industry and encompass a wide range of materials. The common link across these materials is that they all exhibit features only present at the nanoscale that potentially offer performance enhancements over existing materials. Nanomaterials typically measure in the range of 1 to 100 nanometres (nm).

Nanoparticles serve as the "building blocks" for nanomaterials and devices. They include nanocrystalline materials such as ceramic, metal and metal oxide nanoparticles; fullerenes, nanotubes and related structures. By virtue of their structure, nanomaterials exhibit different physical, chemical, electrical and magnetic properties from conventional materials, which can be exploited for a variety of structural and non-structural applications.

In the following sections, a brief overview of the following core nanotechnologies is provided:

- nanoparticles
- nanoparticulate coatings, thin films and surface layers
- nanocomposites
- carbon nanotubes
- nanoporous materials
- quantum dots
- nanofibres
- fullerenes
- nanowires
- nanocapsules.

For each technology area, a brief overview of the technology is provided, together with some examples of possible uses for the technology and an indication of the industrial sectors within which the application may be applicable. A more exhaustive list of possible applications by technology is identified in Appendix 3.

2.3.1 Nanoparticles

Nanoparticles can be defined as particles of less than 100nm in diameter which exhibit new or enhanced size-dependent properties (such as chemical reactivity and optical behaviour) compared with larger particles of the same material. For example, titanium dioxide and zinc oxide become transparent at the nanoscale, are able to absorb and reflect UV light, and have found application in sunscreens. Nanoparticles can also be arranged into layers on surfaces, providing a large surface area and, hence, enhanced activity, relevant to a range of potential applications including catalysts.

Nanoparticles have large surface areas and high surface reactivity and provide enormous flexibility for *in situ* applications. Nanoparticles can be made of a wide range of materials, the most common being ceramics, which are split into metal oxide ceramics (titanium, zinc, aluminium and iron oxides) and silicate nanoparticles (generally in the form of nanoclays). They are generally designed and manufactured with physical properties tailored to meet the needs of the specific target application.

Nanocrystalline materials, made up of nanometre-sized grains, also fall into the nanoparticles category and can be engineered by increasing the defect density in a material, to a point where the grain size approaches the nanoscale. The increased density of grain boundaries impedes the migration of defects within a crystal and, ultimately, makes the material harder. Similarly, other physical, chemical, electrical and magnetic properties are affected by the small grain size and by the nature of the grain boundaries.

Examples of nanoparticle-based applications are illustrated in Figure 13 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Gold nanoparticles with high performance for low-temperature combustions as catalysts	✓	✓	✓			✓			
Stain-resistant fabrics		✓					✓	✓	
Nanoparticulate drug delivery		✓						✓	
Nanosilver dressings							✓	✓	
Display technologies including field-emission devices (e.g. using conducting nanoscale oxides)	✓	✓		✓					✓

Figure 13: Applications vs. Industrial Sectors : Nanoparticles [Source : ITI Techmedia]

2.3.2 Nanoparticulate surface coatings, thin films and layers

Nanotechnology in the field of surface functionalization and refinement is already in a relatively advanced stage. Nano-multilayers and nano-composite-layers with improved mechanical and lubrication properties are already in industrial use.

Other examples are quasi "self-cleaning" surfaces and optical-functional surfaces for façades, vehicles, solar cells etc. (e.g. for antireflective surfaces, sunshade glazing, antireflective coating for instrument panels).

Highly sophisticated surface-related properties, such as optical, magnetic, electronic, and catalytic can be obtained by advanced nanostructured coatings. This makes such coatings attractive for industrial applications in high-speed machining, tooling, biomedical, automotive, optical applications and magnetic storage devices.

The addition of nanoparticles to conventional coatings yields new and improved nano-based colour effects. Black pigments consisting of agglomerated nanoparticles are already in use in high-quality black coatings. Coatings which can be switched, e.g. can change their colour or are self-healing are under development.

Nanomaterials such as thin films and engineered surfaces have been developed and applied across a wide range of industries (electronics, chemical and engineering to name three) for decades. For example in the silicon integrated-circuit industry many devices rely on thin films for their operation, and control of film thicknesses approaching the atomic level is routine. Thin-film coatings engineered at the nanoscale not only have advanced hardness and toughness characteristics, but they can also take advantage of some of the properties of quantum physics. Effects include UV blocking, anti-static and conductive capabilities. Paints and coatings industries were among the first to take advantage of these capabilities. Companies also found that with the incorporation of nanoparticles, both in and on the film, thin film coatings have stronger bonds and better flexibility, with little cost difference. These coatings are smoother, stronger and more durable.

Examples of coating and film-based applications are illustrated in Figure 14 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Scratch-resistant coatings					✓				
Self-healing coatings	✓	✓				✓			✓
Photocatalytically active surfaces for self-cleaning and disinfection	✓	✓	✓				✓	✓	
Hard coatings for wear reduction and for corrosion protection	✓		✓		✓	✓			
Self-cleaning surfaces (e.g. using TiO2 based nanostructured coatings) and sprays	✓		✓			✓	✓	✓	

Figure 14: Applications vs. Industrial Sectors: Surface coatings and thin films [Source: ITI Techmedia]

2.3.3 Nanocomposites

Nanocomposites have the ability to alter the properties of two or more materials to create a material designed for a specific purpose, and to exhibit overall the best properties of each component. They are an important use of nanoparticles and nanotubes, and their multi-functionality applies not only to mechanical properties as they also offer optimized mechanical, friction, optical and thermal capabilities.

A particular type of nanocomposite is where nanoparticles act as fillers in a matrix e.g. carbon black used as a filler to reinforce car tyres. New composites can be designed to exhibit the overriding strength, dimensional, and thermal stability of ceramics with the fracture properties, processability, and dielectric properties of polymers.

Nanoparticulate polymer composites are one of the key materials in the future application of polymers in general. Various properties of polymers like stiffness, hardness, UV-stability, bio stability and conductivity can be modified or enhanced by using nanoparticles.

One key challenge is to disperse and stabilize nanoparticles so that they can be incorporated into different polymeric media like paints, coatings or plastics. Using a novel combination of nanoparticles made using gas phase synthesis at commercial quantities, together with surface-active ingredients, allows the formation of nanoparticle master batches that can be easily applied to various types of polymers. A small amount (typically less than 5% filler) of nanoparticles can enhance significantly the scratch resistance of polymeric coatings without any influence on other important properties such flexibility, transparency or gloss.

Examples of nanocomposite-based applications are illustrated in Figure 15 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Magnetic nanocomposite materials for high temperature applications e.g. transformers, DC-DC power converters	✓	✓							
Polymer nanocomposites with increased tensile strength, clarity and barrier improvement	✓	✓			✓	✓			
Flame retardant plastics	✓	✓							
Shape memory polymer nanocomposites	✓	✓			✓				
Polymer-clay nanocomposites to substitute glass materials e.g. smash-resistant organic glass or new shock absorber materials	✓	✓			✓		✓		

Figure 15: Applications vs. Industrial Sectors: Nanocomposites [Source: ITI Techmedia]

2.3.4 Carbon Nanotubes

Carbon Nanotubes (CNTs) are an important nanomaterial due to their novel chemical and physical properties. They are mechanically very strong (as stiff as diamond), flexible (about their axis) and conduct electricity extremely well. Carbon nanotubes (CNTs) are hollow cylinders of carbon atoms. Their appearance is that of rolled tubes of graphite, such that their walls are hexagonal carbon rings, and are often formed in large bundles.

They are not unlike other carbon materials, such as diamond or the carbon black that can be found in pencils or car tyres. They have a completely different structure, however, which gives them interesting and very promising properties. Normal graphite is built of sheets with a honeycomb structure of carbon atoms. These sheets are very strong, stable and flexible, but adjoining sheets lack a strong cohesion. In nanotubes, however, these sheets are larger and are “rolled-up” to form long, thin spiral patterns.

