OAKDENE HOLLINS
RESEARCH & CONSULTING

Nanotechnologies relevant to Defra
Supplement to report on the 'Benefits of Nanotechnology'

Sustainable products and services
Clean technologies
Resource efficiency

A report for Defra

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1 Nanotechnologies relevant to Defra

1.1 Preamble

This document is part of a five piece set of reports that describe a methodology for performing a comparative valuation of a nanotechnology against an incumbent technology. The reports are entitled:

- **"A comparative methodology for estimating the economic value of innovation in nanotechnologies."** This provides a comprehensive overview of the methodology, supporting evidence and some worked examples.
- **"A working guide for determining the value of nanotechnology innovation."** This provides a simpler document designed for non-economists to make less rigorous calculation.
- **"A calculation spreadsheet for valuing nanotechnology."** This is a spreadsheet in MS Excel format that is designed to accompany the working guide.
- **"Methodology Case studies."** Provides a series of case studies that use the methodology for valuing nano-enabled products relevant to Defra
- **"Nanotechnologies relevant to Defra."** A short literature review to identify nanotechnologies that are relevant under Defra's remit.

If they are not readily available, these documents can be obtained from Oakdene Hollins Ltd.

1.2 Introduction

This report gives an overview of the current and possible future applications of nanotechnology relevant to Defra. The areas relevant to Defra include: Adapting to climate change, Animal diseases, Animal welfare, Atmospheric quality and industrial pollution, Biodiversity, Farming, Floods, Local environmental pollution/noise, Marine, People and landscapes, Rural development, Soils, Sustainable consumption and production, Sustainable development, Waste, Water, and Wildlife and countryside.

This document is designed to give a brief description of activities within areas relevant to Defra. In order to give an estimate of the possible impact of nanotechnology, either the market size for the incumbent technology is stated or, where available, the current and future market projections of the nano-enabled product.

Three products have been valued using the developed methodology, the results of which are contained in the separate "Methodology Case Studies" document:

- nano zero valent iron used in land remediation
- marine anti-fouling paint
- gas sensors to monitor atmospheric quality.

1.3 Animal welfare

Within livestock and animal husbandry, the ability to monitor the health of animals in real time can prevent the spread of disease. It is likely that the majority of the gain in this area will be from spill-over of innovation in the medical sector. Sensitive assays that are more compact could speed up detection of any pathogen that may affect farm animals. Real-time monitoring of the animals' health will also reduce losses from illness and disease. Systems for these purposes do currently exist but they are generally impractically expensive and too bulky for use under normal conditions. A key advantage that nanotechnology promises in this area is a reduction in costs, and therefore further adoption. For example, the US Department of Agriculture is pursuing a project to cover farmers' fields and herds with small wireless sensors to replace farm labour and expertise with a ubiquitous surveillance system.

1.4 Animal diseases

Similar to the application of sensors to livestock, the drive for using nano-enabled veterinary medicines is likely to be led by research into human biomedical research. Encapsulation and slow release of pharmaceuticals is expected to become more prevalent, leading to more effective treatments of common agricultural diseases.

Alternatively, new therapies may be possible such as those being developed to reduce our reliance on antibiotics in industrial chicken production; researchers are feeding chickens with bio-active polystyrene nanoparticles that bind with bacteria, as an alternative to chemical antibiotics.[a]

1.5 Atmospheric quality and industrial pollution

1.5.1 Monitoring and control of pollutants

Effective monitoring of air-borne pollutants is an important step in controlling the exposure to toxic and environmentally damaging compounds. There are incumbent technologies that target air-borne chemicals but there are deficiencies with these systems surrounding their weight, cost and sensitivity. Sensor development and application based on nanoscale science and technology is growing rapidly due, in part, to the advancements in the microelectronics industry and the increasing availability of nanoscale processing and manufacturing technologies. Sensors using nanotechnology may result in lower material costs along with reduced weight and power consumption, leading to greater applicability and enhanced functionality.[b]

Much of the new generation nanoscale sensor development is driven by defence and biomedical fields. These areas possess high-need applications and the resources required to support sensor research. The environmental measurement field is a cost-sensitive arena with fewer available resources for leading-edge development.[c]

The sensors market is estimated to be worth approximately £100m, while gas detection (which includes sensors as one of the component) is worth approximately £1.5bn to £2bn. The UK is the world leader in gas sensing, with over 75% of all electrochemical gas sensors produced here. The main competitors for such technology are based in Germany, US and Japan.[d]

It is anticipated that sensors using nanotechnology will not lead to price improvements over their incumbents. The main benefit of using nanotechnology in sensors is to improve the quality and sensitivity of gas sensing/detection. Areas of active research include monitoring devices for common air-borne pollutants such as PM10, PM2.5, NOx, and SOx; monitoring for noxious gases such as solvents and other environmental pollutants. Potential applications include the monitoring of urban air quality, volcanic plumes, landfill gas and airport gas emissions.

Metal oxides

The development of sensors has exploited the interactions of metal oxide semiconductors with gases for decades. Their sensing properties are based on surface reactions with gases in the atmosphere, causing a change in the semiconductor's resistivity. It has been shown that using nanoparticulate materials increases the surface/bulk ratio, which improves responsiveness and lowers operational temperatures.[e]

Nanowires of semiconducting metal oxides such as zinc, tin or indium oxides have shown promise as an emerging class of sensing devices. As with the use of nanoparticles, the use of nanowires greatly enhances gas sensitivity of these oxides by increasing the surface/volume ratio. To this end, there have been studies of the conductivity of nanowires sensing devices in an atmospheric environment, targeting sensing capability toward gases such as NO_2 and CO, ethanol and ammonia.[f]

The technology is currently being commercialised but is not yet in common use.[g]

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[a] *Small size that matters: Opportunities and risks of nanotechnology, Report in cooperation with the OECD futures programme, OECD and Allianz, 2005*

[b] *U.S. Environmental Protection Agency, Nanotechnology White Paper (EPA 100/B-07/001 February 2007*

[c] *ibid*

[d] *Private communication with John Saffell at Alphasense, May 2010.*

[e] *MNT Gas Sensor Roadmap, December 2006*

[f] *Crystalline Nanowires of Semiconducting Metal Oxides as a New Generation of Gas Sensors OECD Conference on Potential Environmental Benefits of Nanotechnology: Fostering Safe Innovation-Led Growth, OECD Conference Centre Paris, 15-17 July 2009*

[g] *"Review Article Conductometric Gas Nanosensors", Journal of Sensors, Volume 2009 (2009), Article ID 659275,*

Further research is needed to develop this technology, particularly interfacing the nanoparticles with wider electronics systems. Companies including UK-based Alphasense are working on sensors in this area.

