PRIME MINISTER'S SCIENCE, ENGINEERING AND INNOVATION COUNCIL

FOURTH MEETING - 26 NOVEMBER 1999

AGENDA ITEM 4

NANOTECHNOLOGY – THE TECHNOLOGY OF THE 21ST CENTURY: The Economic Impact of Emerging Nanometre Scale Technologies[1].

1 nanometre = 10^{-9} metre or 1 billionth of a metre

Nanotechnology is the ultimate in engineering precision and control, and is engineering at the scale of atoms and molecules.

EXECUTIVE SUMMARY

Nanotechnology represents a new frontier in science and technology with long term goals and benefits. Nanotechnology alters the way we think. It requires a *bottom up approach*, where working devices and materials are constructed by the precise manipulation and assembly of atoms and molecules and not by the machining of bulk materials.

Nanotechnology is a ubiquitous technology with a potential to impact on every aspect of science, technology and education. Nanotechnology is producing many revolutionary, applications such as: quantum computing, surface and materials modification, novel separations and sensing technologies, and human biomedical replacements. Interfacing materials with biology is widely believed to be the exciting new frontier for nanotechnology.

The importance of nanotechnology is evident from the interest shown by governments around the world. Many major studies have been undertaken on the impact of nanotechnology on the world's economy. Although the development of nanotechnology worldwide is still at a very early stage, there is sufficient evidence to indicate that Australia is well placed relative to other more advanced countries. In fact, Australia leads the world in a number of areas.

The development and commercialisation infrastructure essential for nanometre scale technologies is however, absent in Australia. A key requirement for Australia is to develop a national nanotechnology toolbox of facilities and expertise to address this lack of infrastructure.

CSIRO is an example of an organisation that could form the backbone of the national nanotechnology toolbox as it already has many of the necessary capabilities. Key Research Centres would provide a particular emphasis for some centres. Project-based government

[1] Prepared by Dr Bruce Cornell, Senior Vice President and Chief Scientist, AMBRI Pty Ltd, Chatswood NSW and Dr Leong Mar, Business Development Manager, National Nanofabrication Facility, Chatswood NSW.

programs such as the Cooperative Research Centres scheme could easily be used to facilitate the process.

Australia needs a national strategy to ensure that the development of nanotechnology is coordinated and focused to bring about the maximum benefits. As a first step in this process it is proposed that an international workshop on nanotechnology be held in August 2000.

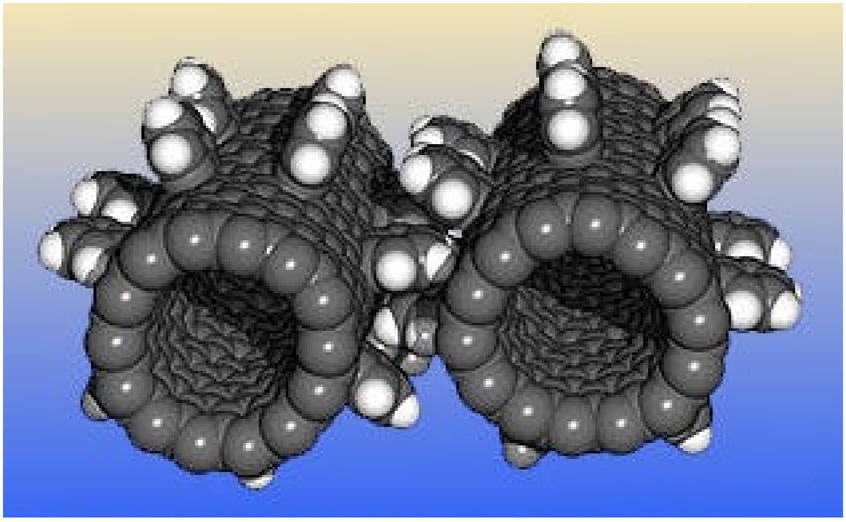
1. Introduction - Nanotechnology: The Technology of the 21st Century

Nanotechnology is the ultimate in engineering precision and control, and is engineering at the scale of atoms and molecules.

In his address to the United States Congress (June 1999) on nanotechnology, 1996 Nobel Laureate Richard E Smalley said:

> *There is a growing sense in the scientific and technical community that we are about to enter a golden new era. We are about to be able to build things that work on the smallest possible length scales, atom by atom with the ultimate level of finesse.*
>
> *The resultant technology of our 20th century is fantastic, but it pales in comparison when we learn to build things at the ultimate level of control, one atom at a time.*

Technical sophistication is the best indicator of a society's wealth and potential for growth. Silicon chip technology, information technology, biotechnology and genetic manipulation have all stimulated wealth creation in their time. However, these advances could well be dwarfed by the impact and generality of nanotechnology.



Molecular nano gears approximately five nanometres (nm) in diametre and comprising teeth of aligned benzene groups on a carbon nanotube shaft. (NASA Ames Research

Nanotechnology ignores the boundaries between physics, chemistry and biology. These traditional disciplines blur to become the fundamental skill set of nanotechnology. The elimination of these boundaries will pose many challenges and new directions for the organisation of education and research.

If our small minds, for some convenience, divide this universe into parts, physics, biology, geology, astronomy, psychology and so on – remember that nature does not know it! (Richard Feynman)[2]

Nanotechnology alters the way we think. It requires a *bottom up approach*, where working devices and materials are constructed by the precise manipulation and assembly of atoms and molecules and not by the machining of bulk materials. Whether it is in a future industry or in an existing market, nanotechnology will generate new dimensions of unexploited value and will span all society.

