Nanotechnology Benchmarking Project

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Contents

Executive summary

A benchmarking methodology for assessing emerging areas of science and technology in Australia has been piloted by assessing Australia's capability in nanotechnology. The methodology includes:

- developing a comprehensive list of keywords related to the field;
- performing a comprehensive bibliometric analysis of the field;
- comprehensive peer review to validate the keywords and the findings from the bibliometric analysis.

The bibliometric analysis found that Australia produced 1.41 per cent of the world's nanotechnology publications from 1980-2003 and 1.49 per cent from 1998-2003. This is lower than for science as a whole, where Australia produced 2.0-2.4 per cent of the world's science publications between 1990-99 (see Section 3.2.3). The number of Australian nanotechnology publications has increased fairly steadily each year since 'taking off' around 1990 (see Figure 1).

A citation analysis of Australian nanotechnology publications indicates that Australian nanotechnology papers are being published in relatively high impact journals, and are receiving a higher than average citation rate in those journals (see Section 3.2.4).

The percentage of world science publications relating to nanotechnology has been increasing linearly since 1990, indicating that nanotechnology is rapidly becoming an important area of research throughout the world. The percentage of Australian science publications that contain nanotechnology is also increasing, indicating that nanotechnology is becoming an important area of research in Australia. However, it appears that this increase is less rapid than for the world as a whole. Australia's share of world nanotechnology publications peaked in the mid to late 1990s but has decreased slightly since then, suggesting that while Australia's nanotechnology capability is increasing, we have not been keeping pace with the rest of the world in the past 5 years (see Figure 2). From an analysis of the publication outputs of leading nanotechnology countries', nanotechnology appears to be a smaller sector of science in Australia compared with all the other leading nations or regions (see Section 3.2.5, Figure 6).

The percentage of Australian nanotechnology publications with international collaboration has been generally increasing since 1990. Australian nanotechnology publications have a higher level of international collaboration than for Australian science as a whole. The rate of collaboration with Asia is increasing, increasing slightly with Europe, steady with North America, and declining with England (see Section 3.2.6, Figures 7 and 8). Australia appears to have at least some collaboration with most of the world's leading nanotechnology research institutions (see Section 3.2.7, Table 1).

Australia's publication outputs are consistent across the major nanotechnology sub-fields and key topics, indicating a broad level of expertise in all areas of nanotechnology (see Sections 3.2.8 and 3.2.9).

Australia ranks 7th in the world (excluding the USA) in US nanotechnology patents, based on a number of different ranking criteria, not just absolute number of nanotechnology patents (where we rank 9th) (see Section 3.3).

Australia has no formal national nanotechnology initiative, although an informal network is currently in the process of developing a formal structure. Other countries have formal national nanotechnology initiatives that not only pour (in some cases) large amounts of money into nanotechnology R&D, but also serve to focus and direct the national effort. Australia risks falling behind if a similar organisation is not set up here. However, there is significant government investment in Australian nanotechnology research from the Australian Research Council (ARC) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), plus funding from state governments. Various ARC-funded nanotechnology projects that commenced in 2002 and 2003 have been allocated a total of A$53,013,909 over their project lives (see Section 3.4).

The benchmarking results were 'peer reviewed' by sending preliminary results to leading Australian nanotechnology researchers for comment, along with a survey aimed at identifying world-leading researchers in the field, who subsequently were also surveyed. While the size of the sample was small, the survey confirmed that Australia has a small number of 'world leaders' in nanotechnology, but in some sub-fields the international researchers found it difficult to name Australian researchers. This is consistent with the bibliometric result that Australia's involvement in nanotechnology is not keeping up with the rest of the world (see Section 3.6).

In summary, the study has found that Australian nanotechnology researchers are producing high quality work across all areas of nanotechnology, but there is evidence that we are not advancing our capabilities as quickly as the rest of the world. The findings also suggest that Australia may fall further behind in the future unless nanotechnology is maintained as a national research priority and funded accordingly. It is recommended that Australia's nanotechnology research performance be regularly evaluated using the methodology established in this study.

The benchmarking methodology used in this project is suitable for assessing other emerging areas of science and technology in Australia, such as biotechnology, bioinformatics, complex systems, ICT, genomics/phenomics, quantum computing and photonics.

Acknowledgements

The Australian Academy of Science would like to acknowledge that this project was made possible by funding from the Australian Research Council under their Learned Academies Special Projects grant scheme. The need for a project of this kind was identified by Dr Michael Barber, FAA (Secretary, Science Policy, Australian Academy of Science), who developed the project proposal and drove the early stages of the project. We are also grateful for the significant input from the expert steering committee, consisting of Professor Bruce McKellar, FAA (Chair), Professor Frank Caruso, Professor Bob Clark, FAA, Dr Bruce Cornell, Associate Professor Andrew Dzurak, Professor Chennupati Jagadish and Professor Paul McCormick, FAA. We would also like to thank Linda Butler (Research Evaluation and Policy Project, Research School of Social Sciences, ANU) for providing data and expert advice on the bibliometric analysis.

1 Introduction and aims

1.1 Introduction

Nanotechnology is a high-profile emerging area of science and technology. It can be defined as 'the ability to work at the molecular level atom by atom to create large structures with fundamentally new properties and functions'. Nanotechnology is producing many revolutionary applications such as quantum computing, surface and materials modification, novel separations, sensing technologies, diagnostics and human biomedical replacements. Interfacing materials with biology is widely believed to be the exciting new frontier for nanotechnology. Nanomaterials have already been set as a priority research area for the ARC.

Policy makers and agencies responsible for public sector investment in emerging areas of science and technology need to be able to assess how well Australia is doing. As new areas emerge and develop, performance needs to be tracked and evaluated in order to determine the areas in which we are relatively strong and the areas in which we are weaker. This relative performance then needs to be related to strategic policy objectives. Weak performance in critical areas will require action to be taken to address these problems whereas weak performance in non-critical areas may suggest that funding could be reduced.

1.2 General project aims and objectives

This project seeks to provide Australia with an effective means of benchmarking research performance in emerging areas of science and technology. Benchmarks of this type will provide a baseline against which the outcomes from subsequent public sector investments in research can be assessed, particularly in the context of national research priorities. They will also help to identify areas of weakness in research performance that may require attention by government. The project has the following primary objectives:

- to adapt a benchmarking methodology developed in the United States by the Committee on Science, Engineering and Public Policy (COSEPUP) to suit the Australian context;
- to pilot this adapted methodology by examining Australian research performance in nanotechnology;
- on the basis of the findings from the pilot exercise define a benchmarking methodology for general use by government departments and agencies in assessing research performance in emerging areas of science and technology.