Carbon nanotubes

The nature of high-quality semiconductor nanotubes means that even the adsorption of a single molecule can produce changes in the electrical properties, which could result in a significant increase in sensitivity compared to conventional sensors. Both single-walled and multi-walled carbon nanotubes have potential applications in gaseous, chemical and biological sensing in sectors including process, automotive and extraction industries as well as environmental monitoring and health and safety.

Research is on-going in this area but the technology is still in its infancy. The benefit and likely success of the product are currently difficult to establish. Until synthesis and post-processing methods have been developed, which generate materials with selected electronic and structural properties, it is unlikely that these systems will be mass produced.

Mass spectroscopy

Conventional mass spectrometers detect and identify chemicals based on their mass. Innovations in detection methods and the scaling-down of components are being used to reduce the size and cost of mass spectrometers. The goal of this research is to develop mass spectrometers that are small enough to be used on board spacecraft. Further into the future, such devices could be employed in the detection of environmental toxins.[a] Several organisations are examining this area, including NASA and the Nanoscience Centre at the University of Cambridge.

1.5.2 Photocatalysis[b]

Nanoparticles of titanium dioxide (TiO_2) have the potential to use sunlight (photocatalysis) to turn NO_x and VOCs present in the atmosphere into harmless gases. There are commercially available paints that incorporate these compounds and which are marketed as 'self cleaning'. Their mode of action is to destroy the grease encapsulating the dirt, enabling rain water to wash off the resultant 'free' dirt particles. These materials also reduce NOx concentrations by up to 80%. Although not marketed for the purpose, these paints could significantly improve local air quality. These products are currently available with large manufacturing bases in Japan and China. The overall market size is difficult to estimate, but the improvement in local air quality could reduce the estimated £20bn loss associated with air pollution in the UK.[c]

1.5.3 Pollution prevention/fuel additive

Commercial additives for diesel fuel have been developed based on nanoparticles of cerium oxide. This system relies on delivering low parts per million (ppm) concentrations of nanoparticles to the combustion chamber of diesel engines, which catalyses a lower combustion temperature for carbon deposits and cleaner burning. This has delivered 5-10% reductions in fuel consumption in UK trials. Associated with this have been similar reductions in exhaust pollutants, for example particulates. This is largely a 'drop in' replacement, with surfactants used to stabilise the dispersion of the nanoparticles in a hydrocarbon solvent. There is then a requirement to meter-in the additive to the fuel (or indeed to an individual fuel tank), either at a fuel terminal or a fleet operator's premises, depending on the nature of the customer.

There are competitive systems based on cerium salts such as the Rhodia 'EOLYS' system, which meters-in a concentrate into the engine in order to clean up diesel particulate traps by lowering its regeneration temperature but does not claim to improve fuel efficiency. Another similar cerium-based system, which also includes a platinum salt is marketed by CDT in the USA.

A reduction in diesel consumption by 5% could reduce the UK fuel bill by approximately £1.25bn. Energenics (based partly in the UK)

[a] *Micro- and Nano-technology Enabled Platforms for Environmental Monitoring, OECD Conference on Potential Environmental Benefits of Nanotechnology: Fostering Safe Innovation-Led Growth, OECD Conference Centre Paris, 15-17 July 2009*

[b] *Observatory Nano, Report on Nanotechnology Sector: Environment, 2009*

[c] *http://framework.rcuk.ac.uk/Hsoc/hcase.htm*

produces and sells a diesel fuel additive under the trade mark name of Envirox™.

1.5.4 Engine efficiency[a]

Nanostructures improve adherence and integrity of ceramic coatings on key components within gas turbines (jet engines), particularly in aircraft. These coatings enable higher temperatures and hence higher efficiencies to be obtained within the turbine, with consequent fuel savings . Companies such as Rolls-Royce, Turbine Surface Technologies (a Rolls-Royce joint venture) and UK universities such as Loughborough and Oxford are researching coatings on engine components such as nozzle guide vanes (which guide the hot gas stream), aerofoils and gas seals. Generally, nanostructured coatings are in the advanced research or development phase, with a time to market of around one to five years depending on approval and certification requirements.

The target temperature increases made possible by these coatings are of the order of 10°C in a system that might be operating around 600°C. The efficiency gains and fuel savings attributable may be of the order of 0.2% to 0.6%, depending on which component(s) are addressed and the degree of success of the research. There are also potential land-based turbine applications where these coatings are implemented, but these have not been estimated at present.

Development is continuous and it seems likely that the benefit of these technologies will be incorporated into later iterations of turbine design.

1.5.5 Catalytic traps/catalytic converters

Catalytic traps are employed in both industry and the automotive sector to reduce emissions of particulate matter from various combustion and oxidation processes. These devices reduce emission of potentially harmful emissions by oxidising the material (generally forming CO_2 and water). One of the main areas of use is in the reduction of particulates from diesel engines. These particulate filters reduce the emission of PM20 soot particles from diesel engines, reducing the amount of toxic material emitted during use. The gradual incorporation of these filters into the automotive sector will reduce emissions of PM20, consequently reducing human health problems. They are also employed to eliminate the release of chemicals from flues of chemical plants. An American company, Nanostellar, is leading research in this area.

It has been shown that the use of tailored catalytic nanoparticles improves on the incumbent technologies. Several companies are investigating and marketing the use of nanoparticle-based catalysts as catalytic traps and catalytic converters for diesel engines. It is claimed that these materials offer improved efficacy and reduce material use over incumbent products.[b]

Nanotechnology has been used in catalytic converters in cars for some years in order to reduce the use of expensive platinum group metals and improve performance. The further use of nanotechnology is focusing on[c]:

- Incremental improvements to further reduce platinum group metal use and improve performance of the metal component and refractory support.
- Substitution of platinum group metals with cheaper nanoscale materials. Similar nanoscale catalysts are also being developed for applications in the chemical industry to replace platinum group metals.