Their remarkable properties give CNTs a range of potential applications: for example, in reinforced composites, sensors, nanoelectronics and display devices, field emission-based flat panel displays, novel semiconducting devices, chemical sensors,and ultra-sensitive electromechanical sensors.

Examples of carbon nanotube-based applications are illustrated in Figure 16 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Advanced high strength polymers	✓	✓			✓	✓			
Hydrogen storage for fuel cells	✓		✓			✓			
Field emitters in high resolution flat panel displays		✓		✓					
Ultra-sensitive electromechanical sensors	✓	✓							
Hybrid Semiconductors				✓					

Figure 16: Applications vs. Industrial Sectors: Carbon nanotubes [Source: ITI Techmedia]

2.3.5 Nanoporous Materials

As a general characteristic, nanoporous materials contain holes less than 100 nm in diameter and may be bulk materials or membranes. Nanoporous materials could have open (interconnected) pores or closed pores and could have amorphous, semi-crystalline or crystalline (e.g. lamellar, cubic, hexagonal) frameworks. These two characteristics very much influence the applications a specific nanoporous material is suitable for.

Nanoporous materials can be natural or synthetic, organic or inorganic. Examples of materials considered for bulk materials and membranes are, amongst others, carbon, silicon, silicates, polymers, metal oxides, organic/metals and organic/silicon.

Nanoporous materials combine the advantages of porous materials with the biological functionality of the material itself. The materials' properties are enhanced or inhibited by the nanometer-sized porous structure, but still depend on the material chemical composition. Above all others, the most remarkable properties exhibited by nanoporous materials include: high specific surface area, control over pore size, morphology and distribution.

Examples of nanoporous-based applications are illustrated in Figure 17 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Controlled release through nanoporous membranes									
Nanoporous silica thermal insulation			✓						
Nanoporous electrodes for fuel cells	✓		✓						
Nanoporous plasma coatings for textile finishing	✓	✓						✓	
Protective clothing for uniforms		✓						✓	

Figure 17: Applications vs. Industrial Sectors: Nanoporous materials [Source: ITI Techmedia]

2.3.6 Quantum Dots

Nanoparticles of semiconductors (quantum dots) were theorised in the 1970s and initially created in the early 1980s. If semiconductor particles are made small enough, quantum effects come into play, which limit the energies at which electrons and holes (the absence of an electron) can exist in the particles.

Changing the size, the composition, or even the geometry, of a quantum dot will change its properties. A key property is a tunable band gap that allows for tuned electromagnetic wavelength. This has a large impact on the absorptive and emissive behaviour of the material, as their energy states and, therefore, the optical and electronic properties of the material, can be controlled.

Recently, quantum dots have found applications in composites, solar cells and fluorescent biological labels (for example, to trace a biological molecule), using both the small particle size and tunable energy levels.

Examples of quantum dot-based applications are illustrated in Figure 18 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Anti-counterfeiting, security tagging									✓
Semiconductor lasers based on photons emitted by quantum wells, wires				✓					
Single-electron transistors with quantum dots				✓					
Quantum computing				✓					
Recording/memory: metal quantum dots				✓					

Figure 18: Applications vs. Industrial Sectors :: Quantum dots [Source: ITI Techmedia]

2.3.7 Nanofibres

Nanofibrous materials have an easily accessible, large surface area, which makes them very bioactive. When fitted with a chemically active surface, this property can be used, for example, in manufacturing adsorbents that demonstrate rapid removal of toxic substances from biological media. The same surface area also allows for relatively good bonding between a nanofibre yarn and a matrix material, in which the yarn is embedded, for example, in a nanofibre-reinforced polymer. Porous nanofibres can be used in drug delivery systems, and it has been shown[6] that fibrous activated carbon bandages achieve faster rate of wound healing if loaded with certain enzymes and metal ions.

[6] *Use of High Surface Nanofibrous Materials in Medicine*, Sergey Mikhalovsky, Lyuba Mikhalovska, Vladimir Nikolaev

A number or companies and research centres are developing carbon nanofibres for conductive and reinforcement applications in composites (e.g. Pyrograf-III® from Applied Sciences Inc.), and processing nanotubes to functionalise and disperse into plastics and coatings.

Examples of nanofibre-based applications are illustrated in Figure 19 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Adsorbents that demonstrate extremely fast kinetics of removing toxic substances from biological media		✓			✓	✓	✓		✓
Nanofibre-reinforced polymer	✓	✓			✓			✓	
Air and water filtration			✓		✓	✓	✓		
Protective clothing and breathing masks		✓				✓		✓	✓
Nanofibre catalyst systems for use in the production of fuel cell electrodes	✓	✓							

Figure 19: Applications vs. Industrial Sectors: Nanofibres [Source: ITI Techmedia]

2.3.8 Fullerenes (Carbon C60)

Fullerenes, discovered in 1985, are spherical molecules about 1nm in diameter, comprising 60 carbon atoms arranged as 20 hexagons and 12 pentagons. They are also known as “Buckyballs” and the term fullerenes is given to any closed carbon cage.

Fullerenes present opportunities for robust engineering, via optimising surfaces for improving friction and reducing wear. The target for fullerene R&D is to achieve both effects simultaneously, forming spheres of a few nanometres in diameter and forming layers like onion skins, which act as “nano ball bearings” between the surfaces in contact.

Applications include:

- hard layers: in which fullerenes display greater thermal stability than the bisulphates in their conventional state
- polymeric layers and paints: products in which it is thought that the addition of fullerenes will increase “wetability” , thereby enabling the rapid evacuation of the surface-deposited water (of particular interest in aeronautics, as the rapid removal of water minimises the negative effects of ice on the moving control structures)
- lubricants (oils and fats): with the aim of reducing the coefficient of friction (there are already references in the literature that these are highly efficient in this function) and increase load resistance capacity.

Several other applications are envisaged for fullerenes, including drug delivery vehicles and in electronic circuits. Examples of fullerene-based applications are illustrated in Figure 20 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Anti-corrosion materials	✓	✓			✓	✓			
Polymeric layers and paints					✓				
Lubricants	✓	✓			✓				
Telecommunication: optical properties of fullerenes change when exposed to light (non-linear optical response), making them attractive for photonic device applications.		✓		✓					✓
Solar cells: ultra-thin layers of fullerenes have been used as electron acceptors in flexible organic solar cells			✓						

Figure 20: Applications vs. Industrial Sectors: Fullerenes [Source: ITI Techmedia]

2.3.9 Nanowires

Nanowires are ultrafine wires or linear arrays of dots, formed by self-assembly, which can be manufactured from a wide range of materials. Semiconductor nanowires made of silicon, gallium nitride and indium phosphides have demonstrated remarkable optical, electronic and magnetic characteristics. For example, silica nanowires can bend light around very tight corners.

The preparation of these nanowires relies on sophisticated growth techniques, which include self-assembly processes, where atoms arrange themselves naturally on stepped surfaces, chemical vapour deposition (CVD) onto patterned substrates, electroplating or molecular beam epitaxy (MBE).

Examples of nanowire-based applications are illustrated in Figure 21 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
High-density data storage				✓					
Chemical separation					✓	✓			
Quantum cryptography				✓					✓
Electronic devices: including field-effect transistors, sensors, detectors and light-emitting diodes (LED's)				✓					
High-density data storage (as magnetic read heads or patterned storage media)				✓					

Figure 21: Applications vs. Industrial Sectors: Nanowires [Source: ITI Techmedia]

2.3.10 Nanocapsules

Nanocapsules are generally described as nanoparticles with a hole inside, where different types of substances can be added (fragrances, enzymes, catalysts, oils, adhesives, polymers, other nanoparticles or even biological cells). Technologies for microencapsulating materials have already been in use for a number of years.

Recently, polymeric nanocapsules have been created, and have the advantage of being functionalised by relatively easy means. Manufacturing conditions of nanocapsules are not extreme, chemically or thermally, which makes it possible to encapsulate 'living' (biological) material inside them for drug delivery purposes. Furthermore, nanocapsules enable radical decrease in drug dosages, reducing the harmful side effects of drugs, because they have the ability to deliver the drug exactly to the target.