This pilot project will also allow the following secondary objectives to be met:

- to assist the ARC in assessing Australia's current and future research performance in one of its National Research Priority Goals – *Frontier Technologies*;
- to generate useful information on the current performance of Australian nanotechnology research for use across federal and state/territory government departments and agencies, higher education, and the business sector;
- to identify possible weaknesses in Australian nanotechnology research activity that could prevent Australia from benefiting from this key emerging area of science and technology research;
- to assess the effectiveness of the links between Australian nanotechnology research groups and overseas research groups.

2 Methodology development

2.1 Adapting COSEPUP methodology to suit emerging fields in an Australian context

The COSEPUP methodology

The US Committee on Science, Engineering and Public Policy (COSEPUP) was interested in evaluating how the US is performing relative to the following two goals:

- the US should be among the world leaders in all major areas of science; and
- the US should maintain clear leadership in some major areas of science.

They chose to evaluate this through

> 'the establishment of independent panels consisting of researchers who work in a field, individuals who work in closely related fields, and research users who follow the field closely. Some of these individuals should be outstanding foreign scientists in the field being examined.'

This 'international benchmarking' technique was then applied to assessing three fields – mathematics, immunology, and materials science and engineering. For each field, an oversight group was set up and asked to define sub-fields and select an expert panel to carry out the benchmarking assessments. The expert panels were then charged to answer the following three questions:

- What is the position of US research in the field relative to that in other regions or countries?
- On the basis of current trends in the US and worldwide, what will be the relative position of the US in the near and longer-term future?

- What are the key factors influencing relative US performance in the field?

All of the expert panels chose to augment conventional performance indicators (such as bibliometric analysis, R&D investment, numbers of scientists/graduates etc.) with a novel technique they termed the virtual congress. This method sought to identify the world leaders in a sub-field by asking researchers to imagine they were the organiser of an international conference in their sub-field, and then to list whom they would ideally invite to speak at such a conference. The expert panels then considered the results of the various performance indicators and made conclusions in response to the three questions above.

The adaptation

For the purposes of this project it is necessary to modify the COSEPUP approach for the following reasons:

- We are dealing with an emerging field of science – nanotechnology – whereas the COSEPUP studies dealt with established fields. Hence, conventional performance indicators may not adequately capture performance in nanotechnology.
- The US's goals of being amongst the world leaders in all areas of science and to maintain clear world leadership in some areas of science are not appropriate for Australia, considering the smaller scale of our R&D budget and the smaller population of our country in general.
- The current project has tighter budget and time constraints compared with the COSEPUP study, and it is intended that the general benchmarking methodology that will be developed should be able to be implemented with a minimum of resources.

Therefore, the goals of this study should be to explore whether Australia currently has researchers and/or research groups:

- whose contributions are seen by the rest of the world as contributing to the development of the field;
- who have links with the major research groups who are seen as the world leaders in nanotechnology, wherever they may be; and
- who have the requisite background and/or cognate skills and knowledge to enable Australian science and technology to capture international developments for Australia.

In the context of these goals, the three questions asked of the expert panels in the COSEPUP studies are still relevant, namely:

- What is the position of Australian research in nanotechnology relative to that in other regions or countries?

- On the basis of current trends in Australia and worldwide, what will be the relative position of Australia in nanotechnology in the near and longer-term future?
- What are the key factors influencing relative Australian performance in nanotechnology?

2.2 Benchmarking methodology used

1. Establish an expert steering committee. This expert steering committee is charged with consideration of the three questions specified in the previous section, with regard to the goals specified for the Australian context.
2. The expert committee's initial tasks are to:
    - identify relevant sub-fields of nanotechnology to be considered in the project;
    - identify relevant keywords to be used in the bibliometric analysis.
3. Once the sub-fields and keywords are identified, perform a comprehensive bibliometric analysis.
4. Compile a preliminary report on the bibliometric analysis.
5. The expert steering committee is then to oversee the leadership survey/virtual congress peer assessments, as follows:

- From the bibliometric analysis (and recommendations from the expert steering committee), identify all Australian researchers/research groups working in nanotechnology.
- Survey all the Australian nanotechnology researchers/research group leaders. Provide them with the preliminary bibliometric analysis report, including a list of leading Australian researchers identified from the bibliometric analysis and ask:
    a) What sub-field(s) are you (or your research group) working in?
    b) Name the world leaders in that sub-field.
    c) Are any key researchers missing from the list of Australian researchers identified in the bibliometric analysis?
- Based on the results of the survey of Australian nanotechnology researchers (and recommendations from the expert steering committee), identify a panel of world experts in each nanotechnology sub-field.
- Survey the panel of world experts and ask:
    a) Name the world leaders in the sub-field.

b) Name any Australian nanotechnology researchers/research groups whose work you are aware of.

6. Examine the responses from the surveys to see if any prominent researchers have been missed. If not, it can be concluded that the keywords used have adequately captured the bulk of Australia's nanotechnology publications. If some important researchers have been missed, investigate why this has happened and modify the keywords if necessary.
7. The expert steering committee may then analyse the results of the bibliometric analysis, the leadership surveys, and any other supporting data to assess Australia's nanotechnology capability.

3 Nanotechnology results

3.1 Expert steering committee

An expert steering committee was chosen to oversee the project, with expertise across the major areas of nanotechnology (nanomaterials, nanobiotechnology and nanoelectronics/ photonics); members from academia and industry; and a wide geographical representation. The membership of the committee was as follows:

- **Professor Bruce McKellar, FAA (Chair)**, Secretary, Physical Sciences, Australian Academy of Science, and Professor of Theoretical Physics, University of Melbourne;
- **Professor Frank Caruso**, ARC Federation Fellow, Department of Chemical and Biomolecular Engineering, University of Melbourne;
- **Professor Bob Clark, FAA**, Director
- **Dr Bruce Cornell**, Senior Vice President and Chief Scientist, Ambri Ltd;
- **Associate Professor Andrew Dzurak**, Node Manager; Centre for Quantum Computer Technology, University of New South Wales;
- **Professor Chennupati Jagadish**, Dept of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, Australian National University;
- **Professor Paul McCormick, FAA**, Director, Special Research Centre for Advanced Mineral and Materials Processing, University of Western Australia.

3.2 Bibliometric analysis

3.2.1 Introduction

A database of Australian nanotechnology publications was compiled using the ISI Web of Science's on-line search facility. A comprehensive list of keywords and phrases relevant to nanotechnology was assembled by an iterative process including:

- consultation with the expert steering committee and other leading researchers;
- examination of the keywords used in publications by leading Australian and international nanotechnology researchers;
- 'trial and error' testing of each suggested keyword/phrase to determine relevance.