In catalytic converters, nanotechnologies are being employed to improve emissions performance at lower cost, rather than improving fuel efficiency. Research is continually being carried out by automotive manufacturers, catalyst specialists (such as Johnson Matthey) and several UK-based academic research groups including Queen's University Belfast.

The aim of both catalytic converters and catalytic traps is primarily to ensure that vehicles meet increasingly tough emissions standards. This, in turn, is to reduce health issues associated with air pollution, costing approximately £20bn per year to the UK economy.[d]

[a] *Environmentally beneficial nanotechnologies, Defra, 2007*

[b] *http://www.nanostellar.com/*

[c] *Environmentally beneficial nanotechnologies, Defra, 2007*

[d] *http://framework.rcuk.ac.uk/Hsoc/hcase.htm*

1.6 Agriculture

1.6.1 Sensors

Several different sensor applications are being investigated to the cut the cost and environmental impact of food production. These include:

- pathogen and pest detection
- crop growth rate and nutrition levels recording.

There are alternative technologies available within each of these application areas but cost, complexity or insensitivity of these products mean that there is still a significant nascent opportunity for nanotechnology-enabled products.

Within agriculture, the utilisation of sensors could enable farmers to gain real-time data on important aspects of crop husbandry such as nutrient content, soil condition, information on pathogens and ripeness. Such systems do exist for high value crops, such as for the cultivation of grapes[a] at vineyards, but are bulky and expensive. The advent of cheap, readily available nanotechnology-enabled devices would enable a more widespread uptake. Consequences of this could include higher yields and lower resource wastage through targeted 'smart' farming.[b,c]

The use of sensors could lead to precision farming. This enables farmers to identify the nutrient and water needs of individual plants and appropriately address those needs. There is evidence to suggest that with precision technology, up to 25 million litres of water could be saved annually on an 11 hectare farm.[d] Significant savings can also be made in reducing fuel costs and labour by ensuring that the use of agricultural equipment is optimised.[e] It is difficult to estimate the total value to the UK economy but, if implemented, nano-enabled devices will have a significant impact on production costs and a marked reduction in environmental impact.

1.6.2 Disease and pest control

Nanotechnology and nanostructured products may have a big impact on the delivery systems for herbicides and pesticides. Chemical science has developed hugely effective control methods for most common agricultural pests. These solutions, however, bring problems associated with persistence of toxic compounds in the environment, incorrect dosing and the need to reapply product several times over a season. By targeting and controlling the release of these compounds, the amount of material needed to be effective can be reduced, leading to a reduction in environmental damage and also a possible reduction in costs. Also, newer, less persistent, less toxic and more specific herbicides and pesticides are being developed to reduce the impact of controlling pests on the wider environment.[f] Under certain circumstances, these compounds need to be directed more effectively towards their intended target. Nanotechnology may provide a key to enabling effective delivery of these chemicals.

Micro- and nano-emulsions are being actively developed by a number of research groups for use in drug delivery and (relevant to the agriculture sector) pesticides and herbicides. These emulsions are being used to carry oil-soluble pesticides into water-rich environments. These are more easily absorbed into the plant's structure, thus providing greater protection from the targeted pest.[g]

Another approach to improving efficacy whilst reducing the release of toxic material into the environment is to encapsulate the active agent within a nanocapsule. A nanocapsule is a nanoscale shell that can be filled with a therapeutic chemical. Upon triggering by a predetermined factor (such as time, temperature or moisture), the nanocapsule breaks open, releasing the active agent. The system can also be used to protect the active

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[a] *See for example, www.ranchsystems.com or www.xbow.com*

[b] *Nanoforum report: Nanotechnology in Agriculture and food, May 2006*

[c] *Iowa State University (2008, October 27). Wireless Soil Sensors Designed To Improve Farming. ScienceDaily. Retrieved June 4, 2010, from http://www.sciencedaily.com /releases/2008/10/081010135039.htm*

[d] *http://office-software.suite101.com/article.cfm/benefits_of_precision_farming_technology*

[e] *www.putyourfarmonthemap.com*

[f] *Nanotechnology Developments for the Agrifood Sector - Report of the ObservatoryNANO. May 2009*

[g] *ObservatoryNANO: Report on Nanotechnology in the Technology Sector Environment, 2009*

agent against damage from the environment, reducing the need for re-application and therefore reducing costs and environmental over-exposure.

Monsanto, Syngenta and BASF are developing pesticides enclosed in nanocapsules or made up of nanoparticles. Although still at an early stage, a nano-enabled product is reportedly available; however, information on this product appears to have been removed from Syngenta's website.[a] The market for pesticides is worth £388m annually in the UK, representing a large market for these technologies.[b]

1.7 Food production

1.7.1 Food packaging

One key parameter to the effectiveness of packaging is its gas permeability. The more air-tight the packaging, the longer the foodstuff will remain fresh. This extends the shelf-life of the product and reduces losses associated with exceeding its 'use by' date. The use of nanoclay particles as a filler is a commercial technology for enhancing the performance of packaging. These materials act as a barrier which inherently resists a permeating material (gas, water or oil). Also, the incorporation of this 'filler' material reduces the amount of plastic needed.[c] These systems are being commercialised by several companies and are being used in a range of products.

Several different processes have been developed and commercialised to incorporate nanoclays into plastic packaging or as a laminar film to coat the plastic. To give an example, data are available from Nanocor on their product Imperm®. PET bottles coated with Imperm® have a CO_2 shelf-life approximately three times longer than that of standard PET. Oxygen ingress with Imperm® is nine times slower than that with PET.

This product is designed to increase shelf-life and therefore decrease spoilage, losses from which can be substantial. In the UK an estimated 365,600 tonnes of food are wasted within distribution/retail, which equates to £611m of lost profit. Additionally 2.9m tonnes of food are wasted in households because it is 'not used in time', with an estimated value of £6,566m.[d]

1.7.2 Paper and card packaging

The increased focus on recycling and sustainable packaging is driving the trend for water-based barrier coatings for paper and board food packaging to replace fluorocarbon and extruded polymer barrier coatings. For example, the US plans to ban fluorocarbons (Teflon) in packaging by 2015, and plastic coated cardboard packaging is difficult to recycle.