Examples of nanocapsule-based applications are illustrated in Figure 22 below.

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household*	*Textiles*	*Security*
Encapsulation of fragrances, enzymes, catalysts, oils, adhesives, polymers for controlled release			✓		✓		✓	✓	
Magnetic recording and magnetic fluids (magnetic nanocapsules, nanocapsules with a magnetic core)				✓					
Flavour burst foods							✓		
Waste water treatment			✓						
Self-repair	✓	✓			✓				

Figure 22: Applications vs. Industrial Sectors: Nanocapsules [Source: ITI Techmedia]

2.4 Market Structure

Nanotechnology is an enabling technology, not an industry per se, and provides building blocks upon which end-user products can be developed. Figure 23 below presents a generic view of the Nanotechnology value chain, the actors involved in each element of the value chain and examples of such actors.

Given the plethora of product opportunities available, it should be noted that the nature of the value chain will differ markedly between products. Such an exploration is beyond the scope of this report.

	Research	Tools and instrum-entation	Materials production	Product developer	End producer
Actors	Academia, industry labs	Mainly SMEs	Large chemical co's, SME's	Large chemical co's, SME's	Large corporates
Examples	Cambridge Nanoscience Centre	Digital Instruments Physike Obducat	BASF Degussa Nanophase	Oxonica Nanoco Nanogate	Pilkington Boots L'Oreal

Figure 23: Nanotechnology generic value chain [Source: ITI Techmedia]

2.4.1 Research

Research comprises the very early steps in the process of developing end products and applications. This is considered as true research and is often still theoretical or in a test status. Research in academia is generally viewed as more leading-edge than in large company research labs, but without the financial muscle to enable the ultimate development of end-products for specific identified markets. UK examples include the Cambridge Nanoscience Centre.

Given the relative immaturity of the Nanotechnology area, underlying breakthroughs can be expected to occur on an ongoing basis.

2.4.2 Tools and instrumentation

Tools and instrumentation are the hardware, software and supplies used to measure and manipulate structures on the nanoscale. Such tools and instrumentation include microscopes, probes, lithography systems, manipulation and fabrication systems, software and other accessories.

Rarely are these instruments unique to nanotechnologies. Most were developed in other industries, especially in semiconductors and chip-making, where submicron manufacturing principles have fuelled the communications explosion. Chemistry, physics, biology and materials science also have had a significant impact, and it is this interdisciplinary aspect which makes Nanotechnology unique.

While research is likely to uncover new novel Nanotechnology materials and techniques, it is unclear whether or not such innovation will drive requirements for fundamentally novel tools and instrumentation. Instead, the need to deliver high quality, high yield nanomaterials is more likely to be a driver of innovation within this element of the value chain.

Major players in this field include Digital Instruments, JEOL, Carl Zeiss and FEI.

2.4.3 Materials production

Due to their capacity for manufacturing bulk quantities of chemicals and materials, existing chemicals manufacturers have adapted to producing nanomaterials. Once tools and processes have been established, successful materials production will rely on the ability to invest in, and run, such processes in a cost-effective fashion. These skills are at the core of the existing chemicals industry and such players are the most likely to benefit from the requirement for the bulk supply of nanomaterials.

Examples of actors within this element of the value chain include multinationals such as BASF, as well as Degussa and Nanophase.

2.4.4 Product developer

Product developers have special interests in materials which are at the development level of “scientific result / technology invention” or “laboratory prototype”. As these companies have their own research and development laboratories, they are interested in the development of Nanotechnology-based products.

A number of start-ups, set up to produce novel end-products, are emerging. Many such start-ups are university spin outs, and include organisations such as Oxonica and Nanoco.

2.4.5 End producer

End producers are the companies which market and sell nanotech-based products they have typically incorporated into value-added products. These companies are at the consumer end of the value chain, and are, therefore, responsible for shaping the way in which end-users encounter Nanotechnology. End producers will typically only be interested in nanomaterials which are at the stage of being robust and market-ready, and thus in a position to be applied within the chosen marketplace.

Examples in the UK include Pilkington Glass (self-cleaning windows) and Boots (Soltan sunscreen range containing UV filters based on nanoparticle titanium dioxide).

2.5 Market Trends and Drivers

A number of trends and drivers affect, or will affect, the Nanotechnology/nanomaterials sector.

Trends in Nanotechnology are generally market/application specific. However, in this section, some of the generic trends and drivers influencing the Nanotechnology sector as a whole are identified. Nanotechnology is now being applied in an increasingly diverse number of areas. Factors which have led to this increase in commercial exploitation include:

- greater interaction between academia and industry to enable more readily technology transfer and innovation along the value chain
- increasingly coherent technical and funding strategies emerging at the national and international level
- evolving industry focus, away from a technology-orientation towards a more market-oriented focus
- the recruitment of highly-skilled professionals worldwide into the Nanotechnology sector

A number of drivers and inhibitors are affecting the sector, and are summarised in Figure 24 below.

Drivers	*Inhibitors*
Ongoing need for better technological performance	Sub-optimal yield and quality in nanomaterial manufacturing
Improved, cost-efficient, medical treatment	Scalability of nanomaterials from lab-scale pilot plants to industrial-scale commercial plants
Need for enhanced manufacturing and production processes	Identification of profitable commercial end uses/applications
Demand for improved security and defence	The pace of development of effective nanomaterials for such areas as robotics, microfluidics and micromachining lags the pace of applications requirements
	Corporate inertia coupled with competitiveness of established technologies
	Regulatory concerns over the effect of nanomaterials in the wider environment (e.g. toxicity)

Figure 24: Nanotechnology, drivers and inhibitors [Source: ITI Techmedia]

It is expected that the nature of the market drivers and inhibitors will evolve over time. For example, it can be expected that the regulatory environment in which the Nanotechnology industry will operate will mature and stabilise as additional research and analysis becomes available.

3 MARKET ASSESSMENT

3.1 Identification of Key Applications

As highlighted previously within this report, the range of possible applications enabled by Nanotechnology is very diverse. As a result, an assessment of the market opportunity afforded by Nanotechnology has focussed only upon a subset of the identified applications considered by ITI Techmedia to be of greatest interest.

The list of applications was filtered in order to identify those applications areas of greatest interest, specifically:

- that exhibit a large overall market opportunity
- in which nanotechnologies would comprise a significant proportion of the value of end products.

Based on these criteria, a number of application areas were identified as shown in Figure 25 below.

High density data storage	Semiconductor devices
Anti-bacteria and anti-fouling	Environmental filtration and sensing
Corrosion protection	Shape memory alloys
Food packaging	

Figure 25: Identified areas of application [Source: ITI Techmedia]

Each of these opportunities is explored further in the following sections, including:

- an overview of the application
- identification of a Nanotechnology enabler
- issues to be addressed in developing the underlying technology
- scale of Nanotechnology opportunity within the identified application under a high- and low-value scenario[7].

It should be noted that other, non application-oriented, areas of opportunity may emerge. For example, there may be a need to develop some capabilities at the international level that provide certification against certain regulatory criteria and/or industry norms (e.g. confirmation of acceptable levels of toxicity of nanomaterials). The consideration of such opportunities is beyond the scope of this report.

3.2 High Density Data Storage

In general, the permanent storage of large quantities of computer data is achieved using either:

- magnetic storage techniques (e.g. pc hard disk drives)
- optical storage techniques (e.g. CD, DVD)

The market for such information storage systems is vast. According to BCC Research, the information storage market is forecast to be worth some USD40 billion in 2010, up form around USD20 billion in 2005.

Nanoparticles represent a possible next technological step in magnetic storage techniques. While nanoparticles are not currently used in magnetic storage media, research is being carried out in nanoparticles and their use to form superlattices. This will allow for significant improvement in the density of data storage from the reduction of the area required to store a bit of information.

In order to gain market traction, such a technology must demonstrate a clear price/performance improvement over other competing technologies, and the ability to produce robust systems at high volume will have to be proven.