The list of keywords and phrases is given in Appendix 1. The Web of Science was used to identify any publications where the keywords or phrases occurred in the TITLE, KEYWORDS or ABSTRACT fields AND with AUSTRALIA in the ADDRESS field of the publication. The searching was completed on 19 May 2003 and can be considered to include all publications up to that date.

3.2.2 Limitations of bibliometric analysis

When examining the results of the bibliometric analysis, the following limitations should be taken into account:

- Obviously, the choice of keywords will affect which publications are included. The keywords and phrases were chosen in an attempt to capture any work that can be considered nanotechnology without also capturing work that cannot be considered nanotechnology. However, it is possible that the database may contain some publications that are not strictly nanotechnology, and may have omitted some publications that are nanotechnology. Some obviously spurious papers were deleted, however the database has not been screened paper by paper.
- The searches were done on publication titles, keywords, and abstracts, so publications in journals that do not always produce abstracts will not be as likely to be picked up. They will only be picked up if our keywords are present in the title. One implication of this is that researchers publishing in these journals may not appear to be as prominent.
- The Web of Science was searched only for publications with 'Australia' in the author address. This will exclude publications produced by Australian scientists while working in overseas institutions.
- For the citation analysis, 'expected citation' data was only available for papers published prior to mid 2002, which includes 3508 of the 4188 publications. The 'actual citation' values used are therefore as of mid 2002, ie, less than the

actual citations now. These recent publications will mostly have zero or low citations so this should not affect the analysis significantly.

- Similarly, 'cleaned' address data was only available for the same period (the address data from the Web of Science does not come in a user-friendly format). Hence detailed address data (including collaboration data) only comes from this sub-set of the main database.

3.2.3 General results

A total of 4188 Australian nanotechnology papers were identified, compared with 296,239 publications for the whole world using the same keywords. Therefore, **Australia produced 1.41 per cent of the world's nanotechnology publications**, for the period 1980-2003.

For the period 1998-2003, Australia produced 2625 nanotechnology publications, representing around 1.49 per cent of the world's nanotechnology publications. This is lower than for science as a whole, where Australia produced around 2.0-2.4 per cent of the world's science publications for the period 1990-1999 (from *Monitoring Australia's Scientific Research*, Linda Butler, 2001). Figures 1 and 2 show some publication data trends for the period 1990-2003.

Using the search string 'nano*' alone gives 1393 Australian publications compared with 101,292 for the whole world, ie, 1.38 per cent of the world's publications.

A list of prominent Australian nanotechnology researchers obtained from the publications database is given in Appendix 2. **Note that this list will only include researchers whose publications contain one or more of the keywords shown in Appendix 1, and only if those publications contain AUSTRALIA in the address field.** Therefore, publications produced by researchers while working in overseas institutions are not counted (unless co-authored with a researcher at an Australian institution).

A list of prominent Australian nanotechnology institutions and companies is given in Appendix 3.

A list of the main journals in which the papers are published is given in Appendix 4.

Figure 1 – Number of Australian nanotechnology publications

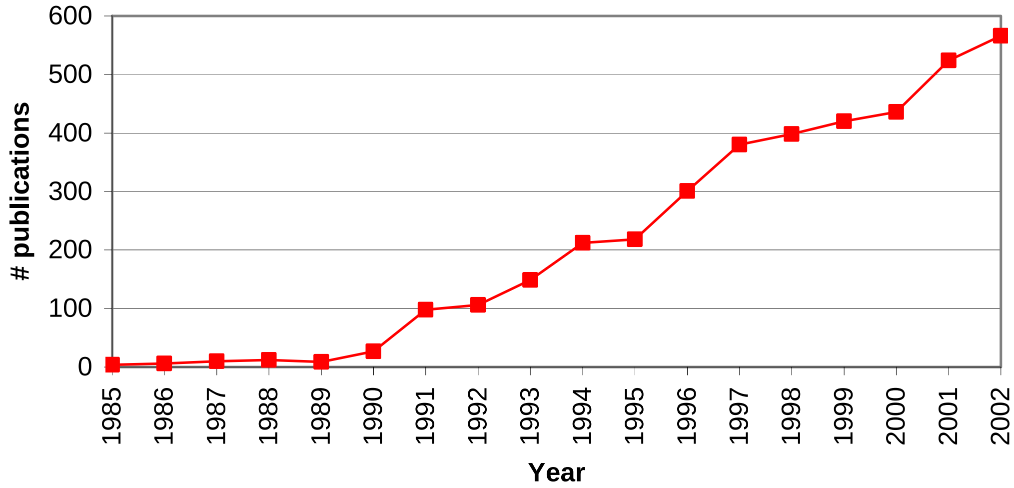
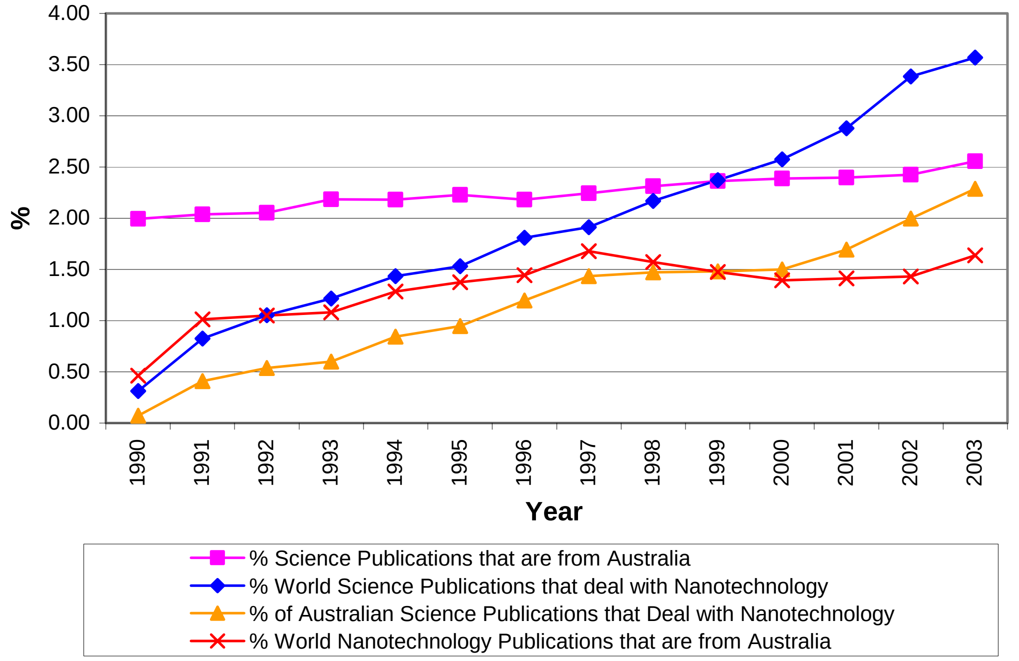


Figure 2 – Nanotechnology publication data trends for the period 1990-2003



From Figures 1 and 2 we see the following:

- The number of Australian nanotechnology publications has increased fairly steadily each year since 'taking off' around 1990.
- Figure 2 indicates that Australia's share of world science publications (squares) has been slowly increasing since 1990.
- Nanotechnology's share of world science publications (diamonds) has been increasing linearly since 1990, indicating that nanotechnology is rapidly becoming an important area of research throughout the world.