Nanoplates of alumino-silicate clays, when incorporated with the appropriate polymer, can provide effective barrier performance against water, gases and grease. It is claimed that these clays improve the barrier performance beyond that of typical latex coatings. These coatings can be applied using existing paper and board coating equipment including size press, blade and curtain coaters, thereby minimising the cost to enter the market. This system is being marketed by Imerys as Barrisurf.

Even though there are benefits in the technology, there is a reluctance to shift away from the incumbent technology due to other cost implications. Therefore, the take-up of this technology may only become significant when the US ban on Teflon packaging is introduced in the next few years.

1.7.3 Food modification

Nanoparticles are being used to deliver vitamins or other nutrients in food and beverages without affecting the taste or appearance. These nanoparticles encapsulate the nutrients and carry them through the stomach into the bloodstream. For many vitamins this delivery method also allows a higher percentage of the nutrients to be used by the body because, when not encapsulated by the nanoparticles, some nutrients would be lost in the stomach. Although there are clear applications for these systems in developed markets, there are also

[a] *http://www.foodfirst.org/en/node/2862*
[b] *UK Pesticides Strategy: A Strategy for the Sustainable Use of Plant Protection Products, Defra, 2006*
[c] *http://www.imerys-paper.com/products/kaolin/barrisurf.html*
[d] *"Waste arisings in the supply of food and drink to households in the UK", Oakdene Hollins for WRAP 2010*

applications for delivery of nutrients during famine relief.[a]

Nanomaterials are being developed to improve the taste, colour, and texture of foods. For example Unilever/Nestlé are undertaking research on spreads and ice creams with nanoparticle emulsions to improve texture.[b]

The future of this research is not yet certain: recent public anger over genetically modified food may be mirrored with nanotechnology incorporated into food. Development is still at a relatively early stage and new products maybe subject to regulatory requirements. Clearly, the size of the market is substantial; the grocery sector in the UK is worth £146bn[c] and even a small percentage gain in this area could result in a large turnover.

1.7.4 Sensors

Gas sensors provide a technology for rapid quality assessment of food, either during production, at the retailer or in the home environment. Indicators for quality, e.g. in connection with fish spoilage (volatile amines), fruit ripening (ethene) and wine production (alcohols) are often gases or vapours that can be detected using sensors. The development of low cost detectors and a visual indicator (such as a dye changing colour) could be used to provide information on the optimum time to consume a product. However, successful application requires knowledge of the complex mixture of components likely to be present in the gas phase, and this knowledge still requires both academic and industrial research and is still in the early stages.[d] Within this area, BASF, Kraft and others are developing new nanomaterials that extend food shelf-life and signal when a food spoils by changing colour.

One of the most promising indicators is the development of a commercial colour-indicator for Modified Atmosphere Packaging (MAP). These systems keep food fresh by packing it under an inert atmosphere. There are examples of indicators available but these are generally too expensive for incorporating into food packaging in supermarkets. Nanoparticle-enabled dyes are being developed that change colour in the presence of oxygen for incorporation into MAP food packaging systems. The functional ink changes colour in the presence of oxygen, alerting a user to the fact that the packaging has failed, and therefore the food has spoiled.[e]

Controlling the presence of food pathogens is a primary driver for sensors in commercial and industrial food preparation environments. Nanosensors could work through a variety of methods, such as by the use of nanoparticles tailor-made to fluoresce different colours, or be made from magnetic materials and selectively attach themselves to food pathogens. Handheld sensors employing either infrared light or magnetic materials could then note the presence of even minuscule traces of harmful pathogens. These systems could rapidly detect the presence of a number of different bacteria and pathogens at an acceptable cost.[f]

The development of sensor technologies ranges from early stage primary R&D through to some limited demonstration trials. In the UK, the Universities of Southampton and Strathclyde are developing food packaging sensors. It has been reported that the overall food-pathogen testing market was $192m (34 million tests) in 2005 in the USA.[g] Clearly any breakthroughs in nanotechnology in this area would result in a significant market for these products.

1.8 Marine

1.8.1 Antifouling paint

Antifouling paints are used on the hulls of ships to reduce the build up of organisms which increase friction caused when the ship moves through the water. The friction caused by these organisms leads to a significant reduction in fuel efficiency. Traditionally, biocides have been used to combat the problem, however, these have been made using toxic metal salts, which

[a] *Nanotechnology White Paper, EPA 100/B-07/001, February 2007*
[b] *Small size that matters: Opportunities and risks of nanotechnology, Report in cooperation with the OECD futures programme, OECD and Allianz, 2005*
[c] *www.igd.com*
[d] *MNT Gas sensors roadmap, 2006*
[e] *http://www.nanowerk.com/spotlight/spotid=4104.php*
[f] *Small size that matters: Opportunities and risks of nanotechnology, Report in cooperation with the OECD futures programme, OECD and Allianz, 2005*
[g] *"Market analysis of biosensors for food safety." Biosens Bioelectron. 2003 May;18(5-6):841-6*

have led to problems of bio-accumulation and destruction of biodiversity within the marine environment. This has been particularly acute in marinas and ports where a high concentration of vessels and relatively slow moving water has resulted in dangerous levels of pollution in the harbour mud.[a]

An alternative type of antifouling paint uses surface interactions to form either a non-stick layer or a surface which is 'ambiguous' to micro-organisms. These are known as foul release paints. The incumbent technology, however, is only effective with deep sea vessels that are constantly moving, which helps remove the organisms nanotechnology may help mitigate this problem. These paints are therefore ineffective on pleasure craft that spend the majority of their time moored up in harbours.

A European FrameWork7 programme has recently been completed that set out to examine nanotechnology-enabled paints to improve the efficacy of foul release paints. Research into this area is currently on-going. There are no commercially available nano-enabled products yet available and any likely breakthrough will take at least five years to achieve.[b] International Paints is the leader in this field. There are reports of alternative products that are currently available that perform a similar function using 'lotus effect' interactions with water.[c] Approximately 64m litres of antifouling paint are used each year, equating to an industry worth nearly €1bn.[d]

1.9 Soil

The use of nanotechnology and its impact on soil is largely discussed within the context of its use in agriculture (Section 1.6). Within soils specifically, the remediation of contaminated land is a promising application for nanotechnology. A large number of land contaminants are water- or liquid-based and therefore some of the applications described in Section 1.11 are also relevant to soil remediation. Major targets are the removal of pollutants from land used for industry, including heavy metals, halogenated organic compounds and solvents. The large array of chemistries involved with these compounds mean that a single solution is unlikely to deliver the needed remediation and that a suite of solutions will be necessary.