From a technology perspective, current limiting factors associated with this technology include the lack of read and write heads that could work with very small information storage areas.

[7] It should be noted that the forecasts developed in this report have been developed as initial high-level estimates, the purpose of which is to indicate the possible magnitude of the opportunity. Any information that would serve to refine such forecasts would be welcomed by ITI Techmedia. Should ITI Techmedia choose to pursue any of the identified applications, further analysis will be undertaken to explore the magnitude of the opportunity in greater detail.

Assuming that the benefits of the technology can be proven, ITI Techmedia forecasts that the value of the Nanotechnology portion of such storage devices (e.g. disk and read/write heads) could be worth between USD1 billion and USD3 billion by 2015, as illustrated in Figure 26 below.

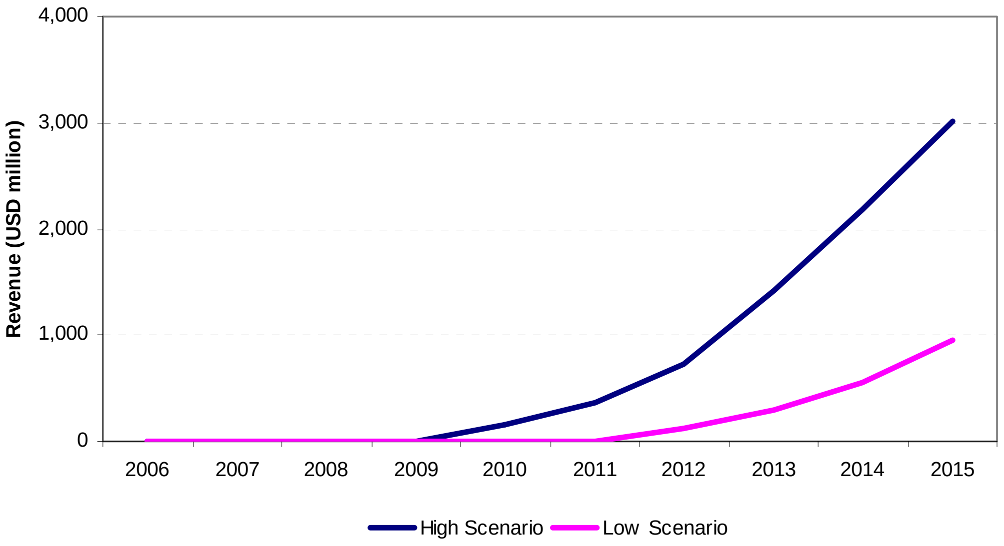

Figure 26: Nanotechnology opportunity within high density data storage devices under High and Low growth scenarios [Source: ITI Techmedia]

3.3 Anti-bacteria and Anti-fouling

The development of protective coatings possessing anti-bacterial and anti-fungal properties is an area of strong interest. One material that exhibits such properties is nanoscale titanium dioxide, and these properties can be activated by near-ultraviolet rays. The free-radicals and electron vacancies activated by this process serve as very powerful oxidising species which attack a variety of organic substances.

As a result of this property, photo-catalytically reactive titanium dioxide fine powders have a range of potential commercial applications including:

- self-cleaning coatings
- anti-bacteria and anti-fouling surfaces
- suspensions for water and air purification systems
- deodorisers
- anti-misting/fogging surfaces

Although the underlying technology exists, the exact nature of the titanium dioxide mix required for a particular application, and the associated manufacturing process, require definition on an application by application basis.

Given the range of possible uses of such a technology, it is extremely difficult to provide a definite size for the market opportunity. However, in order to provide an indication of the scale of the market opportunity, the application of Nanotechnology in the automotive paints and coats market has been analysed and is forecast to reach some USD2.7 billion in 2010, as illustrated in Figure 27 below. As can be seen below, revenue opportunities are expected to grow significantly between 2010 and 2015.

It should be noted that this market projection includes other applications such as scratch-resistant coatings. However, when scaled into other application areas, these figures serve to highlight the massive potential opportunity afforded in this area.

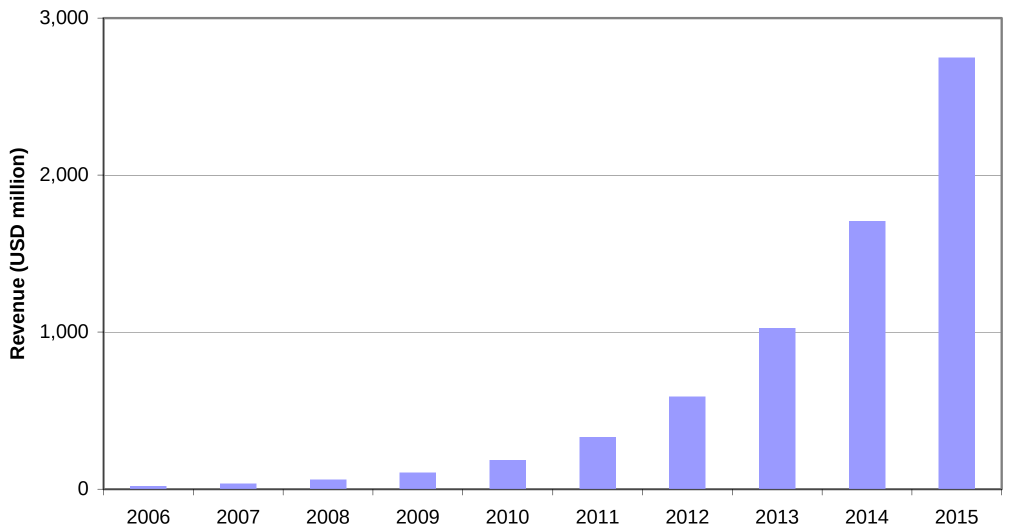

Figure 27: Automotive global Nanotechnology implementation in paints and coats [Source: Frost & Sullivan]

3.4 Corrosion Protection

The corrosion prevention market is large and diverse, and is used to protect machinery in markets such as the chemical and petrochemical industries. ITI Techmedia estimates that the global market for industrial anti-corrosion coatings was worth in excess of USD50 billion in 2006, with 3% to 5% annual growth expected in the medium to long term.

Nanoscale coatings offer excellent corrosion protection. The key benefits expected to influence the level of market adoption include:

- the need for very thin coating layers which are simple to apply
- additional functionality associated with the material, including water-/oil- and dirt-repellent effects, scratch resistance, mechanical and chemical resistance and heat resistance

Inorganic coatings based on nanoparticles are expected to provide the technical basis for such anti-corrosion products. Technical bottlenecks include the lack of understanding of adhesion mechanisms between coating and substrate, and how properties are transferred.

ITI Techmedia forecasts that the value of the Nanotechnology portion of anti-corrosion coatings could be worth between USD0.6 billion and USD4 billion by 2015, as illustrated in Figure 28 below.

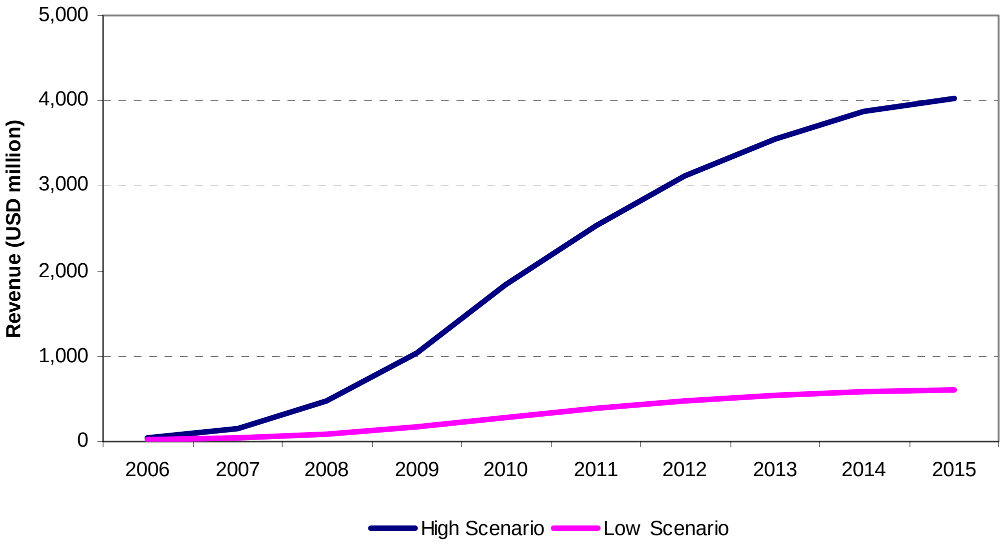

Figure 28: Nanotechnology opportunity within anti-corrosion coatings under High and Low growth scenarios [Source: ITI Techmedia]

3.5 Semiconductor Devices

The world Semiconductor market is large and very diverse. The Semiconductor Industry Association estimated that the total worldwide semiconductor market was worth some USD213 billion in 2004.