- The percentage of Australian science publications that contain nanotechnology (triangles) is increasing, indicating that nanotechnology is becoming an important area of research in Australia. However, it appears that this increase is less rapid than for the world as a whole.
- Australia's share of world nanotechnology publications (crosses) peaked in the mid to late 1990s but has decreased since then.

The data suggests that while Australia's nanotechnology capability is increasing, we have not been keeping pace with the rest of the world in the past 5 or 6 years.

3.2.4 Citation analysis

Simply counting the number of publications only gives a limited indication of a country's contribution to a field. For example, a country producing a small number of high quality publications may be contributing more to the field than a country producing a large number of low quality publications. A standard indicator used to measure a publication's quality is the number of citations it receives. Average citations per paper can be used to indicate the relative impact of a group of publications, eg, from a particular journal, field or country. However, average citation rates vary from year to year (since older publications have more time to accumulate citations) and from field to field, so it is necessary to relate the actual citation rates to 'expected' citation rates. This is particularly true for a multidisciplinary field such as nanotechnology. A citation analysis of Australian nanotechnology papers shows:

Average citations per paper = 11.2

Average expected citations per paper* = 7.8

* Each paper is assigned an expected value by ISI, based on the average number of citations for the type of paper in the particular journal in the particular year in which the paper is published (ie, it is not the expected value for 'nanotechnology' papers).

The analysis indicates that Australian nanotechnology papers are being published in relatively high impact journals (see Appendix 4), and are receiving a higher than average citation rate in those journals. This may be expected in an emerging field such as nanotechnology that is generating interest in the scientific community. However, we cannot determine whether Australian nanotechnology papers are higher impact than the world average nanotechnology papers. To determine this 'world average nanotechnology citation rate' would be an exceedingly large and time-consuming task. Hence, comparisons of citation rates with other countries or regions are difficult.

3.2.5 Comparisons of publication data from other countries and regions

Figures 3, 4 and 5 show a comparison of the publication output of three selected countries with Australia, using the same keywords and criteria that were used to generate the Australian data. A citation analysis for each country would be very time-consuming and would require more data to be purchased from ISI (for expected citation rates) so is not a practical option for this project. However, publication numbers can give some insights into the respective strengths of each country.

Figure 3 - Percentage of world science publications (all science) from selected countries

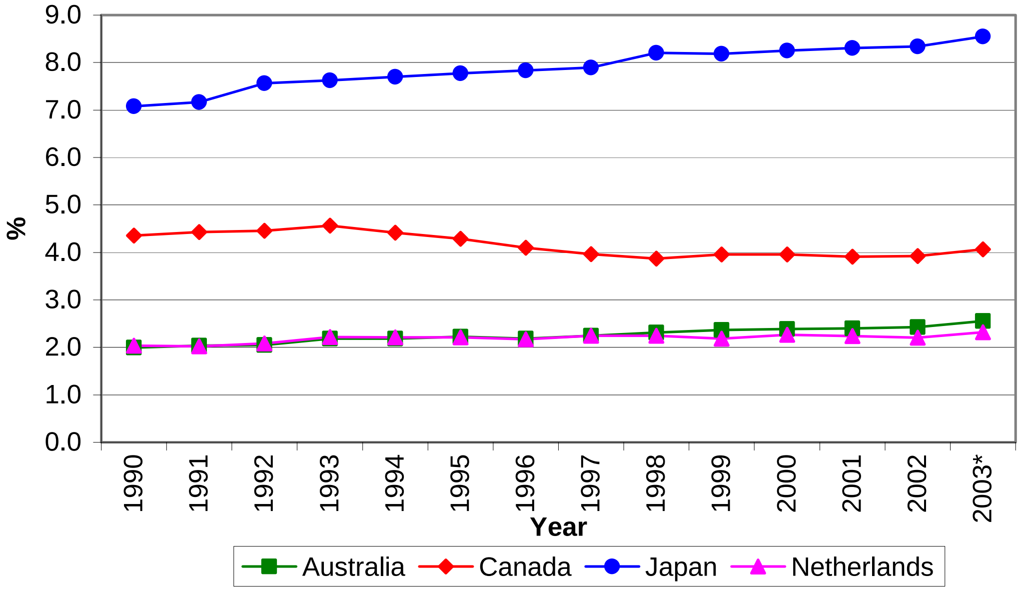


Figure 4 - Percentage of nanotech publications compared to all science publications