1.9.1 Nano-zero-valent iron

Zero-valent iron nanoparticles (nZVI) technology is becoming an increasingly popular choice for the treatment of hazardous and toxic wastes, and for remediation of contaminated sites. Nanoparticles of iron can be injected into contaminated soil. nZVI particles rapidly transform many environmental contaminants into benign products. Their nanoscale size and increased reactivity enables them to be more effective than granular zero-valent iron that is already in use for contaminant remediation in soil and groundwater aquifers.[e] nZVI particles have surface areas that are up to 30 times greater and is 10 to 1,000 times more reactive than larger size powders or granular iron. Due to its large reactive surface area, nZVI promises to be more effective than granular iron, with reaction rates 25-30 times faster and a much higher sorption capacity.

nZVI has been demonstrated to effectively reduce chlorinated organic contaminants and also inorganic material (perchlorate). It can even be used to recover or remove dissolved metals from solution.[fg]

The advantages of nZVI may be summarized as follows:

- fast reaction
- short treatment time (less cost)
- less exposure for workers, fauna and flora
- complete reduction pathway to non-toxic end products is possible
- *in situ* treatment
- less equipment and fewer above-ground structures required, hence lower cost.

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[a] Organotin antifouling paints, EPA information bulletin, June 2000
[b] http://www.ambio.bham.ac.uk/
[c] http://en.percenta.com/
[d] Presentation: Introduction and challenges, RK, Safinah, Materials KTN conference: Cleaning up Antifouling, 29 April 2010

[e] Cook SM, Assessing the Use and Application of Zero-Valent Iron Nanoparticle Technology for Remediation at Contaminated Sites, Report prepared for US EPA, 2009.
[f] ObservatoryNANO, Report on Nano zero-valent iron – THE solution for water and soil remediation?, 2010.
[g] Observatory Nano, Report on Nanotechnology in the Technology Sector: Environment, 2009

Outside the USA, there appears to be a significant concentration of companies using nZVI in the Czech Republic, Germany and Italy. NASA has patented and licensed a technology to several companies, but these are almost exclusively based in the USA.

In Europe an estimated 20,000 sites need to be remediated, and another 350,000 potentially contaminated sites have been identified by the European Environment Agency.[a]

1.9.2 Other nanoparticles

Calcium peroxide has been trialled as a method for removing different organic contaminants such as petrol, heating oil, MBTE ethylene glycol and solvents. The product, marketed by Continental Remediation, is claimed to be more effective than incumbent technologies.[b]

Research from Pacific North Western National Laboratory resulted in the development of a variety of nanomaterials for potential use to adsorb or destroy contaminants as part of either *in situ* or *ex situ* processes. This resulted in the commercialisation of SAMMS, which are particles consisting of a nanoporous ceramic sponge coated with a chemical which absorbs target contaminants. Initial testing of the product was for the remediation of land contaminated with mercury, but (depending on the coating) contaminants including chromate, arsenate, and selenite can be selectively removed.[c]

These products are currently being marketed and have demonstrable small scale trials. They are, however, in the early stages of their commercialisation cycle.

1.9.3 Dendrimers/chelation ligands

The use of large molecules for the removal of heavy metal toxins from soils has been investigated. Dendrimers are branched, well-organized molecules that can have their chemical properties tuned to capture different contaminates. There are reports of dendrimer precursors being used for the remediation of lead from soil. Up to 85% of the target contaminant (lead) was recovered and the dendrimer, in theory, could be reused.[d]
Metallo-porphyrinogens are complexes of metals with naturally occurring organic molecules. Experiments have shown that these compounds are capable of remediating soil contaminated with chlorinated hydrocarbons.[e]

At present these applications of nanotechnology appear to be limited to laboratory scale investigations. Future research into this area will be needed in order to assess the applicability of these technologies to the area of remediation.

1.10 Sustainable consumption and production

1.10.1 Catalysis

Catalysts enable the transformation of one chemical into another, using less energy, generating fewer by-products (waste) and potentially using less harmful chemicals. The development of new catalysts can therefore limit the environmental impact of chemical production. Due to the scale of the activity in this area, it is not possible to categorise all the catalytic research activities that incorporate an aspect of nanotechnology. The entire field of metal-based heterogeneous catalysis will involve, at some level, the use of nanotechnology.[f,g] This is the case because, in general, smaller sized particles are more reactive and therefore result in more efficient catalysts (both in terms of resources and efficacy). As the particle size is reduced, the activity and selectivity of the catalyst can alter, providing new ways to produce chemicals. The nanoscale structure of the catalyst surface is also important to the catalytic process.[h] These factors mean that nanotechnology is a vital tool in the development of new heterogeneous catalysts. Below, three applications are described demonstrating how nanotechnology is influencing this area of manufacture.

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[a] *ObservatoryNANO focus report Nano zero valent iron – THE solution for water and soil remediation?, 2010*
[b] *http://www.continentalremediation.com/*
[c] *White paper: SAMMS technical summary, accessed from http://sammsadsorbents.com*
[d] *ObservatoryNano: Report on Nanotechnology in the Technology Sector Environment, 2009*
e Nanotechnology for Site Remediation Fact Sheet, 2008, EPA
[f] *Nanotechnology in catalysis Volume 3, 2007*
[g] *Catalysts and electrocatalysts at nanoparticle surfaces, 2003*
[h] *Heterogeneous Catalysis: Principles and Applications, G. C. Bond, 1987*

Production of hydrogen peroxide using nano-enabled catalysts[a]

Hydrogen peroxide (H_2O_2) is a substitute for environmentally harmful chlorinated oxidants in many manufacturing operations. However, the current manufacturing process for H_2O_2 is complex, high cost, and energy-intensive. Headwaters Technology Innovation has produced a robust palladium-platinum nanocatalyst that enables the synthesis of H_2O_2 directly from hydrogen and oxygen.

Enhanced performance of ruthenium catalysts[b]

Ruthenium catalysts are widely used for hydrogenation in the chemical, petrochemical, food and pharmaceutical industries. Nanotechnology is used to embed catalyst nanoparticles into pore walls of a solid support instead of dispersing them on the surface, which provides added stability to the catalyst. This enhances the physical and chemical properties of the catalyst.