The role of Nanotechnology within this segment is currently the subject of a significant body of research, and includes the application of both carbon nanotubes and quantum dots.

To take advantage of nanoscale molecular electronic components in semiconductor technology, there will be a desire to integrate new elements such as one-dimensional (1D) carbon nanotubes in conventional 2D or 3D semiconductor systems. In these devices, the semiconductor serves as leads to the nanotubes, forming electronic hybrid nanotube-semiconductor devices. The combination of carbon nanotube and semiconductors may enable new nanoscale electronic and photonic devices.

Semiconductor single electron devices based on quantum dots have attracted much attention due to their small size, low power consumption and unique functionality, such as the ability to be quasi-stable. The ability to control electron charging of a capacitive node by individual electrons makes these devices suitable candidates for memory applications.

To provide some indication of the possible value of this area, the value of carbon nanotube opportunity within the electronics market has been assessed. ITI Techmedia forecasts that the value of the global carbon nanotube market in the electronics sector will be worth between USD500 million and USD1.3 billion by 2015, as illustrated in Figure 29 below.

It should be noted that the figures shown do not represent the value of components constructed using carbon nanotubes. Using benchmarks from the integrated circuit environment, the value of such components could be worth in the region of 3-5 times the values shown in Figure 29 below.

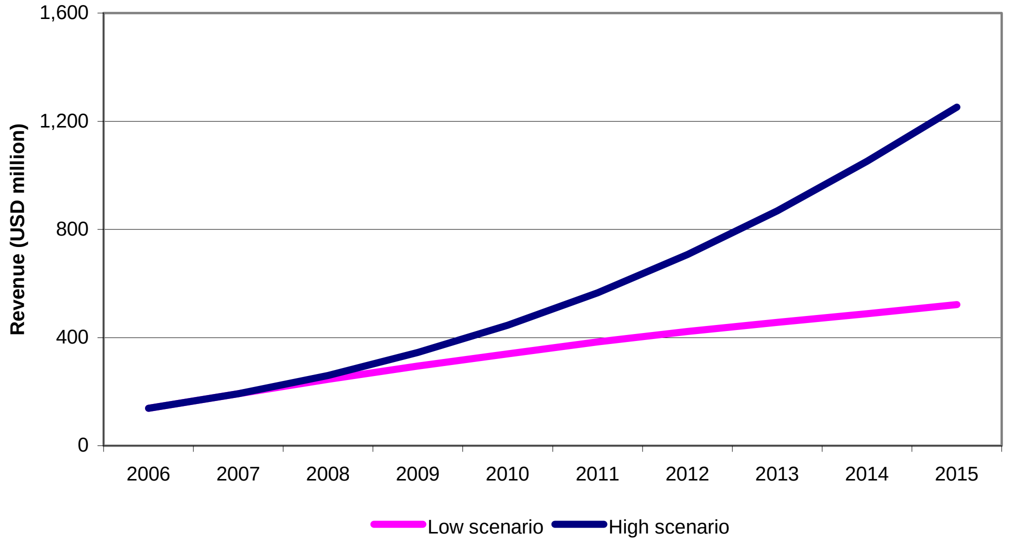

Figure 29: Carbon nanotube opportunity within the semiconductor industry under High and Low growth scenarios [Source: Frost and Sullivan, ITI Techmedia]

3.6 Environmental Filtration and Sensing

In order to assess the market opportunity in the area of environmental filtration and sensing, the focus has been in the area of water treatment and air purification. When taken together, ITI Techmedia estimate that the market for air purification equipment and water treatment chemicals was worth in the region of USD7 billion in 2004[8]

The air purification treatment and water purification chemicals markets both comprise a number of segments, the requirements of which can be addressed to a greater or lesser extent by emerging nanotechnologies. Nanoporous materials possess unique surface, structural and bulk properties, underlining their important uses in fields such as ion exchange, separation, catalysis, sensor, biological molecular isolation and purifications.

Also, nanoporous materials and membranes with well-defined pore sizes and high surface areas are being developed and tested for potential use in energy storage and environmental separation technologies. Silicon nanowires have been used to create highly sensitive, real-time electrically-based sensors for biological and chemical species

ITI Techmedia estimates that the market for nanotechnologies within the air purification and water treatment chemicals markets could be worth between USD100 million and USD380 million by 2015, as illustrated in Figure 30 below.

[8] Based upon data for Europe and North America from Frost and Sullivan, and scaled up to global figures based using GDP.

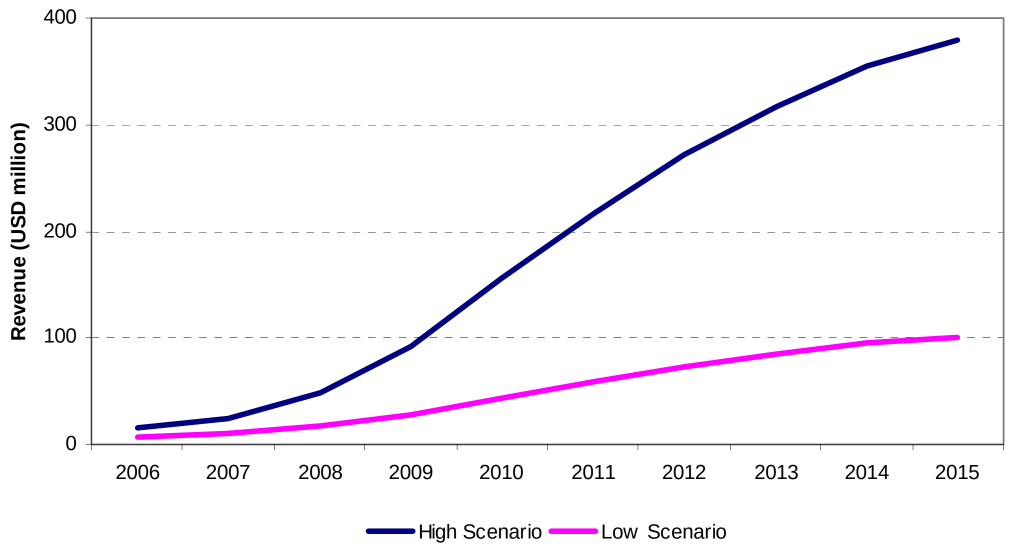

Figure 30: Nanotechnology opportunity within the air purification and water treatment markets under High and Low growth scenarios [Source: Frost and Sullivan, ITI Techmedia]

3.7 Shape Memory Alloys

Shape memory alloys (SMAs) are metals which retain knowledge of their geometry. After deformation, SMAs regain their original geometry either through heating or elasticity effects.

High performance alloys find application in a range of applications, and comprise a range of alloys, both expensive and inexpensive. Given this range, it is no surprise that these alloys have a variety of possible uses in areas as diverse as:

- aerospace components
- architectural components
- electronic components
- food packaging.

ITI Techmedia estimate that the market for high performance alloys was worth in the region of USD30 billion in 2004. For the purpose of this report, SMAs are considered to be a specific class of high performance alloy.