2. What is Nanotechnology?

1 nanometre = 10^{-9} metre or 1 billionth of a metre (from *nanos*, Greek for dwarf)

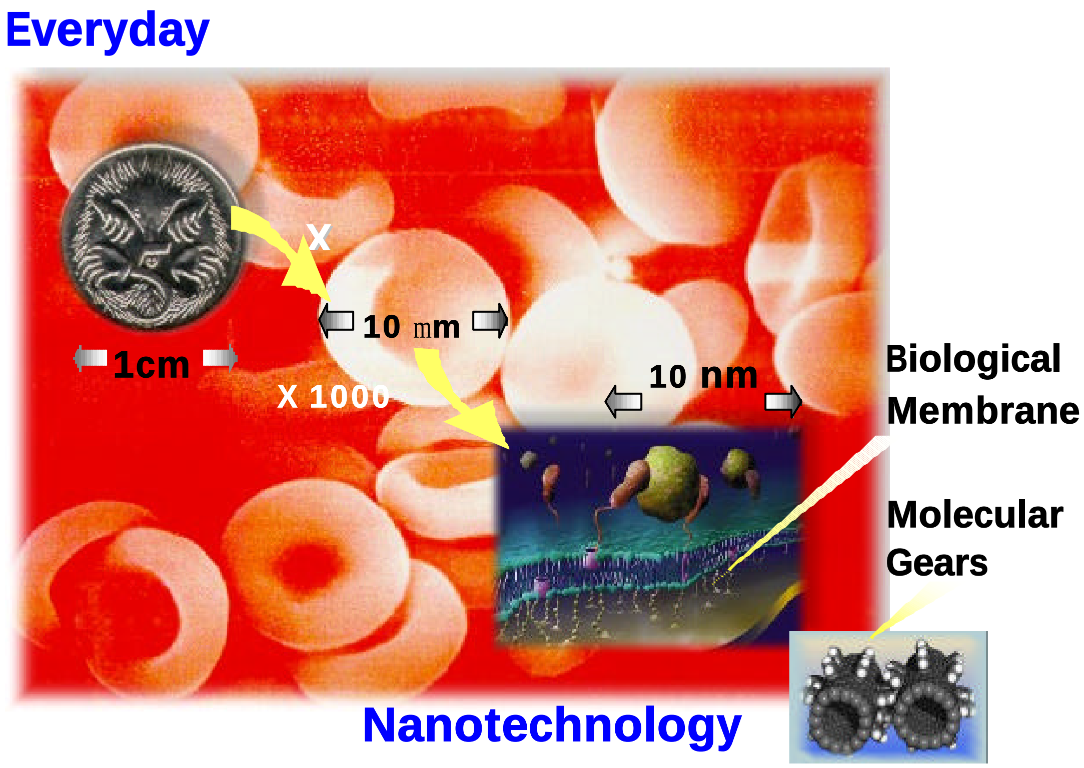
This is the diameter of a few atoms - the scale of individual molecules

Nanotechnology is engineering at dimensions less than 100nm

In a recent report on nanostructure science and technology[3], nanotechnology was defined as

> *. . direct control of materials and devices on a molecular and atomic scale, including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles, supramolecular chemistry, self assembly and replication techniques, sintering of nanostructured metallic alloys, use of quantum effects, creation of chemical and biological templates and sensors, surface modification and films.*
>
> *... producing materials and devices that take advantage of physical, chemical and biological principles whose causes are found in the nanometer scale.*[4]

[2] Richard Feynman, *Six Easy Pieces*, Addison-Wesley Pub. Co., Menlo Park, CA, 1963.
[3] R.W. Seigel, E. Hu, M.C. Roco, *Nanostructure Science and Technology – A Worldwide Study*, International Technology Research Institute (WTEC Division), Baltimore, MD, 1998; for the National Science and Technology Council
[4] *op cit*.



The progression from the familiar world of the *centimetre*, which when magnified by a 1000 reveals the world of the *micrometre*, and the red blood cell. Magnification by a further 1000 reveals the world of the *nanometr*e and the molecular structure of the cell membrane and its surface which defines the bio-materials interface. It is now possible to create molecular structures at this scale which mimic the functions of classical machines which interact directly with biological systems.

Nanotechnology impacts many applications;

Surface modification to a depth of 1-100nm controls surface charge, conductivity, porosity, roughness, wettability, corrosion resistance, friction, physical and chemical reactivity, and compatibility with biological organisms and tissues. Modified surface properties can minimise fouling by moulds, bacteria and algae, which has generated a new class of technologies addressing the purification of water supplies; the processing of biomass in sewerage treatment plants and the food processing industry; and in the elimination and control of taints and off-flavours in the food and wine industry. Modification of surfaces may also improve fermentation control in breweries; process control within the biotechnology industry; separation of metals in the mining industry; and enable improved technologies for bioreactor processing of gasohol based hydrocarbon fuel replacements and to improve internal combustion engine exhaust control.

Separations technologies based on nanoscale engineering may be applied to: minimise biofouling in the supply of pure water in regions of high salinity; aid in the separation of heavy metals for the mining industry; the restoration of polluted soil and waterways; the reduction of air pollution, the generation of hydrocarbon replacement fuels; and the fabrication of novel drug delivery mechanisms for the pharmaceutical and medical device industry.

Sensing Technologies designed and optimised at the nanometre scale can bring major competitive advantages in biological and general research applications, in the development of human and veterinary, "in vitro" and "in vivo" diagnostics, including genetic testing, blood bank applications, haematology and microbiology applications and antibiotic effectiveness screening. Further applications include the development of novel assays to screen for novel drugs, techniques to study pharmacokinetics, clinical and animal trialing and toxicology screening, the development of environmental monitoring applications, and applications for agricultural testing for growth hormones, pesticides and other contaminants in food. An important strategic area is the detection of chemical and biological weapons to combat military and terrorist threats. Applications also include physical testing such as the detection of mechanical stress and strain in the automotive and aircraft industries.

Human biomedical replacements such as modified blood vessels (shunts and stents), artificial skin, "smart" bandages, transdermal and implant drug delivery systems, contact and intra-ocular lenses, pacemaker, defibrillator and cochlea implants represent major scientific and commercial opportunities. Future substantial opportunities also exist in the broader area of human organ function replacement.

One of the most significant impacts of nanotechnology will be at the bio-materials interface. Whether a prosthetic implant is accepted or rejected, whether a drug is effective or whether living tissue will regenerate are all questions directed to the nanometre scale. Interfacing materials with biology is widely believed to be the exciting new frontier for nanotechnology.