A new catalyst for steam reforming[c]

Steam reforming of methane is the main industrial process for producing hydrogen and carbon monoxide. Currently the process uses a nickel catalyst, which has the problem that, when in use, carbon is deposited on the surface which reduces the activity of the catalyst. This by-product is an indication that the catalyst is not performing optimally. By examining fundamental properties on the nanoscale, a new catalyst system was developed that, although less active, limited the build-up of carbon. Although nanotechnology is not used in the production of the catalyst, nor is the catalyst designed on the nanoscale, the fundamental understanding of the catalysis on the nanoscale led to a more effective product.

It is difficult to estimate the impact nanotechnology has had on this sector. From one perspective, nanotechnology has been used to improve the efficiency of catalysts for at least 20 years. More recently however, the advent of advanced imaging technologies has enabled more targeted design approaches that have incorporated nanotechnology. Most chemical companies working in heterogeneous catalysis will be engaged in nanotechnology. UK examples include Johnson Matthey and BP, and the UK has several centres of academic excellence for catalytic chemistry including York, Cardiff and Cambridge.

1.10.2 Construction

Nanotechnology may affect many materials used in construction.[d,e]

Concrete

A large amount of research effort is being directed at applying nanotechnology to cement and concrete manufacture.[f] The addition of nanoparticles has been shown to result in stronger, more durable, self-healing, air purifying, fire resistant, easy to clean and quick-compacting concrete. There are reports of various companies and research organisations adding nano-silica, nanostructured metals, carbon nanotubes and carbon nanofibres to concrete, resulting in beneficial properties. Although there are commercially available nano-enhanced concretes, their application is, so far, limited (largely due to cost constraints). These products are being commercialised by Italcementi, Heidelberg Cement, Lafarge, Clariant, Nanogate AG and BASF.

Cement production is the largest single product, by weight, made through human production. It also accounts for a significant proportion of greenhouse gas emissions.[g] Any enhancement in performance or reduction in impact would have a significant effect.

Ceramics

Nano-enhanced construction ceramics, which include floor- and wall-tiles, counter-top ceramics and sanitary ware products, have found a place on the market with self-cleaning, anti-bacterial, hygienic and scratch resistant features. In Europe companies such as Duravit, Roca, Erlus, and Villeroy and Boch have

[a] *Pollution Prevention, through Nanotechnology Conference, September 25-26, 2007*
[b] *http://www.nanowerk.com/spotlight/spotid=2680.php*
[c] *"Applications of nanotechnology: catalysis", iNano for the NANOCAP project).*
[d] *Nanotechnology in construction 3, Proceedings from NICOM3, 2009*
[e] *ObservatoryNano: Economical Assessment / Construction sector Final report, June 2009*
[f] *"Nanoengineering Materials for Pollution Prevention: Concrete and Reduced CO2 Emissions" Conference proceedings: Pollution Prevention through Nanotechnology, September 25-26, 2007, Arlington, VA*
[g] *www.cementindustry.co.uk*

developed products in this market. Market penetration is relatively modest because the price of these products is significantly higher that the corresponding incumbent technology.

Windows/glass

Thin film technology has been developed to reduce loss of heat through windows. Light- and heat-reactive nanoparticles and thin films are being developed to coat glass. These coatings react to the strength of sunlight reflecting more heat on hot days and so can help to reduce air conditioning use. For marketing purposes, these windows are commonly called ‘smart windows’ which implies that they are multifunctional through their energy saving, easy cleaning, UV controlling and photovoltaic features. Pilkington and Saint Gobain are market leaders in this area.

Steel[a]

Fatigue is a significant issue that can lead to the structural failure of steel. ‘Stress risers’ are responsible for initiating cracks from which fatigue failure results and research has shown that the addition of copper nanoparticles reduces the surface unevenness of steel which then limits the number of stress risers and hence fatigue cracking. Research work on vanadium and molybdenum nanoparticles has shown that they improve the delayed fracture problems associated with high strength bolts.

1.10.3 Energy saving products

Insulation[b]

Water- and space-heating are responsible for approximately 80% of all energy use in the home. Properly installed heating insulation could significantly reduce the energy loss from homes. Most insulation uses entrapped air to prevent convection of heat. This is achieved using highly porous low heat conducting materials.

Several different avenues of research are being explored to develop nanomaterial based insulation. Aerogels (silica matrices which are 99% air) are highly thermally insulating. Although cost is the overriding barrier to commercial use as insulators, steady development in this field may yet develop a product which is cost competitive. Development of transparent aerogels is proceeding so they can be incorporated into glass to thermally insulate windows. Nanoporous foams are being developed to improve insulation properties for inclusion into cavity walls.

BASF, Aspen Aerogels and Cabot Corporation are companies that have products on the market.

Light emitting diodes (LEDs) and organic light emitting diodes (OLEDs)[c]

Domestic and commercial lighting accounts for around 20% of the UK’s electricity consumption. Unlike incandescent light bulbs which use electricity to generate heat through resistivity, LEDs convert electricity directly into light which is considerably (up to ten times) more efficient. In fact, LEDs are approximately twice as efficient as the ‘energy saving’ compact fluorescent lamp (CFL) light bulbs currently on the market. Until recently, LEDs produced light which was either red, yellow or green, which made wide scale use as the main light source in homes and businesses non-viable. However, recent advances have produced commercially viable ‘white light’ LEDs, which are beginning to appear on the market.

LEDs comprise two inorganic semiconductors sandwiched together. Recently, LEDs comprising polymer or organic molecules have been developed. It is expected that these organic light emitting diodes (OLEDs) will become significantly easier and cheaper to produce than the corresponding inorganic LEDs.

Several different strategies using nano-technology are being developed to improve the luminescence of the LEDs. Reductions in size and defects of the crystals used in LEDs are leading to higher light output for smaller quantities of material. Several nanoscale phosphorescent coatings are being developed to improve the quality of the white light generated. These include Quantum Dots (QDs), which are nano-crystals that can be tuned to emit light of any desired colour. Lithography

[a] *Nanoforum report: Nanotechnology and Construction, November 2006*

[b] *Environmentally beneficial nanotechnologies, Defra, 2007*

[c] *ibid*

techniques are also being developed to improve the efficiency of the LEDs.