The development of nanostructured materials has inspired a renewed interest in SMAs. Better fracture characteristics and changes in the mechanical properties of SMAs are expected at the nanoscale because of small grain size at the micron scale, and this small grain size has been shown to affect the transformation and mechanical behaviour of the alloys.

SMAs have not yet gained any significant degree of market traction, but ITI Techmedia expect the value of such alloys to expand significantly in the period to 2015. As such, ITI Techmedia estimates that the market for Nanotechnology in SMAs could be worth between USD700 million and USD1.8 billion by 2015, as illustrated in Figure 31 below.

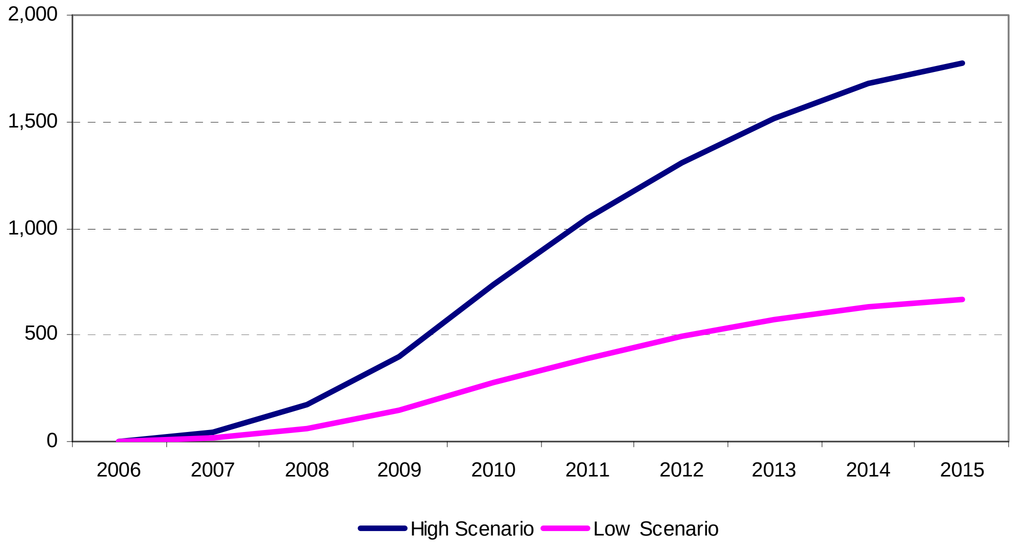

Figure 31: Nanotechnology opportunity for shape memory alloys under High and Low growth scenarios [Source: Frost and Sullivan, ITI Techmedia]

3.8 Food Packaging

Food is packaged in a range of container types including plastic, metal and glass. Such containers may include a diverse range of coatings and films, the primary purpose of which is to ensure the quality of the food contents over as long a period as possible. The scale of the food packaging market is huge – ITI Techmedia estimates that the market for plastic packaging alone was worth over USD60 billion globally in 2004.

In the food-packaging arena, nanomaterials are being developed with enhanced mechanical and thermal properties to ensure better protection of foods from exterior mechanical, thermal, chemical or microbiological effects. Innovation via nanoscale coatings and thin films and the incorporation of nanocomposites includes:

- modifying the permeation behaviour of foils
- increasing barrier properties
- improving mechanical and heat-resistance properties
- developing active antimicrobic and antifungal surfaces
- sensing and signalling microbiological and biochemical changes

Nanotechnology has been used in food packaging for a number of years and ITI Techmedia expects the value of Nanotechnology components to expand significantly in the period to 2015. As such, ITI Techmedia estimates that the market for Nanotechnology in food packaging could be worth between USD600 million and USD3 billion by 2015, as illustrated in Figure 32 below.

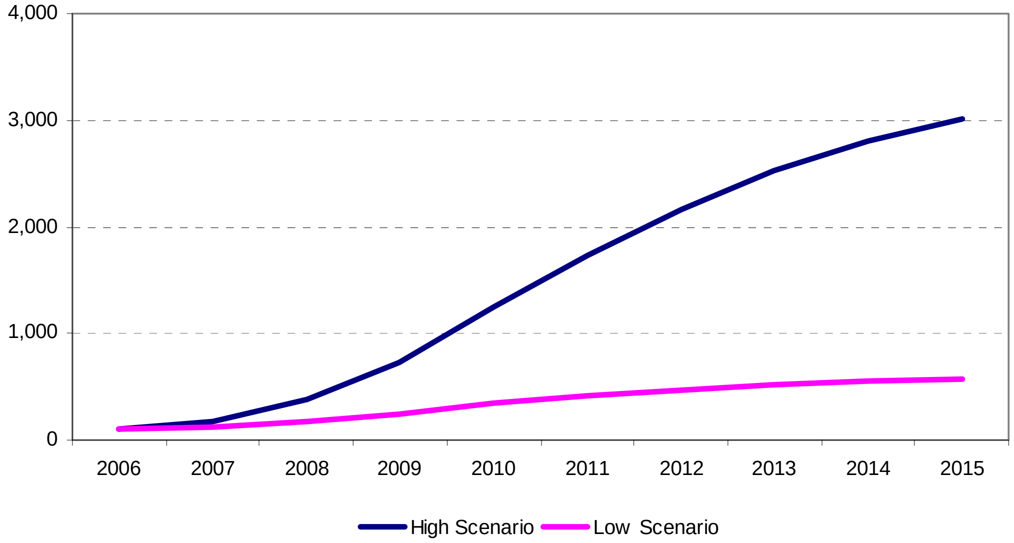

Figure 32: Nanotechnology opportunity in the food packaging market under High and Low growth scenarios [Source: Frost and Sullivan, ITI Techmedia]

3.9 Functional Requirements

The functional needs[9] that support Nanotechnology applications identified in Section 3, together with their state of developments, are illustrated in Figure 33 below.

In general, a significant body of work is being undertaken in relation to the identification and characterisation of materials that may be suitable for the applications. Likewise, the areas of tools and instrumentation would appear to have attracted significant interest and funding.

However, the productisation of these materials would appear to be relatively undeveloped, whilst end product functions would appear to be even more immature.

[9] A definition of the identified functional needs can be found in Appendix 2.

Functional need	*Data Storage*	*Anti-bacteria*	*Corrosion Protection*	*Semiconductors*	*Environmental*	*Shape Memory Alloys*	*Food Packaging*
Research							
Material identification	🚧	📢	📢	🚧	🚧	🚧	🚧
Material characterisation	🚧	📢	📢	🚧	🚧	🚧	🚧
Tools and instrumentation							
Analytical tools	🚧	🚧	🚧	🚧	🚧	🚧	🚧
Process-oriented tools	■	📢	📢	🚧	🚧	🚧	🚧
Materials production							
Process definition	🚧	🚧	🚧	🚧	■	🚧	🚧
Process operation	■	📢	🚧	🚧	■	■	■
Product development							
Definition	🚧	📢	🚧	■	■	🚧	🚧
Characterisation	■	🚧	🚧	■	■	■	■
Production	■	🚧	🚧	■	■	■	■
End producer							
Definition	■	🚧	🚧	■	■	■	■
Characterisation	■	🚧	🚧	■	■	■	■
Production	■	🚧	■	■	■	■	■

Figure 33: Functional needs for identified Nanotechnology applications [Source: ITI Techmedia]

Key to Figure 33

Maturity	Well Developed	In progress	Immature
	📢	🚧	■

4 SUMMARY

This document provides market intelligence into the sector defined as Nanotechnology. The acquired knowledge will be used as base input to ITI Techmedia's programme selection process. ITI Techmedia will continue to report to Members on progress, and Members are encouraged to provide comment and input to this process and to become actively involved in any resulting programmes.

Significant activity is occurring in the Nanotechnology area, sparked by the promise of Nanotechnology offering new and cost-effective products. Nanotechnology is surrounded by hyperbole and for good reason. It, arguably, shows as much promise in both science and business as any other major technology of the past century.