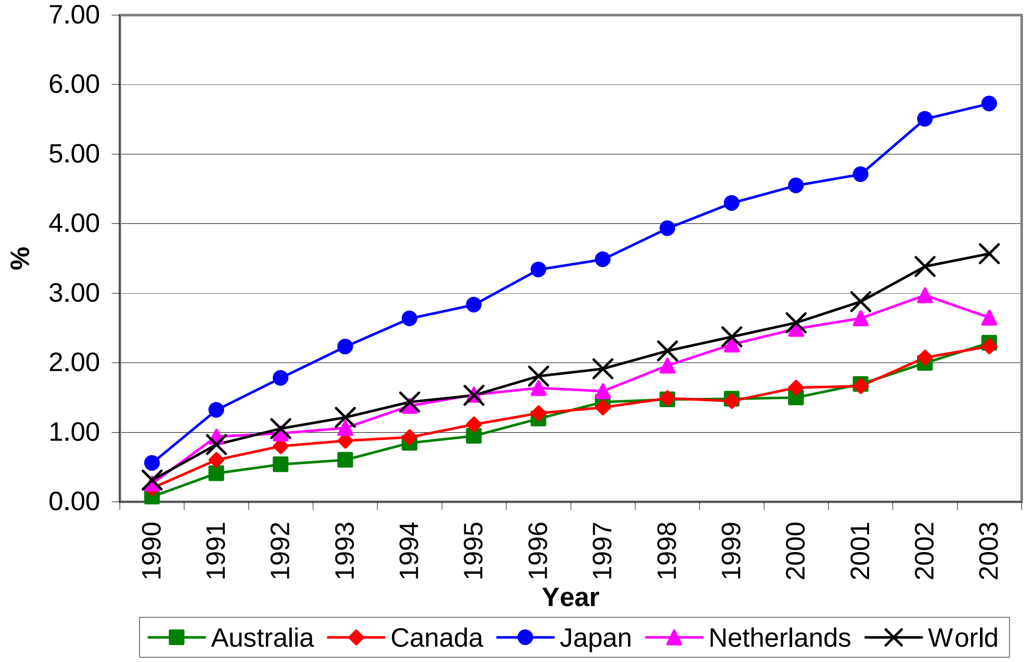
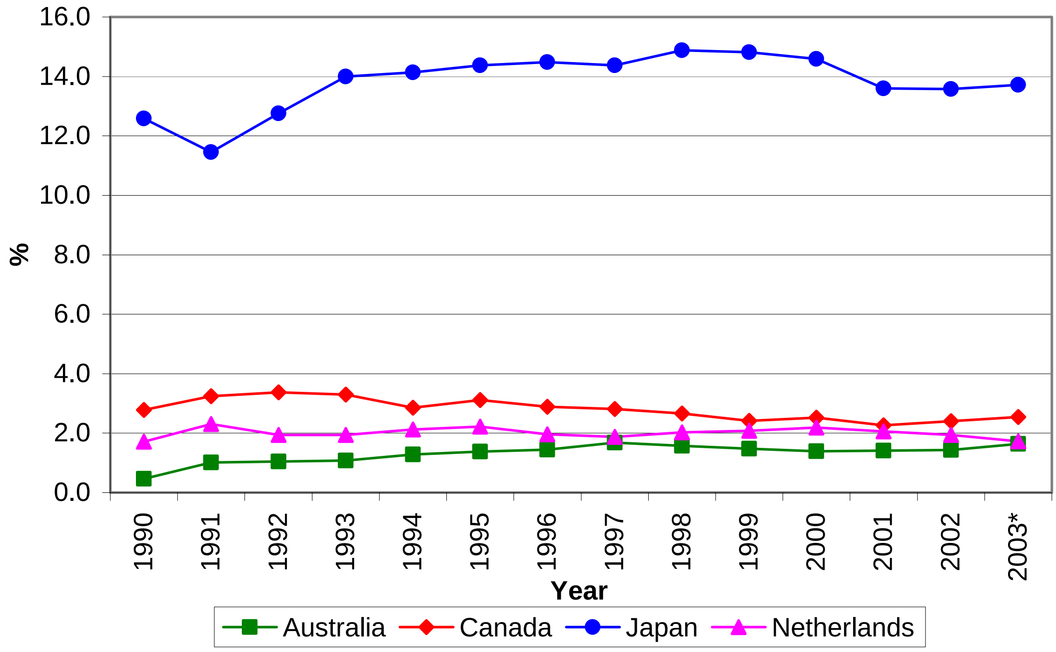


Figure 5 - Percentage of world nanotech publications from selected countries

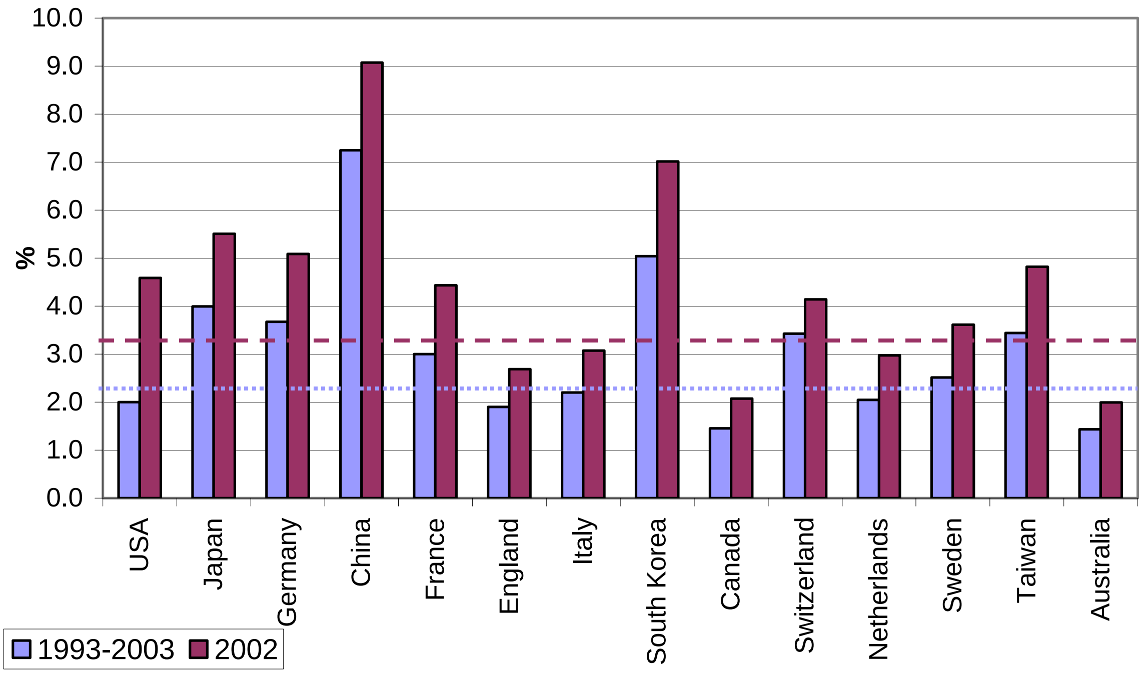


From the above figures we observe the following:

- Japan is the only country of the four whose share of world nanotechnology publications is higher than their share of all science publications. The Netherlands' share of world nanotechnology publications is similar to their share of all science publications; Australia's is slightly lower; and Canada's share of nanotechnology publications is much lower than their share of all science publications (about half). This suggests that nanotechnology is a high priority area in Japan, average priority in the Netherlands and Australia, and low priority in Canada.
- Australia seems to be catching up with Canada and the Netherlands in nanotechnology, but losing ground to Japan.

Figure 6 shows publication data for some more of the prominent nanotechnology countries and regions, using the same keywords and criteria that were used to generate the Australian data. The graph shows the percentage of each country's science publications that deal with nanotechnology for the period 1993-2003 (August) and for the year 2002. The world averages for each period are also shown as horizontal lines. As would be expected, nanotechnology represents a larger portion of each country's science publications in 2002 compared with over the past 10 years, indicating the increasing interest in nanotechnology. Clearly, nanotechnology appears to be a smaller sector of science in Australia and Canada compared with all the other leading nations. Perhaps because these two countries have economies based on the primary industries, rather than manufacturing. In the Asian countries or regions, nanotechnology makes up a larger sector of their science outputs compared with the world average, indicating that the Asian region is focusing on nanotechnology more than the rest of the world.