OLEDs use nanoscale layers of semi-conducting polymers. This requires advanced nano-processing techniques such as chemical deposition and inkjet printing. Advances in this area will lower production costs of these devices. The lifetime of current blue OLEDs is preventing large scale use although there are current applications for use in small displays. One of the leading companies in this field is Nanoco, a UK-based spinout from the University of Manchester,[a] which has developed QDs that are free from hazardous heavy metals and is currently exploiting the technology, with multinational partners, in both LED and OLED devices.

1.10.4 Batteries[b]

In a lithium ion (Li-ion) battery, the recharge and discharge rates are limited by the rate of adsorption and desorption of lithium from the anode and cathode of the battery. An increase in surface area of the electrode will allow more lithium to absorb faster onto the surface of the electrode. Also, in theory, these systems can store greater charges because there is a larger surface area for the lithium to react with. Research on batteries involving nanotechnology is focused on developing nanostructured electrodes which provide a high surface area, are low cost, easy to produce and stable (to avoid reduction in battery performance over its lifetime). This research is being driven by the need to develop higher power, higher charge density batteries for use in portable electronic devices, but more importantly for use in the development of the electric vehicle.

In the USA, Altairnano have replaced the carbon graphite electrode of a standard Li-ion battery with a nanostructured lithium titanate spinel oxide (LTO) electrode. These electrodes are claimed to have a surface area 100 times higher than the standard graphite electrode, speeding the recharge and discharge rate of the battery. Qinetiq are collaborating with several major battery and automotive manufacturers to develop new batteries. The research is industrially sensitive but does involve using nanostructures to improve battery performance. Researchers at the University of St Andrews are developing nanostructured materials which are able to hold more lithium than standard Li-ion battery electrodes. The development of these materials is likely to result in batteries with higher charge density.

Currently the number of hybrid and electrics vehicles using lithium is very low. It is expected though that this number will increase dramatically to 0.38 million in 2015 and 1.26 million by 2020. This is new demand that could be met by nano-enabled batteries.[c]

1.10.5 Lightweighting[d]

A lighter vehicle and cargo results in higher transport fuel efficiency. The development of lightweight nanocomposite materials which are as strong as conventional materials but lighter and thinner could significantly reduce the amount of fuel required for a specific function. These materials could also be used to reduce packaging weight which may reduce fuel consumption.

Near-term developments with nanopowders are producing metals with enhanced physical properties such as improved strength, elasticity and ductility, which allow manufacturers to use less material but provide similar performance.

Metal matrix composites incorporate nanorods or particles into a bulk material. Similar to steel reinforcing concrete or carbon fibre, nanomaterials are incorporated into plastics or metal. This increases the strength and flexibility of the composite materials. These materials are being incorporated into high value goods such as golf clubs but, as the technology and costs improve, these materials are likely also to be incorporated into automotive and aerospace sectors.

The incorporation of nanoclays into polymers can significantly increase their strength and durability. Such materials could reduce packaging weight which, in turn, will reduce transportation energy costs of goods.

a http://www.nanocogroup.com/content/Library/NewsandEvents/articles/Nanoco_Signs_Agreement_with_Major_Japanese_Electronics_Company/136.aspx

b Environmentally beneficial nanotechnologies, Defra, 2007

c Abicenne, Minor metals conference, London, 2010

d Environmentally beneficial nanotechnologies, Defra, 2007

1.10.6 Flame retardants

Over the last century, artificial plastics and rubbers have revolutionised our use of materials. One unfavourable property of these materials is their inherent flammability. To mitigate this, various flame retardants have been added to plastics. Unfortunately, the most common flame retardants are highly brominated and have issues of toxicity and environmental persistency.[a] Nanoclays, similar materials to those being marketed as impermeable gas barriers, are being used as alternatives without the known negative toxicological/ecotoxicological impacts of traditional flame retardants. Nanoclays have been used as plastic flame retardant additives for several years. They do not at present appear to be able to completely replace traditional flame retardants, and are used in a synergistic manner.[b] The unique nature of nanoclay reduces the burning rate of plastics; it also enhances the char-forming and anti-dripping properties of the burning plastics.[c]

There are concerns that need to be addressed to ensure that the incorporation of nanoclays into plastics does not result in the replacement of one toxic compound with another.

Within Western Europe, approximately 500,000 tonnes of flame retardants are consumed.[d] Companies marketing gas impermeable membranes for packaging applications are selling virtually identical formulas for flame retardancy. In addition, the UK has expertise in several academic institutions including the University of Sheffield, UCLAN and the University of Bolton.

1.11 Water

Conventional water-treatment technologies include filtration, ultraviolet radiation, chemical treatment and desalination; whereas the nano-enabled technologies include a variety of different types of membranes and filters based on carbon nanotubes, nanoporous ceramics, magnetic nanoparticles and other nano-materials.

There are projections that applications of nanotechnology products in water and wastewater worldwide will reach $1.6 billion in 2007 and $6.6 billion by 2015. Filtration was the dominating application in 2007 (43%) but desalination and irrigation are expected to be more important by 2015. Nanotechnologies will help to reduce the desalination process costs and reduce the water use in irrigation. One of the fastest growing market segments is disinfection, with broad applications and benefits. It is expected that China will become a technology leader in this area, joining countries like USA, Germany and Japan.[e] Companies actively marketing these technologies include: Catalyix, NanoH2O, Seldon and NanoChem.

1.11.1 Nanotechnology for wastewater treatment

Some of the problematic substances in wastewater include organic matter (POPs), oestrogenic activity and nitrates, while industrial wastewater may contain heavy loads of metals or dyes.[f]

Depending on the target compounds, there are several methods that can be employed to tackle this issue such as:-

Photocatalysis

As with air pollutants, sunlight can be used to breakdown toxic chemicals. In water, typically this method employs the use of nanoscale TiO_2 or ZnO, it can be used to target POPs, metal ions, formic acid, estrogenic activity, pesticides and dyes. For example, TiO_2 is an effective method for the degradation of pollutants in water and for water disinfection.