3. World Scene

The importance of nanotechnology is evident from the interest shown by governments around the world. In the last decade, many major studies have been undertaken on the impact of nanotechnology on the world's economy and a number of national and multinational initiatives have been funded. (see Appendix 1 for more details)

These studies has highlighted the need for establishing national networks of shared facilities, expertise, and equipment.

The world investment in nanotechnology has been dominated by the United States and Japan (see Table I). This is expected to continue. However, increasing investment is expected by European countries such as the UK, Germany, France, Sweden, Switzerland and Asian countries such as China, Taiwan and Korea. Since the release of this report the US has increased this investment for 1998/1999 to US$232m and projects US$500m for 1999/2000.

Table I - Government Expenditures on Nanotechnology Research in 1997.[5]

Geographical area	Annual budget for nanotechnology research (US$ million)
Japan	120
United States	116
Western Europe	128
Other countries#	70
Total	432

Other countries: China, Canada, Australia, Korea, Taiwan, Singapore and former Soviet Union countries.

4. Australian Scene

Nanotechnology has already impacted many promising growth industries around the world and draws on many scientific disciplines. Although the development of nanotechnology Worldwide is still at a very early stage, there is sufficient evidence to indicate that Australia is well placed relative to other more advanced countries. In fact Australia leads the world in a number of areas. Some of the highlights of the applications being pursued in Australian are given below. A more detailed survey of activities would require an extensive process of consultation and review, spanning many research and commercial organisations. Included in Appendix 2, however, is an outline of work now underway within or funded by the Defence Science and Technology Organisation, the Australian Research Council and CSIRO.

A breakthrough has occurred at the University of New South Wales's Semiconductor Nanofabrication Facility demonstrating the feasibility of quantum computers. These quantum devices are a paradigm shift on existing computers, in that *at the nanometre scale, new physics is encountered* permitting massive parallel processing and ultrafast computing. Researchers aim to demonstrate functioning devices in 2003.

[5] R.W Seigel, E. Hu, M.C. Roco, *Nanostructure Science and Technology – A Worldwide Study*, International Technology Research Institute (WTEC Division), Baltimore, MD, 1998; for the National Science and Technology Council

Researchers at CSIRO in Melbourne have developed a novel electronic display screen based on carbon nanotubes. The method enables the manufacture of display screens that are thinner and require less power than conventional screens. Nanotubes are tiny hollow cylinders of pure carbon that are *only nanometres in diametre but can be up to 70 micrometres in length.* With the application of an external voltage these tubes emit a highly focussed beam of electrons that can be directed at a fluorescent screen, producing very high resolution images. In early 1999, CSIRO signed a research agreement with the Austrian technology company, Electrovac, to help bring the flat screen display technology to a commercial demonstrator. This is anticipated to take a further 12 months and commercially available screens are expected to become available in 2004.

In 1998 AMBRI Pty Ltd (a wholly owned subsidiary of Pacific Dunlop) obtained a world-wide exclusive license for sensing applications for the ion channel switch technology from the Cooperative Research Centre for Molecular Engineering and Technology. This device has received world press coverage as the *first purpose built nanomachine operating with moving parts that are nanometres in dimension*. Its function depends on an insulating biomimetic membrane coated over a gold substrate. Within the membrane, molecular channels permit the passage of sodium ions. When a molecule of interest is present, these channels close, turning off the flow of ions, and reporting on the presence and concentration of the molecule. The technique has been demonstrated to detect bacteria, drugs, proteins, and medically important minerals such as potassium and calcium. Australian applications of the technology are being pursued with Australian Water Technologies Ltd, a wholly owned subsidiary of the Sydney Water Corporation and with the Defence Science and Technology Organisation (DSTO).

Alliances have been formed with international pharmaceutical companies for adaptation of the technology to drug discovery applications and with diagnostic companies for use of the technology in the human healthcare industry. In 1998 the US Defense Department provided $3.5m to develop the technology for application to the detection of biological weapons such as Anthrax, Plague, Q fever and Tularemia.

Elastomedic Ltd was founded in 1997 to commercialise an exclusive world-wide licence obtained from the Cooperative Research Centre for Cardiac Technology to exploit Elast-Eon™ , a novel biocompatible polymer. Elastomedic has also received R&D *Start* grant funding of $2.25m. Elast-Eon™ represent a breakthrough in biocompatible polyurethane technology. The Elast-Eon™ *surface features are engineered at the nanometre scale* to result in a material that has minimal tissue adhesion, an essential attribute of its biocompatibility. Start up equity of $2.8m has been obtained from a strategic investor and licensee for heart valves, Aortech plc, a European device company based in Scotland. Aortech's share price sky rocketed from a low of 77.5p early this year to 363.0p in August 1999. After meeting major development milestones the shares underwent a further jump in early November to 532.0p . Elastomedic and Aortech are developing a biocompatible tri-leaflet Elast-Eon™ heart valve. If clinical trials are successful, this new generation heart valve is likely to capture a significant part of the $800m heart valve market. Durability testing of the valve has achieved over 250 million cycles and should reach the European threshold of 380 million cycles (or equivalent to 10 years in patients) in the near future.

Cochlear Ltd was founded in Australia in 1981. It arose from research undertaken at University of Melbourne. Cochlear's technology is an advanced implanted device that restores hearing to the profoundly deaf by electronically stimulating the auditory nerve. In 1985 it was the first implant to gain US Food and Drug Administration (FDA) approval for use by adults and in 1990 was the first to gain FDA approval in the US for use by children. The key to the technology is the *nanoscale bio-material interface between the metal electrode implanted in the cochlea and the nerve endings they stimulate.* Cochlear Ltd has supported its development activities through the granting in 1992 of a Cooperative Research Centre with research participants being the University of Melbourne, the Bionic Ear Institute and Australian Hearing Services. Cochlear Ltd was listed on the Australian Stock Exchange in December 1995 and raised $125m. Its current capitalisation has now increased to $850m with sales revenue for 1999 of $127m and growing at 39 per cent per annum.