Nanotechnology is not a market per se. Rather, it is an enabling technology that offers both new opportunities with existing markets and entirely new market opportunities. This report has identified that a plethora of potential opportunities exists, across a range of industry sectors. However, successful adoption will only occur where Nanotechnology-based products can demonstrate significant functional benefits at the appropriate price point for that market.

Nanomaterials, and their associated manufacturing and processing technologies, are the key enablers of a Nanotechnology industry. A wide range of such nanomaterials exist, the common link being that they all exhibit features only present at the nanoscale and which potentially offer performance enhancements over existing materials. A vast array of potential applications that exploit these nanoscale features is identified in this report.

Nanotechnology can be viewed as a component within a wider end-product value chain. In general, a significant body of research is being undertaken in relation to nanomaterial characterisation. However, the productisation of these materials would appear to be relatively undeveloped at present.

The broad list of applications identified in this report has been filtered to identify those of greatest interest. As a result, the following application areas have been identified as being worthy of further consideration:

- high density data storage
- anti-bacteria and anti-fouling
- corrosion protection
- food packaging
- semiconductor devices
- environmental filtration and sensing
- shape memory alloys

APPENDIX 1: GLOSSARY OF TERMS

Term	*Description*
Chemical vapour deposition	A chemical process often used in the semiconductor industry for the deposition of thin films of various materials. In a typical chemical vapour deposition process the substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit. Frequently, volatile by-products are also produced, which are removed by gas flow through the reaction chamber
CNT	Carbon nanotube
Cosmeceutical	A substance that combines features of both a cosmetic and a pharmaceutical
CVD	Chemical vapour deposition
Giant Magmagnetoresistance effect	A quantum mechanical effect observed in thin film structures composed of alternating ferromagnetic and nonmagnetic metal layers. The effect manifests itself as a significant decrease in resistance from the zero-field state, when the magnetization of adjacent ferromagnetic layers are antiparallel due to a weak anti-ferromagnetic coupling between layers, to a lower level of resistance when the magnetization of the adjacent layers align due to an applied external field.
GMR	Giant Magmagnetoresistance effect
Hydrogel	a network of polymer chains that are water-soluble, sometimes found as a colloidal gel in which water is the dispersion medium. Hydrogels are superabsorbent (they can contain over 99% water) natural or synthetic polymers.
ICT	Information and communication technology
MBE	Molecular beam epitaxy
Molecular beam epitaxy	Molecular beam epitaxy (MBE) is a method of thin-film deposition. In solid-source MBE, ultra-pure elements such as gallium and arsenic are heated in separate quasi-knudsen effusion cells until they each slowly begin to evaporate. The evaporated elements then condense on a wafer, where they react with each other, forming, in this case, single-crystal gallium arsenide. The term "beam" simply means that evaporated atoms do not interact with each other or any other vacuum chamber gases until they reach the wafer, due to the large mean free path lengths of the beams

Term	*Description*
Molecular electronics	Sometimes called moletronics, molecular electronics is a branch of applied physics which aims at using molecules as passive (e.g. resistive wires) or active (e.g. transistors) electronic components.
Nm	Nanometres
Nutraceutical	A substance that may be considered a food or part of a food and provides medical or health benefits, including the prevention and treatment of disease
Paradentosis	Bacterial infections of the gums in the mouth.
Pathogen	An organism that causes disease in another organism
Photocatalysis	The acceleration of a photoreaction in the presence of a catalyst. In catalysed photolysis, light is absorbed by an adsorbed substrate. In photogenerated catalysis the photocatalytic activity depends on the ability of the catalyst to create electron-hole pairs, which generate free radicals able to undergo secondary reactions. Its comprehension has been made possible ever since the discovery of water electrolysis by means of the titanium dioxide
Photovoltaics	The technology of solar cells, and also the field, discipline, and approach of creating electricity that is made possible by solar cells
Powertrain	The totality of components in a vehicle that generate power and deliver it to the road surface, water, or air. This includes the engine, transmission, driveshafts, differentials, and final drive (drive wheels, caterpillar track, propeller, etc).
Quantum computing	Computation that makes direct use of distinctively quantum mechanical phenomena, such as superposition and entanglement, to perform operations on data. The basic principle of quantum computation is that the quantum properties of particles can be used to represent and structure data, and that quantum mechanisms can be devised and built to perform operations with this data.
Quantum cryptography	An approach to securing communications based on certain phenomena of quantum physics. Quantum cryptography is focused on the physics of information. Using quantum phenomena such as quantum superpositions or quantum entanglement one can design and implement a communication system which can always detect eavesdropping, since measurements on the quantum carrier of information leaves traces.

Term	*Description*
Remediation	Clean-up of a site to levels determined to be health-protective for its intended use
SMA	Shape memory alloy
Superlattices	Structures with periodically interchanging solid layers. Such structures possess additional periodicity on a scale larger than atomic. This leads to apparition of characteristic satellite peaks in X-ray diffraction patterns. Depending on the nature of components, magnetic, optical and semiconductor superlattices are distinguished
Thermoplastic olefin	Mouldable alkenes that exhibit a single carbon-carbon double bond
TPO	Thermoplastic olefin

APPENDIX 2: FUNCTIONAL NEEDS DESCRIPTION

Functional Need	*Description*
Research	
Material identification	The identification of one or more materials that have the potential to exhibit properties necessary to satisfy the requirements of an application
Material characterisation	Development of an understanding of the properties exhibited by a material in order to understand whether it offers potential benefit in the context of a particular application
Tools and instrumentation	
Analytical tools	Tools and techniques to enable the process of Nanotechnology research
Process-oriented tools	Tools and techniques to enable the process of Nanotechnology materials production
Materials production	
Process definition	The combination of tools, techniques and human input to enable the manufacture of nanomaterials at production quantities
Process operation	The know-how involved in order to optimise the cost and quality of the Nanotechnology materials production process to deliver acceptable yields
Product development	
Definition	The combination of nanomaterials with other components in order to design a novel end product
Characterisation	The development of prototype end products for the demonstration of the required product characteristics
Production	The refinement of product prototypes to meet the requirements of end consumers and available production processes
End producer	
Definition	The combination of tools, techniques and human input to enable the manufacture of products incorporating nanomaterials at production quantities
Characterisation	The development of prototype production processes for the demonstration of end product production at limited quantities
Production	The refinement of the production process to produce end products, incorporating nanomaterials, in commercial quantities at acceptable cost and acceptable yield

APPENDIX 3: APPLICATIONS BY TECHNOLOGY

This section provides a more exhaustive list of applications by area of Nanotechnology technology than is presented in the report text. As well as describing applications by technology, this section also identifies the possible industry sectors in which the application may be used. The results are presented in a tabular format in the following sections.

Nanoparticles

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Gold nanoparticles with high performance for low-temperature combustions as catalysts	✓	✓	✓			✓			
Stain-resistant fabrics		✓					✓	✓	
Nanoparticulate drug delivery		✓						✓	
Nanosilver dressings							✓	✓	
Nanoscale magnetic particles for high-density data storage				✓					
Nano-sized titanium dioxide and zinc oxide for UV absorbency							✓		
Nanoparticles in Tagging, Tracking and 'Smart Barcodes'									✓
Fluorescent biological labels									✓
Display technologies including field-emission devices (e.g. using conducting nanoscale oxides)	✓	✓		✓					✓
Nanoparticle Conductors for Flexible Electronics	✓			✓					
Lubricant / hydraulic additives (e.g. Cu MoS2)	✓	✓							
Magnetic nanoparticle shock absorbers	✓	✓							
Nanoparticles in catalytic converters	✓	✓							
Improved anode and cathode materials for solid oxide fuel cells	✓	✓		✓					

Figure 34: Applications vs. Industrial Sectors: Nanoparticles [Source: ITI Techmedia]