Figure 6 - Percentage of science publications that are nanotech, for selected countries or regions



World average 1993-2003 = ················ World average 2002 = – – – – – –

3.2.6 Collaboration data from Australian nanotechnology publications

Australian nanotechnology publications with collaborations are given in Appendix 5, by country and number. The main countries that Australia collaborates with are the USA, England, Japan, Germany and China.

Figure 7 shows collaboration trends for Australian nanotechnology publications. The categories are:

- single Author – one author only, ie, no collaboration;
- institutional – more than one author from the same institution is listed in the address field;
- national – more than one Australian institution is listed in the address field;
- international – publications with multiple authors where at least one country other than Australia is listed in the address field.

Note that it is possible for a publication to be included in both the national and international categories (ie, collaboration with a number of Australian institutions as well as one or more overseas institution).

Figure 7 – Levels of collaboration in Australian nanotechnology publications

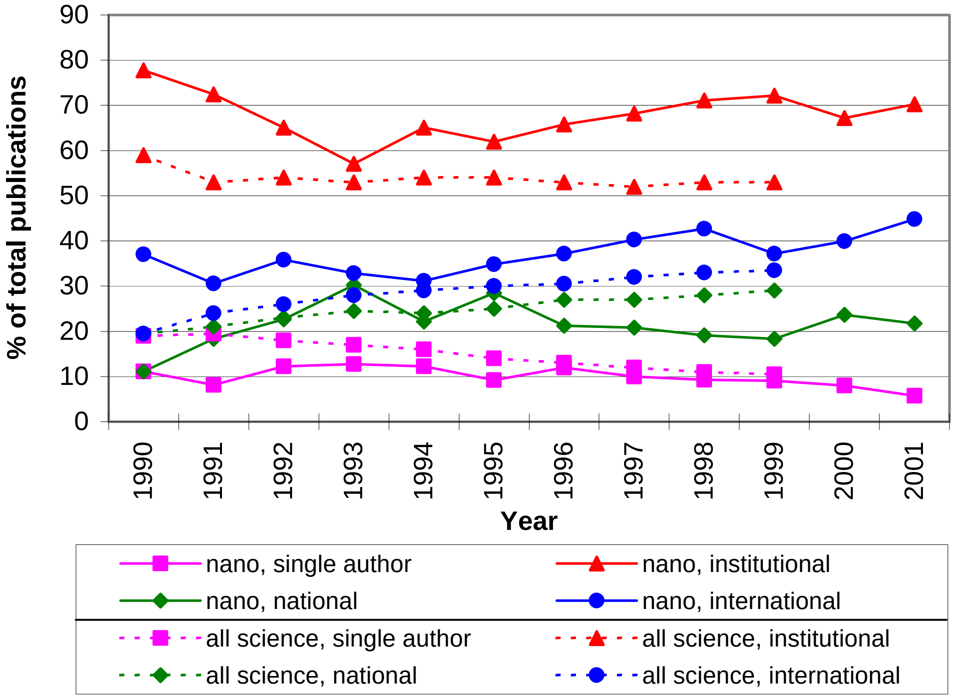


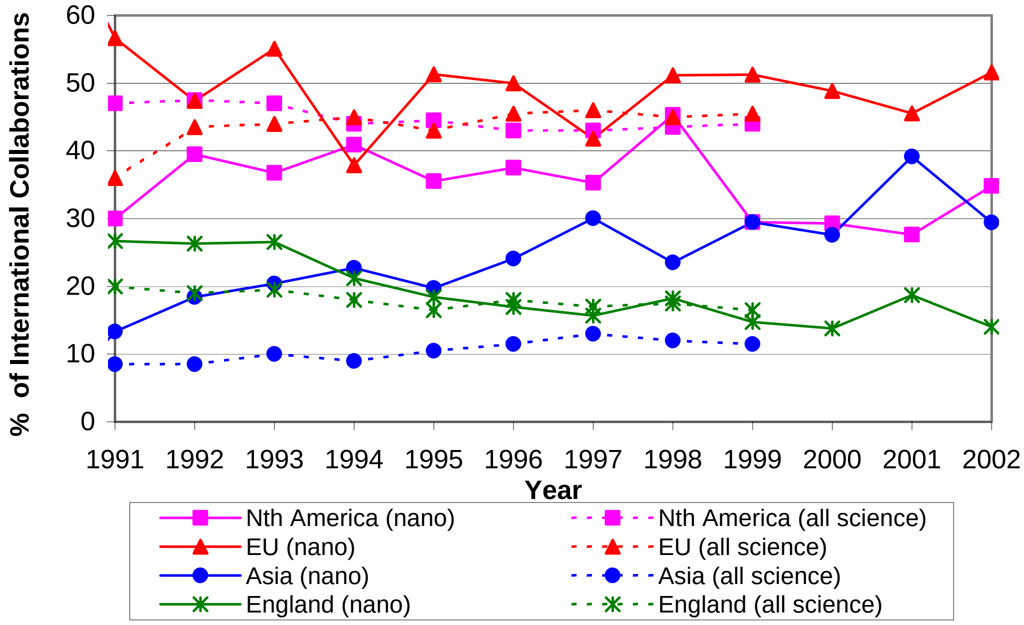
Figure 7 shows that the percentage of nanotechnology publications with international collaboration has been generally increasing since 1990. Also shown are data for Australian science in general (from *Monitoring Australia's Scientific Research*, Linda Butler, 2001), indicating that Australian nanotechnology publications have a higher level of international collaboration than for Australian science in general. The figure also shows a lower level of national collaboration (ie, between Australian institutions) in nanotechnology compared with all Australian science.

Figure 8 shows the percentages of nanotechnology publications with collaborations with different regions. Also shown are data for Australian science in general (from *Monitoring Australia's Scientific Research*, Linda Butler, 2001). Note that the data relates only to publications that have international collaboration. The data for nanotechnology is 'noisy' due to the low sample numbers. From the graph we observe that:

- There is a higher level of collaboration with Asia in Australian nanotechnology publications compared with all Australian science, indicating that Australian researchers are recognising and taking advantage of Asia's relative strength in nanotechnology. This collaboration with Asia in nanotechnology is increasing, as it is for Australian science in general.
- Australian nanotechnology collaboration with Europe and North America is relatively steady and reflects similar levels of collaboration to that seen for Australian science in general (note that the EU data includes England).

- Collaboration with England is decreasing and, when contrasted with the relatively steady collaboration level with Europe, this implies that collaboration with 'continental' or 'non-English-speaking' Europe must be increasing. This applies for nanotechnology and for Australian science in general.