Each of the above examples clearly demonstrate the commercial impact and breadth of nanotechnology across an incredibly diverse range of industries. Although many more projects and businesses could have been included here, these were chosen as they exemplify areas of significant commercial opportunity for Australia.

5. A Strategy for Australia to Capitalise on the Growing Impact of Nanoscale Technologies

Many applications could enhance existing manufacturing and public good outcomes, and could trigger many totally new outcomes. In the longer term, however, we must become more selective and direct our investment to those areas of high value and competitive advantage.

Australia has a history of worldwide successes in the biological and molecular sciences and is ideally suited to gaining a strong position in nanotechnology applications for the human biomedical replacement industry. It has an enviable track record in the commercialisation of new technologies in the human medical device market and currently has greater than 85 per cent of the world market in cochlea implants. Up to 1997 it also had over 18 per cent of the world market in cardiac pacemakers and was entering the implantable defibrillator market. These markets will be revolutionised by advances in nanotechnology. The next generation of human biomedical replacement technologies will lead to artificial skin, artificial blood, accommodating intraocular lenses, whole organ replacement in areas such as the artificial pancreas, prosthetic blood vessels, heart valve and whole heart replacement, kidney replacement, prosthetic lungs, joints and spinal injury repair and ultimately neuronal repair and replacement. The technology base of the human biomedical replacement industry is already well advanced. The controlled release of pharmaceuticals, human "in vitro" diagnostic assays, screens for new pharmaceutical drugs and an ever-increasing family of biocompatible materials are some examples.

5.1 A National Nanotechnology Toolbox of Facilities and Expertise

Australia has within its existing research institutions only some of the elements of a strategic plan for growing industries based on nanotechnology. The development and commercialisation infrastructure essential for nanometre scale technologies is absent in Australia. In the US, Japan and Europe, much of this essential infrastructure is found in corporate R&D laboratories which don't exist in Australia. Australia does not have multinational corporations which have the enormous R&D budgets required to fund the infrastructure for nanotechnology development and commercialisation.

We need to find a mechanism to provide this missing toolbox of equipment, staff and facilities. The key proposal of this paper is the need for Australia to develop a national nanotechnology toolbox of facilities and expertise. This would provide some of the missing elements necessary for the successful capitalisation of nanotechnology.

The extensive range of capabilities within such a toolbox is required by most projects working with nanotechnologies and needs to be available at a common site. The capabilities that form a minimal set include: clean rooms, analytical services, materials fabrication, organic and inorganic chemical synthesis, bio-molecular, molecular biology, thin films deposition and analysis capabilities. The high capital and maintenance cost of these facilities is a significant barrier to small to medium enterprises (SME's) and many large organisations from acquiring them independently.

Nanotechnology research and development is multidisciplinary. Key capabilities already exist within Australia, but may not be visible to researchers working outside a particular field. Alternatively, the capabilities may be known but are not utilised because they are ineffectively clustered. It is proposed that as part of the overall strategy of the national nanotechnology tool box, key capabilities are identified and used as centres around which to build the nanotechnology toolbox infrastructure. It is also proposed that once these key capabilities are identified, they are networked as part of the nanotechnology toolbox. The internet could then be used to provide better visibility for these capabilities and give the wider community better access.

An additional dimension to the national nanotechnology toolbox would be the inclusion of financial and administrative capabilities which would fulfill an incubator role for commercialisation projects. This nanotechnology toolbox may also be extended to include span clinical trials and links with health providers in the hospital and clinical community.

The toolbox concept is epitomised by Cochlear Ltd which resulted from the rare combination of world class medical research at the University of Melbourne complemented by access to a world class commercial facility in the then AWA Microelectronics facility.

CSIRO is an example of an organisation that could form the backbone of the national nanotechnology toolbox as it already has many of the necessary capabilities. Regional nanotechnology toolboxes can be set up around the current infrastructure of existing CSIRO sites and Australian Research Council (ARC) Key Research Centres. This would ensure that the centres of excellence developed by the universities are also an integral part of the nanotechnology toolbox. The proximity of Key Research Centres would provide a particular emphasis for some centres. This would also provide a link for the toolbox back to universities and ARC research centres. This would also aid in the education and training of a new generation of nanotechnologists by providing a base from which to operate.

A national toolbox would encourage commercial ventures, especially SME’s to enter the new markets opened up by the technological advances by providing an incubator environment for new ventures. In order to make it attractive for such groups to work together, project-based government programs such as the Cooperative Research Centres scheme could easily be used to facilitate the process.

The core users of the toolboxes would be from projects aimed at commercialising the outcomes of science in the nanotechnology area and would be organised similar to Cooperative Research Centres involving CSIRO, universities and industries. The life cycle of these nanotechnology projects could also involve staff returning to the toolbox for a period (say under a five year fellowship) prior to participating in a further project or electing to pursue a career within the toolbox. This could become a career path for publicly funded scientists at the leading edge within their disciplines within Australia.

5.2 The National Nanofabrication Facility (NNF) and Network

The National Nanofabrication Facility was established in 1994 following a presentation to the Prime Minister's Science Council in late 1992. The objective of the NNF was to test the concept of a national toolbox of leading edge equipment and to facilitate and promote scientific research and technological development in nanotechnology. The NNF has successfully demonstrated the viability of the toolbox concept. In addition it has shown the way to a national strategy addressing the needs of a far larger group of activities within Australia.

The NNF was funded through a $3m government grant which was used to purchase capital equipment and to network with other facilities strategic to nanotechnology based research and development. The use of this facility has now grown to exceed its ability to satisfy the needs of all the actual and potential customers applying for use of its equipment and laboratory space. Users initially focussed on a small number of CRC's (such as Molecular Engineering and Technology, Cardiac Technology, Eye Research and Technology, Waste Management and Pollution Control) but has now grown to include companies from a range of industries, the DSTO, the CSIRO and many universities. Appendix 3 provides a case study of the value of the NNF to a local small to medium enterprise in the manufacturing industry.

The NNF is located at Chatswood NSW, which is the heart of what has been dubbed Australia’s ‘Silicon Valley’.