Nanoparticulate surface coatings, thin films and layers

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Scratch-resistant coatings					✓				
Anti-graffiti coatings	✓								✓
Self-healing coatings	✓	✓				✓			✓
Easy-to-clean, antimicrobial coatings								✓	
Stain resistant fabrics								✓	
Photocatalytically active surfaces for self-cleaning and disinfection	✓	✓	✓				✓	✓	
Glass coatings for anti-glare, anti-misting mirrors, screens and solar cells (e.g. using TiO_2)	✓	✓				✓			
Scratch resistant films				✓	✓				
Oxygen resistant films							✓		
Hard coatings for wear reduction and for corrosion protection	✓		✓		✓	✓			
Self-cleaning surfaces (e.g. using TiO_2 based nanostructured coatings) and sprays	✓		✓			✓	✓	✓	

Figure 35: Applications vs. Industrial Sectors: Surface coatings and thin films [Source: ITI Techmedia]

Nanocomposites

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Magnetic nanocomposite materials for high temperature applications e.g. transformers, DC-DC power converters	✓	✓							
Polymer nanocomposites with increased tensile strength, clarity and barrier improvement	✓	✓			✓	✓			
Oxygen scavenging barrier materials							✓		
Flame retardant plastics	✓	✓							
Biodegradable nanocomposite packaging							✓		
Shape memory polymer nanocomposites	✓	✓			✓				
Polymer-clay nanocomposites to substitute glass materials e.g. smash-resistant organic glass or new shock absorber materials	✓	✓			✓		✓		

Figure 36: Applications vs. Industrial Sectors : Nanocomposites [Source: ITI Techmedia]

Carbon Nanotubes

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Advanced high strength polymers	✓	✓			✓	✓			
Lighting elements (advanced emission)	✓			✓					
Electromagnetic (EM) shielding		✓		✓					
Fracture resistant ceramics	✓	✓			✓				
Hydrogen storage for fuel cells	✓		✓			✓			
Field emitters in high resolution flat panel displays		✓		✓					
Reinforced plastics or composite materials by using CNTs or CNTs fibre	✓	✓			✓	✓			
Sensors (chemical and biological sensors)		✓	✓		✓		✓		✓
Braking systems & other cooling applications	✓								
Ultra-sensitive electromechanical sensors	✓	✓							
Hybrid Semiconductors				✓					
Plastics that conduct electricity and heat without altering the performance of the plastic	✓	✓		✓					

Figure 37: Applications vs. Industrial Sectors: Carbon nanotubes [Source: ITI Techmedia]

Nanoporous Materials

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Controlled release through nanoporous membranes									
Membranes for gas separation					✓				
Nanoporous optical films for Fraud-Proof Security Markings		✓							✓
Filter media for absorption of gas pollutants			✓			✓			
Photonic crystals fabricated in nanoporous silica				✓					
Nanoporous silica Thermal insulation			✓						
Nanoporous Electrodes for fuel cells	✓		✓						
Nanoporous plasma coatings for textile finishing	✓	✓						✓	
Nanosilica spheres as slow release containers for controlled release of scents and anti-bacterials					✓		✓	✓	
Nanoporous cyclodextrin-silica nanocomposites for the trapping of malodorous organic molecules					✓			✓	
Membranes for environmental remediation does require high adsorption/absorption properties			✓		✓				
Protective clothing for uniforms		✓						✓	
Nanoporous Catalysts	✓	✓	✓						
Nano, micro- and mesoporous composites (porous pellets) for air purification			✓				✓		
Proton exchange membrane (PEM) fuel cells	✓	✓							
Inorganic nanoporous adsorbents for fuel refining	✓					✓			
Filtration membranes					✓	✓	✓		
Supercapacitors	✓								

Quantum Dots

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Quantum dot-based resins, sol-gels, insulating polymers, and composite films	✓	✓	✓		✓	✓	✓		✓
Anti-counterfeiting, security tagging									✓
Semiconductor lasers based on photons emitted by quantum wells, wires				✓					
Single-electron transistors with quantum dots				✓					
Quantum computing				✓					
Recording/memory: metal quantum dots				✓					
Photosensors	✓			✓					
Solar cells (replacing dyes' molecules)									
Biosensors		✓							✓
Infrared paints		✓			✓				✓

Figure 38: Applications vs. Industrial Sectors : Quantum dots [Source: ITI Techmedia]

Nanofibres

Applications	*Transport/ Automotive*	*Aerospace and Defence*	*Environment/ Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Adsorbents that demonstrate extremely fast kinetics of removing toxic substances from biological media		✓			✓	✓	✓		✓
Nanofibre-reinforced polymer	✓	✓			✓			✓	
Wound healing bandages									
Air and water filtration			✓		✓	✓	✓		
Protective clothing and breathing masks		✓				✓		✓	✓
Thermal insulation	✓	✓	✓						
Energy storage devices	✓	✓							
Electrostatically generated nanofibres for wearable electronics		✓		✓				✓	
Biosensors and probes		✓			✓	✓			✓
Packaging: specially adapted polymers that prevent contamination							✓		✓
Sensory fabrics				✓					
Nanofibre catalyst systems for use in the production of fuel cell electrodes	✓	✓							

Figure 39: Applications vs. Industrial Sectors: Nanofibres [Source: ITI Techmedia]

Fullerenes (Carbon C60)

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Anti-corrosion materials	✓	✓			✓	✓			
Hard layers in which fullerenes display greater thermal stability than the bisulphates in their conventional state					✓				
Polymeric layers and paints					✓				
Lubricants	✓	✓			✓				
Electronic circuits.	✓	✓		✓					
Telecommunication: optical properties of fullerenes change when exposed to light (non-linear optical response), making them attractive for photonic device applications.		✓		✓					✓
Solar cells: ultra-thin layers of fullerenes have been used as electron acceptors in flexible organic solar cells			✓						
Catalysts: bucky-onions have been used for the conversion of ethylbenzene into styrene					✓	✓			
Fuel cells: fullerene-based membranes	✓	✓							
Hydrogen storage									
Long life Li-ion batteries		✓		✓					
Slow-release textiles							✓	✓	
Reinforcing composites	✓	✓			✓	✓			

Figure 40: Applications vs. Industrial Sectors: Fullerenes [Source: ITI Techmedia]

Nanowires

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
High-density data storage, either as magnetic read heads or as patterned storage media, and electronic and optoelectronic nanodevices, for metallic interconnects of quantum devices and nanodevices				✓					
Chemical separation					✓	✓			
Quantum Crytography				✓					✓
Electronic devices: including field-effect transistors, sensors, detectors and light-emitting diodes (LED's)				✓					
High-density data storage (as magnetic read heads or patterned storage media)				✓					
Electronic and opto-electronic nanodevices (for metallic interconnects of quantum devices and nanodevices, allowing replacement of copper in computers and electronics)				✓					
Energy transport				✓					
Superconducting wires that can make space-based electrical generators lighter and more efficient		✓		✓					

Figure 41: Applications vs. Industrial Sectors: Nanowires [Source: ITI Techmedia]

Nanocapsules

Applications	*Transport / Automotive*	*Aerospace and Defence*	*Environment / Water*	*ITC and Leisure*	*Materials and Chemicals*	*Oil and Mining*	*Food Processing and Household Products*	*Textiles*	*Security*
Encapsulation of fragrances, enzymes, catalysts, oils, adhesives, polymers for controlled release			✓		✓		✓	✓	
Magnetic recording and magnetic fluids (magnetic nanocapsules, nanocapsules with a magnetic core)				✓					
Surface cleaning /sweeping		✓					✓		
Electrodes and electrolytes		✓		✓					
Supercapacitors				✓					
Cosmeceuticals							✓	✓	
Aromatic additives to leather or other textiles								✓	
Flavour burst foods							✓		
Nutraceuticals							✓		
Household fragrancing							✓	✓	
Cleaning products			✓				✓		
Wastewater treatment			✓						
Membranes			✓		✓				
Environmental remediation			✓			✓			
Self-repair	✓	✓			✓				
Catalysts	✓	✓			✓		✓		

Figure 42: Applications vs. Industrial Sectors: Nanocapsules [Source: ITI Techmedia]