Figure 8 - Percentages of Australian nanotechnology publications with international collaborations with different regions



3.2.7 Collaborations with key nanotechnology organisations

One of the aims of this study is to examine whether Australian nanotechnology researchers have links with the major research groups who are seen as world leaders in nanotechnology, wherever they may be. A useful source of information to decide on world-leading groups is a study currently being conducted by the Center for Science and Technology Studies (CWTS) at Leiden University, in association with the Fraunhofer Institut fur Systemtechnik und Innovationsforchung (FhG-ISI). See http://www.cwts.nl/ec-coe/cgi-bin/izite.pl?show=home.

There is a (limited) searchable interface on their website which provides some bibliometric data for a number of fields, including nanotechnology. The keywords they used to generate their database of publications are a subset of the ones used in this report, and their data comes from the period 1996-2000 only. This interface can be used to give some quantitative data on which institutes are the world leaders in nanotechnology publications. Table 1 lists the top organisations in the world according to the data from the CWTS site. To rank them, a combination of number of papers, total citations, and number of papers in the top 10 per cent of publications was used. The last column gives the number of publications from our Australian nanotechnology publications database that have collaborations with each of the organisations listed. The table indicates that Australian researchers have at least some collaboration with most of the world's leading nanotechnology research institutions.

It is possible to compare some of Australia's top nanotechnology institutions with the rest of world, using data available from CWTS website. Only three Australian institutions appear on the top 100 lists for any criteria. The details are given in the following table.

Institutions	P	CX	P10	CPP	CPP/ FCSm	Comb Index
Univ Melbourne	190	1046	12	5.51	2.46	5.86
UNSW	266	748	5	2.81	1.72	1.71
Departments						
Univ Melb, Sch Chem	26	371	1	14.27	7.83	0.08
Univ Qld, Dept Biochem, Ctr Prot Struct Funct & Engn	12	113	2	9.42	2.15	0.03
UNSW, Sch Phys, Semicond Nanofabricat Facil	11	239	1	21.73	7.64	0.02

P = number of nanotechnology publications;
CX = total number of citations to those publications;
P10 = number of papers in the top 10 per cent of most highly cited papers in nanotechnology;
CPP = average citation rate for the nanotechnology papers;
CPP/FCSm = the number of citations per publication (*CPP*), divided by the *mean* number of citations per publication in the field to which the publication belongs (*FCSm*);
Comb. Index = a combination of all indices = P*CX*P10*(CPP/FCSm)/10^6.

Table 1 – Australian collaborations with top ranked overseas organisations

Organisation	P	CX	P10	CPP	CPP/ FCSm	Comb. Index	# Aust Collabs
Univ Calif Berkely, USA	841	4794	61	5.70	3.23	794.38	7
Rice Univ, USA	327	4193	46	12.82	5.41	341.21	0
MIT, USA	661	3556	54	5.38	2.65	336.36	7
Univ Calif Santa Barbara, USA	472	3310	48	7.01	2.99	224.22	14
Univ London, UK	823	3341	42	4.06	1.91	220.58	24
Harvard Univ, Cambridge USA	365	3266	42	8.95	3.53	176.74	2
Univ Illinois, USA	625	2827	29	4.52	2.52	129.12	11
Univ Minnesota, USA	450	2277	40	5.06	2.65	108.61	3
Stanford Univ, USA	448	2178	38	4.86	2.33	86.39	3
Cornell Univ, USA	492	2039	31	4.14	2.33	72.46	12
Univ Michigan, USA	419	2333	22	5.57	3.21	69.03	8
Georgia Inst Technol, USA	340	2080	27	6.12	3.54	67.59	5
Northwestern Univ, USA	395	2056	22	5.21	3.64	65.03	4
Swiss Fed Inst Technol Epfl, Switzerland	542	2060	22	3.80	2.59	63.62	7
Univ Pennsylvania, USA	360	2299	22	6.39	2.48	45.16	1
Univ North Carolina, USA	290	1717	26	5.92	3.31	42.85	10
Penn State Univ, USA	440	1746	23	3.97	2.36	41.70	3
Res Ctr Julich, Germany	460	1602	26	3.48	2.06	39.47	2
Univ Wisconsin, USA	420	1826	23	4.35	2.17	38.28	5
Natl Inst Hlth, USA	309	2094	31	6.78	1.89	37.91	3
Tohoku Univ, Japan	1046	1680	15	1.61	1.41	37.17	9
Univ Cambridge, UK	685	1769	20	2.58	1.50	36.35	43
US Navy, USA	504	1781	17	3.53	2.31	35.25	0
Univ Washington, USA	335	1549	23	4.62	2.58	30.79	11
Oak Ridge Natl Lab, USA	467	1615	19	3.46	2.13	30.52	12
Delft Univ Technol, Netherlands	268	1859	12	6.94	5.00	29.89	4
Univ Oxford, UK	491	1840	18	3.75	1.78	28.95	30
Univ Munich, Germany	390	1602	23	4.11	1.99	28.60	4
Tech Univ Munich, Germany	420	1577	19	3.75	2.27	28.57	2
Univ Strasbourg 1, France	308	1624	21	5.27	2.67	28.05	5
Univ Ulm, Germany	332	1511	22	4.55	2.52	27.81	2
Nth Carolina State Univ, USA	337	1323	21	3.93	2.97	27.81	4
Natl Inst Stand & Technol, USA	358	1369	17	3.82	3.26	27.16	9
Tokyo Univ, Japan	914	1571	15	1.72	1.25	26.92	6
European Molec Biol Lab, Germany	79	2722	18	34.46	6.46	25.00	3
Univ Calif La Jolla, USA	312	1555	22	4.98	2.26	24.12	4
Argonne Natl Lab, USA	316	1356	20	4.29	2.58	22.11	13
Univ Basel, Switzerland	339	1416	23	4.18	1.90	20.98	0
IBM Corp, USA	201	1306	18	6.50	4.02	18.99	24
Univ Calif Los Angeles, USA	388	1424	17	3.67	2.01	18.88	10
Johns Hopkins Univ, USA	284	1419	20	5.00	2.32	18.70	2
Texas A&M Univ, USA	282	1235	22	4.38	2.23	17.09	3
Princeton Univ, USA	193	1412	21	7.32	2.85	16.31	5
Univ Paris 06, France	557	1232	13	2.21	1.62	14.45	8
Sandia Natl Labs, USA	229	1236	14	5.40	3.40	13.47	5
Autonom Univ Madrid, Spain	293	1210	17	4.13	2.17	13.08	1
Univ Birmingham, UK	306	1655	12	5.41	2.07	12.58	4
Univ Toronto, Canada	364	1242	15	3.41	1.81	12.27	0
Swiss Fed Inst Tech ETHZ, Switzerland	384	1042	13	2.71	1.87	9.73	3

3.2.8 Sub-field analysis

Three main sub-fields of nanotechnology are widely acknowledged by the worldwide nanotechnology community and are examined here, namely:

- nanomaterials;
- nanobiotechnology;
- nanoelectronics/photonics.