The NNF has developed to include world class facilities in Surface and Materials Characterisation, Lithography, and Microfabrication The "tools" in the toolbox include: Class 3.5 Clean room; Laboratories; Electron Beam Lithography; Nuclear Magnetic Resonance Spectroscopy; X-Ray Photoelectron Spectroscopy; Auger Electron Spectroscopy; Secondary Ion Mass Spectrometry; Thin Film Deposition technologies; Ellipsometry and Contact Angle Measurement; Laser Micromachining.

6. Recommendations

I National Nanotechnology Toolbox

Australia needs to maintain a competitive position in nanotechnology based industries relative to countries that have a strong focus on emerging technologies, such as Japan and United States. To achieve this, it is proposed that a strategic plan addressing potential roadblocks be drafted as a matter of national priority.

Nanotechnology based industries are beginning to emerge around the world. A window of opportunity exists for Australia to establish such industries. However, a major roadblock is the absence of essential infrastructure. A key proposal of this paper is to provide this infrastructure through the establishment of a national network of nanotechnology toolboxes.

II Nanotechnology Workshop

To generate a national strategy for Australia, the overall status and impact of nanotechnology must be assessed. It is proposed that an International Workshop on Nanotechnology be held in August 2000. It is also proposed this workshop be held in the name of the joint academies: the Australian Academy of Sciences and the Australian Academy of Technological Sciences and Engineering.

Proposed objectives of the workshop include:

- increase awareness of nanotechnology by researchers in the various disciplines, especially those who may not have the necessary multi-disciplinary skills
- assess the status and trends of nanometre scale research and development in Australia.
- catalogue the infrastructure and capabilities available
- identify new research and commercial opportunities in the field of nanotechnology
- benchmark Australian activities against the rest of the world
- identify a long term strategy to capitalise on emerging opportunities for Australia.
- stimulate and promote interdisciplinary nanoscale research in Australia
- identify and promote international collaborations
- showcase Australian advances in nanotechnology to both the local and international community
- make the workshop a continuing event and an event on the world nanotechnology calendar.

APPENDIX 1

World Scene

The following is a brief survey of government funded nanotechnology activities worldwide. Further details can be obtained from the cited literature.

United States

The United States and Japan has been at the forefront of nanotechnology activity around the world. There have been a number of government sponsored reports into nanotechnology research in the United States. The earlier reports were conducted by the Office of Technology Assessment[6], the RAND Corporation[7], the National Academy of Sciences[8] and the Department of Defense[9].

Recently, 2 major studies were conducted into the potential of nanometre scale research and technologies. The first report, *R&D Status and Trends in Nanoparticles, Nanostructured Materials and Nanodevices in the United States*[10], examined the research, capabilities and potential of nanotechnology within the United States. A subsequent study, *Nanostructure Science and Technology – A Worldwide Study*[11] looked at the worldwide scene. These two later studies were commissioned by the US National Science and Technology Council (NSTC) and sponsored by a range of the major agencies. These included: the National Science Foundation (NSF), the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), the Department of Commerce (DoC), the National Institutes of Health (NIH), the National Institute for Standards and Technology (NIST), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DoE).

As a consequence of these government funded reports, nanotechnology was identified as a priority area and a series of major programs and initiatives were implemented, including a National Nanofabrication User Network (NNUN) in 1994. NNUN comprises of nodes for Instrument Development, for Nano-science and Engineering, Synthesis, Processing, and Utilisation of Functional Nanostructures. The Network brought together many interdisiciplinary centers to provide a coordinated infrastructure for nanotechnology research.

[6] *Miniaturisation Technologies*, Office of Technology Assessment (OTA-TCT-514), Washington, DC, 1991.
[7] M. Nelson and C. Shipbaugh, *The Potential of Nanotechnology for Molecular Manufacturing,* RAND Corporation, Santa Monica, CA, 1995.
[8] *Biomolecular Self-Assembling Materials*, National Academy of Sciences Panel Report Washington, DC, 1996: National Academy of Sciences, Panel on Biomolecular Materials, Solid State Sciences Committee, Board on Physics and Astronomy, Commission on Physical Sciences, Mathematics and Applications, National Research Council.
[9] Olson R et .al. *MHSS 2020 Focused Study on Biotechnology and Nanotechnology*, Department of Defense (DASW01-96-D-0057), Washington, DC, 1997.
[10] R.W. Siegel, E. Hu, M.C. Roco, *WTEC Workshop Report on R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States*, International Technology Research Institute (WTEC Division) Report, Loyola College, Maryland, 1997.
[11] E. Hu, M.C. Roco, *Nanostructure Science and Technology – A Worldwide Study*, R.W. Siegel, International Technology Research Institute (WTEC Division) Report, Loyola College, Maryland, 1998, prepared under the guidance of US National Science and Technology Council.

These reports stated that it is expected that most relevant short term outcomes will come from miniaturisation within the microelectronics industry. In longer term, the approach of building up from molecules, nanoparticles, nanolayers, nanotubes and biological aspects of nanotechnology are seen as offering greater potential. The greater impact of nanotechnology is seen to span science, education, innovation and commercial/industrial activities.

US government spending on nanotechnology related research through the major funding agencies, with the bulk of it from the NSF, has increased from US$116m in 1997/98 to US$232m for year 1998/99 and is expected to further double to US$500m for year 1999/00.

Japan

Japan has by far had the greatest investment from the government and large corporations for nanotechnology related research. Government research organisations and funding agencies have established considerable infrastructure in Japan with strong nanotechnology focus. As a result research activities are generally grouped in relatively large well established industrial, government and academic laboratories.

Funding for basic research in general and in particular nanotechnology is expected to continually increase as a result of Japan's Science and Technology Basic Law. The main government agencies are: Ministry of International Trade and industry (MITI), the Science and Technology Agency (STA) and Ministry of Education, Science, Sports and Culture (Monbusho). It is estimated that these agencies in total have a annual budget of US$120m for nanotechnology. The funding is spread over a range of long and short term programs. In 1992 MITI launched a program, Research and Development of Ultimate Manipulation of Atoms and Molecules. As a result a joint effort between the National Institute for Advancement of Interdisciplinary Research (NAIR) and the Agency of Industrial Science and Technology (AIST) established the Joint Research Centre for Atom Technology (JRCAT) with 10 year budget of US$220m. Other initiatives include the Research on Cluster Science program, Research on Bionic Design program, Quantum Functional Devices program, Frontier Materials Research Initiative and the Exploratory Research for Advanced Technologies (ERATO) program.