Nanofiltration

Typically, this method uses ceramic membranes, nanowire membranes and polymer membranes amongst others to target metals, anions, viruses/bacteria, organic material and dyes. For example, the Indian Institute of Technology (IIT) has developed a nanocomposite adsorbent which is capable of removing dye molecules and

[a] *Flame Retardant Technologies: safe products with optimised environmental performance, Defra, February 2010*
[b] *Flame retardant polymer Nanocomposites, AB Morgan CA Wilke, 2007*
[c] *www.nanoclay.com*
[d] *European Flame Retardants Association*
[e] *http://www.hkc22.com/nanowater.html*
[f] *Observatory Nano, Report on Nanotechnology in the Technology Sector: Environment, 2009*

odours from factory wastewater, making it suitable for industrial or agricultural use.[a] Carbon nanotube membranes have the advantage that only water molecules can pass along their interior while viruses, bacteria, toxic metal ions and other organic molecules are separated.[b]

Adsorption
Analogous to a sponge, nanoscale metals and metal oxides can be used for the adsorbance of metals. They can be used to target metals, radionuclides and arsenic. For example, cadmium ions were removed from simulated industrial wastewater using nanoparticles of silica and alumina. The results show that it is possible to reduce the cadmium concentration from 140 ppm to less than 5 ppb.[f]

Electrochemical oxidation
Nanostructured boron doped diamond (BDD) can be used to target both organic and inorganic contaminants in water. For example, BDD can effectively oxidize pollutants in wastewater regardless of water turbidity, and up to five times faster than conventional chlorine dosing.[f]

1.11.2 Nanotechnology for the treatment of drinking water

The challenges for drinking water production are very diverse with different nanotechnological approaches. For example, in developing countries microbes are the major challenges, whereas desalination of seawater is discussed in industrialized regions with water scarcity. In some countries, contamination with arsenic is an issue.[f]

Nano-enabled technologies for water treatment are already on the market with nanofiltration currently being the most mature technology. Nanofiltration membranes are already widely applied to remove dissolved salts and micro-pollutants, soften water and treat wastewater. These membranes act as a sieve, capturing particles and micro-organisms bigger than their pores, and selectively rejecting substances. Nanotechnology is expected to further improve membrane technology and also drive down the prohibitively high costs of desalination.[c]

A team of Indian and US scientists has developed carbon nanotube filters that remove bacteria and viruses more effectively than conventional membrane filters.[d] Separation membranes with structure at the nanoscale can also be used in low-cost methods to produce potable water. For example in South Africa, several polymeric nanofiltration and reverse osmosis membranes were shown to produce potable water from brackish groundwater.[e]

Zeolites (structured aluminosilicate compounds) have been demonstrated to separate harmful organics from water and to remove heavy metal ions. Researchers in Australia have reported a low-cost synthetic clay, hydrotalcite, that attracts arsenic, removing it from water.[f] They have suggested an innovative packaging for this product for low-income communities — a 'teabag' that can be dipped into household water supplies for about 15 minutes before drinking.

Nanocatalysts and magnetic nanoparticles can transform heavily polluted water fit for drinking, sanitation and irrigation. They can be used to bind with contaminants such as arsenic or oil and then be removed using a magnet.[g] Rice University has developed magnetic iron oxide particles that are capable of removing arsenic from drinking water.[h]

1.11.3 Sensors

As well as treating water, nanotechnology can also detect water-borne contaminants. Researchers are developing new sensor

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[a] *http://cleantech.com/news/4271/iit-uses-nanotech-cheap-textile-was*

[b] *http://cleantech.com/news/3436/indian-water-purification-goes-nano*

[c] *David Grimshaw, Nanotechnology for clean water: Facts and figures, http://www.scidev.net/en/features/nanotechnology-for-clean-water-facts-and-figures.html*

[d] *Efficient Filters Produced From Carbon Nanotubes Through Rensselaer Polytechnic Institute-Banaras Hindu University Collaborative Research, http://news.rpi.edu/update.do?artcenterkey=435*

[e] *Hillie, T et al. Nanotechnology and the challenge of clean water, Nature Nanotechnology 2, 663 - 664 (2007)*

[f] *Gillman, G.P. A simple technology for arsenic removal from drinking water using hydrotalcite. Science of the Total Environment 336 (2006)*

[g] *Hillie, T et al. Nanotechnology and the challenge of clean water, Nature Nanotechnology 2, 663 - 664 (2007)*

[h] *Yavuz, CT et al. Low-Field Magnetic Separation of Monodisperse Fe3O4 Nanocrystals, Science 10 November 2006, Vol. 314. no. 5801, pp. 964 – 967.*

technologies that combine micro- and nano-fabrication to create small, portable and highly accurate sensors that can detect chemical and biochemical substances in water. For example, a team at Pennsylvania State University has developed a way of detecting arsenic in water by using nanowires on a silicon chip.[a] NanoSelect has developed a sensor based on carbon nanotubes to monitor the quality and safety of the local municipal water supply systems.[b]

1.11.4 Nanotechnologies for water remediation

Groundwater is the main source for drinking water in many parts of Europe. It is therefore important to ensure clean groundwater. Polluted groundwater may also affect the soil ecosystem and/or other water compartments such as lakes and rivers.

Groundwater sources are typically contaminated with pesticides and sometimes with heavy metals or halogenated compounds. It has also been reported that nitrate concentrations in groundwater are increasing and are often close to, or above, safety limits. Landfill leakage, agriculture and chemical accidents are the main sources of groundwater pollutants.[f]

Depending on the target compounds, there are several methods that can be employed to tackle this issue such as:-

Redox-reaction/adsorbtion

Nanoscale zero valent iron (nZVI) has been proven to be effective for the degradation of halogenated solvents, nitrates, dissolved metals, pesticides and dyes.[f] Iron oxide minerals can also be used to remove heavy metals and arsenic contaminants. The increased surface area of minerals through nanostructuring results in a greater take up of pollutants. (This was discussed in more depth under Section 1.9.1.)

Nanofiltration

Nanofiltration has been demonstrated to remove pesticides, 'hardness' and nitrates. It was shown that pesticide rejections and removal of hardness are effective, whereas only a small fraction of nitrate is removed by most membranes.[c]

Photocatalysis

Typically TiO_2 nanoparticles have been employed to effectively remove pollutants such as pertechnetate anions from groundwater.

[a] *Patel, P. Nanosensors made easy. Technology Review (2009)*
[b] *http://www.nanoselect-sensors.com/index.htm*

[c] *Van der Bruggen, B. et al. Application of nanofiltration for removal of pesticides, nitrate and hardness from ground water: rejection properties and economic evaluation, Journal of Membrane Science, 193, pp 239-248*

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