United Kingdom and other European countries

There are a combination of national and collaborative European programs that fund Nanotechnology research in Europe. Multinational programs include:

- the PHANTOMS Initiative (Physics and Technology of Mesoscale Systems)
- the European Consortium on Nanomaterials (ECNM)
- the European Society for Precision Enginering and Nanotechnology (EUSPEN)
- the NANO network sponsored by the European Science Foundation
- the European Network of Excellence on Organic Materials for Electronics (NEOME), and
- the European Network of Excellence in Multi-functional Microsystems (NEXUS).

United Kingdom

The UK Parliamentary Office of Science and Technology (POST) commissioned a report on technology *Making it in Miniature* released in November 1996[12]. Even prior to this, nanotechnology was recognised as the technology for the future in that a number of national initiatives were instigated in the late 1980s. The first was the National Initiative on Nanotechnology launched in 1986 jointly by the National Physical Laboratory and the Department of Trade and Industry. The next was a LINK Nanotechnology Program launched in 1988, initially by the Department of Trade and Industry, later joined by the Science and Engineering Research Council and the Defence Research Agency.

The success of these initiatives was reflected in the involvement of about 1000 companies, 30 universities and 7 research establishments with projects with applications in medical, measurement instrumentation, environment, process control, manufacturing, military, marine, automotive, aerospace, safety and security, information technology/communications, household goods and home automation.

However, there were concerns expressed in the POST report that, although nanotechnology was identified as a potential future technology not enough was done, especially in terms of recognising it as a broad based generic technology on which future technological developments and innovations was to be built on.

The total spending in UK on nanotechnology activities from 1986 to 1996 was approximately £50m.

Germany

The Germany Federal Ministry of Education, Science, Research and Technology has provided substantial national support for nanotechnology. There are at least 14 Fraunhofer Institutes related to nanotechnology. The Fraunhofer Institutes, Max Planck Institutes and a number of universities have established centres of excellence in nanotechnology. The BMBF support for nanotechnology programs was approximately US$50m per year (based on 1997 figures).

[12] *Making it in Miniature – Nanotechnology, UK Science and its Applications*, Parliamentary Office of Science and Technology, Report No. 86, 1996.

APPENDIX 2

DSTO'S NANOTECHNOLOGY INTERESTS

To provide a wide perspective of DSTO's nanotechnology activities, we will take nanotechnology as covering techniques and devices able to work at a scale between 1nm and 1000nm[13].

DSTO has a small, but growing, number of activities in Biosensors, Micro-Electromechanical Systems (MEMS), and Multiple Quantum Well (MQW) applications. In addition, DSTO possesses some nanotechnology and microengineering facilities.

1. Ion Channel Switch (ICS) Biosensor

Ion Channel Switch (ICS) technology is being developed by AMBRI Pty Ltd, based on technology originally developed by CSIRO and then the CRC for Molecular Engineering and Technology. DSTO has commenced a collaborative program with AMBRI to develop AMBRI's Ion Channel System (ICS) Biosensor for the rapid detection of biological warfare agents. The sensor should outperform any existing fielded equipment, delivering sensitivity, selectivity, robustness, and small size. In addition, the ICS technology can be developed to provide genuinely continuous sensing (as distinct from a sequence of individual assays).

The program has two projects: development of a hand held sensor (HHS) for rapid diagnosis of exposure of personnel, and production of an Unmanned Biological Warfare Agent Detector as a Defence Capability Technology Demonstrator.

2. Micro-Electromechanical Systems (MEMS) Activities

MEMS are miniature devices that combine the computing power of silicon technology, with miniature sensors and actuators which are all mounted/constructed on the one device. The most common example is the air bag sensor in vehicles and the "bubble jet" head in printers. DSTO is currently working on a MEMS condition-based monitoring sensor for adhesively bonded components. The sensor detects moisture ingress and interface degradation in structural adhesive bonds through measuring changes in conductance. Military aircraft have many critical adhesive bonds which need to be monitored to ensure structural integrity. A licensee (Analatom Inc., Sunnyvale, USA) will provide DSTO with prototype sensors for evaluation in 2000.

DSTO is also exploring the possible use of MEMS technologies in areas such as:

- smart, autonomous strain gauges to monitor strains in inaccessible and critical areas of aircraft and submarine structures;
- corrosion rate sensors small enough to be included under protective films.

Future research is planned or being considered in a number of areas, namely:

- arrays of "smart" strain gauges for routine large-area monitoring, for example, welds in submarine hulls;

[13] ie, between 10^{-9} and 10^{-6}m. A more restrictive definition of nanotechnology is that of a manufacturing technology giving control of the structure of matter on a molecule-by-molecule basis. This is sometimes called molecular nanotechnology (other terms, such as molecular engineering, molecular manufacturing, etc. are also often applied).

- smart patches, where the strain sensor is integrated with condition-monitoring systems in aircraft;
- eddy-current arrays to detect cracks and monitor crack-growth in aircraft structures;
- MEMS-based magnetometers and accelerometers for weapon applications;
- micro inertial measurement and navigation units, for weapons guidance and control applications.

3. Multiple Quantum Well (MQW) Materials

DSTO has some projects that utilise multiple quantum well (MQW) materials. Deposition of these materials on an atomic layer scale, by means of very large scale integration (VLSI) techniques permits the construction of MQW self electro-optic effect devices (SEEDs), infrared photodetectors (QWIPs), and infrared quantum cascade lasers (QCLs). Applications include fast analogue-to-digital converters for digital signal processing.

4. Nanotechnology & Microengineering Facilities

DSTO's Scientific and Engineering Services (SES) has a class 35/350 cleanroom that is suitable for nanotechnology applications (ie, for products in the size range of 10^{-9} m). However, the bulk of SES's current equipment is designed for applications in the microengineering ($1x10^{-6}$) scale rather than nanotechnology. SES's activities in microengineering include: mask making, thin film (including micro-machining) and thick film processes, with applications in infrared sensors, digital micro-mirrors, multi-chip modules, thermal conductivity micro-sensors.

October 1999

ARC FUNDING OF NANOTECHNOLOGY RESEARCH

The ARC funds nanotechnology projects under various programs - Large grants, Fellowships, SPIRT and REIF. It was recently announced that the Centre for Quantum Computer Technology at the University of New South Wales will receive funding under the ARCs Special Research Centres Programme from 2000. The Centre's programs will focus on the fundamental physics and technology of building, at the atomic level, a revolutionary prototype solid state quantum computer in silicon and will enable Australia to play a central role in the development of 21st century computer technology.

The ARC is funding, through its Research Equipment and Infrastructure Facilities (REIF) scheme, the development of a unique, free electron laser at the University of Newcastle. The laser will produce intense beams of ultraviolet light, to make the world's most sensitive detector for elements, including hydrogen, carbon, oxygen and phosphorous, on surfaces. This work will revolutionise ultratrace elemental analysis and greatly benefit the development of new quantum computing and optoelectronic devices and new sensors for biotechnology.

ARC funded nanotechnology projects relating to **processing of materials** include topics such as: Molecular interaction stimulated by light or electricity; quantum phase transitions in magnetic materials; chemical reactions through photoinduced charge separation; conductivity in molecular electronics; reliability of piezoelectric packages; behaviour of electron wave semiconductor billiards; quantum affine superalgebra structures; time dependent magnetic behaviour; mechanisms of nano-grinding silicon monocrystals; rapid micro-thermal analysis for nano-structure probing of complex polymeric materials; nanoscale characterisation of structural indicators for embrittlement in pressure equipment; quantum teleportation of optical information; development and application of a new generation of atomic frequency standards; defects and quantum dots in semiconductors; and quantum transistors.

ARC funded nanotechnology projects relating to **design or fabrication of materials** include topics such as: Electroluminescence of polymers; nanoporous alumina; heterocumulenes; minitaurising electronic devices – 3d organic molecules as binary switches; nanofilms & supported containers; low noise semi conductor lasers; far infra red lasers; microwave surface acoustic wave devices; quantum-well intermixing for optoelectronic materials and devices; superconductor-semiconductor-superconductor structures on the submicron scale; carbon nanoclusters; light element binary alloy coatings; nanocrystalline magnetic materials; epoxies in microelectronic encapsulation; design of supramolecular structures for use in nanoelectronics; nanofiltration membrane systems based on thin-film conducting electroactive polymers; designed nanostructures for tio2 - based solar cells; intergranular magnetic coupling and soft and hard magnetic properties; third generation thin-film solar cells; reactions of nanosize ceramic materials; defects and microstructure in ion-beam processed iii-v nitrides; binary alloys of nitrogen; and defect structure of materials with wide band gaps.

ARC funded nanotechnology projects with specific **biological** components include topics such as: Proteome characterisation using 2D-gels and the nanospray ion trap mass spectrometer; quantum dots for bioconjugation; long-range electron and energy transfer processes (molecular batteries); nanofabrication of diatom silica; Fullerenes; Quantum ratchets; and DNA nanoshuttles.

November 1999

NANOTECHNOLOGY AND ITS DEVELOPMENT IN CSIRO

CSIRO Research and its Potential

Over the next decade, applications of nanotechnology will most probably have greatest impact in information technology, medicine and health, materials and manufacturing, and energy systems. The development of nanotechnology in Australia needs to be built on the market niches of Australian companies that are working in areas which can benefit from nanotechnology.

CSIRO currently has three Divisions involved in developing world-leading nano-scale devices, each with the potential to address widely different markets. There is active interest in applications of nanotechnology in at least three other Divisions.

Novel aligned carbon nanotube and polymer work at CSIRO Molecular Science is being used as a new electronic and optoelectronic material, for example in a completely new type of computer or television flat screen display in conjunction with the company Electrovac. In collaboration with CSIRO Health Sciences and Nutrition and the Reserve Bank of Australia, the use of carbon nanotubes as novel biosensors and their application as security devices for banknotes are being investigated.

CSIRO Manufacturing Science and Technology is undertaking research into anti-counterfeiting technologies based on microstructures, including optically variable devices generated by nanoscale diffraction gratings. In the same Division, nanometre-sized, ultrafine particles are being used for ultraviolet protection in plastic containers, in cosmetics and as x-ray standards.

The world's first successful biomimetically engineered nanodevice emerged after 10 years of CSIRO multidisciplinary research (Cornell et al, 1997, *Nature* 384, 5 June 1997). The Ion Channel Switch Biosensor is a 10nm nanomachine with individual molecule-based switches triggered by binding of specific target molecules. It is sensitive on the picomolar scale, equivalent to one sugar cube dissolved in Sydney Harbour. It is based on concepts adapted from different examples in nature, rendering them robust by chemical means, and designed through modelling on the basis of the physics required for successful detection of target molecules in human blood. This is now moving into a commercial phase. In complementary work, CSIRO Health Sciences and Nutrition has leading edge technology aimed at providing high-affinity receptors for biosensor applications of nanotechnology in medical devices for the clinical diagnostic market, including point-of-care diagnostic applications.

CSIRO Telecommunications and Industrial Physics is now building upon what was learnt through this ion channel biosensor project in investigations into novel interface materials, and devices for communications, solid state devices, optics and thin film applications.

These examples illustrate one of the strengths of CSIRO's position in the nanotechnology - the technology produced is generic, with broad market applications.

There is strong interest from CSIRO Exploration and Mining in using this technology in detailed geochemical exploration procedures, *in situ* metal concentrating technologies, super-efficient rock drilling and cutting and pollution contaminant and rehabilitation procedures.

CSIRO Energy Technology is considering use of carbon nanotubes for energy storage, in particular hydrogen storage, supercapacitor active materials and battery additives.

The nanoscale also challenges current measurement techniques, and CSIRO has the ability to push the limits in this area through the National Measurement Laboratory.

Research and Development Strategy

- CSIRO through its disciplinary excellence and multidisciplinary approach is well placed to pursue this exciting area of science. Such multidisciplinary capability is a goal being sought by USA, Japan, and Europe. It provides the platform to exploit technologies in many different fields; for example, discussions are under way to look at ultrafine particle technology (developed by CSIRO Manufacturing Science and Technology) in potential drug delivery systems by combining the capabilities of three CSIRO Divisions.

- Although considerable investment has been made in the science underpinning nanotechnology over some 15 years in Australia, so far there has not been corresponding investment by industry. Australia has within its existing institutions the mechanisms to implement a strategy aimed at developing nanotechnology. Such a strategy needs to be built upon matching the market focus of Australian companies which are already working in areas that currently employ nanotechnology, or have the potential to employ it, with appropriate R&D capabilities.

- By consolidating linkages between CSIRO Divisions, between CSIRO and Universities, and incorporating business and market strategies, we are moving to create Australian world-leadership positions in highly specific nanotechnology areas.

- A prime requirement for implementing nanotechnology is the availability of major equipment, skilled staff and specialist facilities to permit a fully integrated approach for commercial ventures.

November 1999

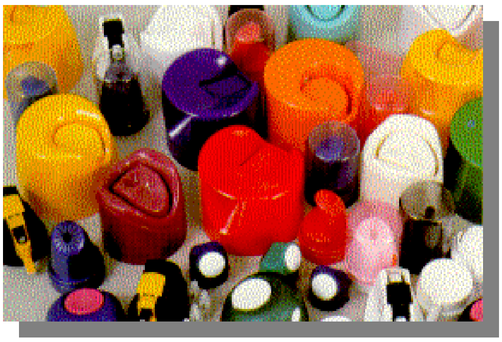
APPENDIX 3

NNF Case Study

Company: Precision Valve Australia Pty Ltd
Ingleburn, NSW
Contact: Barry Connell

Precision Valve Australia (PVA), was formed in 1967 with its principal business being the manufacture of aerosol valves and related components. PVA employs over 150 people and their products are exported to over 20 countries.

At their Ingleburn factory, PVA manufacture over 3.5 billion individual aerosol valve components each year, spread over 2,500 product items. There is a 92 per cent vertical integration in the domestic manufacture. One of the main products are *aerosol valve mounting cups*. Over 600 million cups are manufactured in Australia by PVA each year, requiring approximately 3,000 tonnes of tinplate supplied by BHP. About 400 million of these cups are exported, mainly to South East Asian countries. Approximately 2,000 tonnes of plastic is used each year to manufacture plastic valve components.



In order to provide their customer base with a competitive advantage and point of difference in global markets, Precision Valve Australia has had to focus on two aspects of its business to make it a truly global supplier:

- Product and engineering development
- Low cost base in manufacturing output.

The use of modern technology and Innovation has been fundamental in maintaining this competitive advantage. PVA has a excellent history in relation to technology and innovation. The company has been responsible for many industry "firsts" regarding product and engineering development, the consequence of which has placed Australia in the forefront of packaging technologies.

Some of these innovations include:

- Developed the modern day paint and antiperspirant aerosol valves which are now used in every major market in the world.
- In conjunction with BHP developed epoxy lacquered and laminated tinplate material of which the laminated material is now an industry standard across all quarters of the world.
- Developed the first industrial laser system in Australia in conjunction with the Department of Weapons and Research. The laser system is used to machine the vapour tap holes (with

size ranging from 0.12 mm up to 1.0 mm) in the valve housing of the aerosol valves at a rate of 700 parts per minute.

- Designed and manufactured high speed rotary assembly equipment and machine vision quality inspection system for the assembly and quality inspection of the components of the aerosol valve. These systems are capable of running at speeds in excess of 1000 pieces per minute.

Given PVA's history with innovation, it is not difficult to see why the company would readily embrace the technological advantages of the nanotechnology revolution. The National Nanofabrication Facility (NNF) has been able to assist PVA maintain their competitive edge in terms of:

a) problem solving
b) improving processes and products
c) innovation – new product development

using the materials expertise and surface analysis and materials testing equipment available in the nanotechnology toolbox.

The following problem was recently encountered by PVA. Stains believed to be a result of rust were observed on PVA manufactured aerosol cups which were exported to the Southeast Asia region. The high ambient temperatures and humidity in this region was believed to be causing the stains to appear in the cups after a period of storage. Rust on the cups would render them unusable. Using the surface analysis equipment and expertise that NNF has with its network, the problem was quickly identified as not rust or a result of inferior raw materials but due to the manufacturing process. In combination with PVA's experience in manufacturing, a solution was found without substantial adverse effect to their export market.

NNF is now working together with PVA and BHP in developing product and manufacturing specifications for tinplate materials that meet the needs of high humidity climates such as those in Southeast Asia. The objective is to reduce the cost of raw materials and improve the quality of the finished product. There are potential cost savings of more than $0.5m per year by altering the grade of tinplate used.

In a longer term initiative, PVA, NNF and Hunter Douglas are developing lacquered aluminum metal substrate for the manufacture of aerosol components for export into Southeast Asia. The potential Asian market for aluminum cups is over $6m per year of which PVA hopes to capture a lions share of with the new aluminum product line.

Sharing ideas and technologies with supplier groups has been a successful business initiative for Precision Valve in past years. The NNF now adds a new dimension by being able to provide the materials expertise, leading edge equipment and scientific data necessary to validate improvements in manufacturing processes and product development.

PVA plays a critical role in the Australian aerosol industry, which is estimated at over $500m and employs over 2500 people. Without such a network and access to world class facilities, it will be difficult for PVA to continue to be successful market leader. As a principal supplier to the aerosol industry and household names such as S.C. Johnson, Lever and Kitchen and Reckitt and Rexona, their manufacturing must be viable, competitive and profitable to compete against imports in a time where Australian manufacturing is declining.