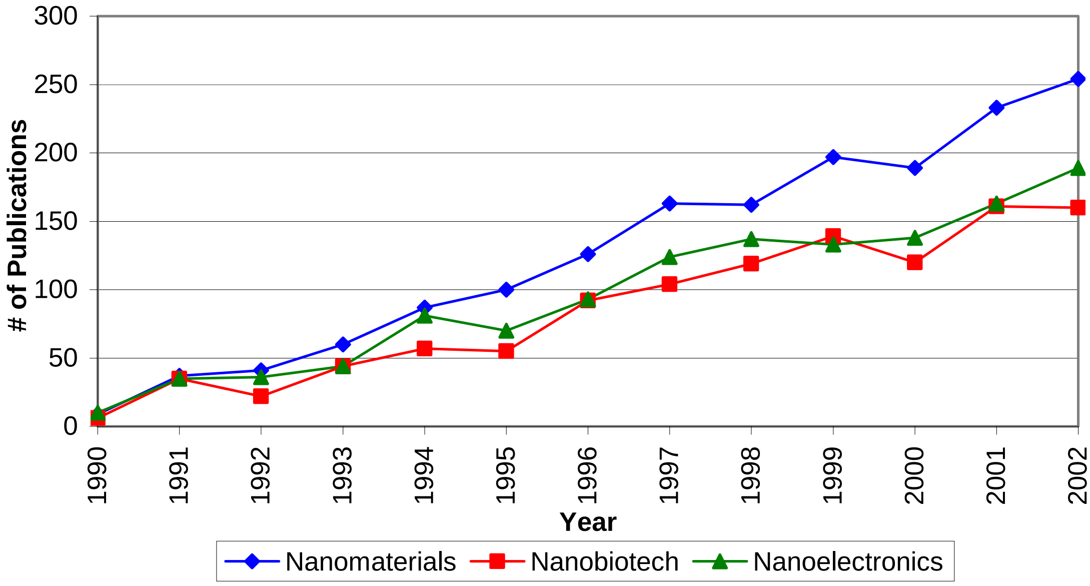
Of the 4188 Australian nanotechnology publications identified from the Web of Science, the sub-field breakdown is:

- Nanomaterials = 2069, average citations per paper = 11.0, expected citations per paper = 7.0;
- Nanobiotechnology = 1213, average citations per paper = 13.0, expected citations per paper = 9.0;
- Nanoelectronics/photonics = 1470, average citations per paper = 9.3, expected citations per paper = 7.4.

Note that the numbers do not add up to 4188 as some publications fit into more than one category.

A graph of the yearly publication trends for each sub-field is given in Figure 9.

Figure 9 – Australian nanotechnology publication trends by sub-field



3.2.9 Key topic analysis

Table 2 lists some key nanotechnology topics and shows the number of publications relevant to each topic. The percentage share of publications for each topic are within about 1 per cent of the average Australian nanotechnology share of 1.41 per cent, indicating no dramatic strengths or gaps for the topics chosen. However, the data does suggest weaknesses in soft lithography, quantum dots and semiconductor nanostructures, and a strength in biosensors.

Table 2 - Number of publications relevant to selected nanotechnology topics

Topic	No. of Aust publications	Percentage of world
Nanocomposites and coatings	186	1.52%
Nanoparticles	612	1.46%
Nanotubes	111	1.23%
Catalysis	287	1.53%
Energy storage and distribution	47	1.63%
Self assembly	204	1.12%
Nano-medicine	220	1.36%
Dendrimers and supramolecular chemistry	114	1.72%
Fullerenes	213	1.61%
Biosensors	250	2.52%
Semiconductor nanostructures	232	1.04%
Quantum dots	121	1.02%
Quantum computing	489	1.17%
Soft lithography (nano-imprinting)	15	0.60%

3.3 Patent data

Some good nanotechnology patent data analyses are provided in the paper 'Nanotechnology Strength Indicators: International Rankings Based on US Patents' by Marinova and McAleer, in *Nanotechnology*, vol. 14, 2003.

The results from the paper are summarised in Table 3, and show that Australia ranks 7th in the world (excluding the USA) in US nanotechnology patents, based on a number of different ranking criteria, not just absolute number of nanotechnology patents (where we rank 9th).

Table 3 – Patent data for the top 12 foreign patenting countries in the USA

Country	P	PI	TS	PS	RAP	CR	Rank
France	1817	31	1.42	4.26	0.85	3.88	1
Japan	3856	30	0.51	9.05	0.97	4.59	2
Canada	1249	40	1.33	2.93	0.48	6.00	3
Germany	1524	19	0.50	3.57	0.74	4.17	4
Switzerland	502	69	0.83	1.18	0.55	5.82	4
Netherlands	384	24	0.89	0.90	0.59	5.00	4
Australia	**313**	**16**	**1.38**	**0.73**	**0.75**	**2.75**	**7**
Great Britain	603	10	1.37	1.41	0.55	2.63	8
Italy	334	6	0.62	0.78	0.66	3.89	9
Sweden	179	20	0.44	0.42	0.70	4.95	10
Taiwan	253	11	0.40	0.59	0.88	3.40	11
Korea	175	4	0.44	0.41	0.81	2.35	12
Mean	*932*	*23*	*0.84*	*2.19*	*0.71*	*4.12*	

P = number of US patents.
PI = Patent intensity. Number of patents per million of population.
TS = Technological Specialization Index. Reflects the relative strength of nanotechnology in the country compared with nanotechnology in all countries, ie, TS>1 represents a strength at the national level compared with international standards (ie, reflects the relative importance of nanotechnology in the particular country).
PS = Patent share. Percentage of all nanotechnology patents from a particular country.
RAP = Rate of Assigned Patents. The number of nanotechnology patents assigned to residents of a particular country divided by the number of nanotechnology patents invented by residents of a particular country (this is a measure of the perceived proximity of patents to commercialisation).
CR = citation rate. The number of citations for the nanotechnology patents in a particular country divided by the number of nanotechnology patents for the country (is a measure of the usefulness of patents to subsequent patents, and hence in the creation of new knowledge).
Ranking = a ranking for each of the listed countries based on their ranking in each of the 4 indicators TS, PS, RAP and CR (each indicator given equal weight).

3.4 Funding data for nanotechnology

Australia has no formal national nanotechnology initiative. Other countries, notably the USA, Japan and the UK, have formal national nanotechnology initiatives that not only pour large amounts of money into nanotechnology R&D, but also serve to focus and direct the national effort (eg, the USA's National Nanotechnology Initiative invested US$847 million on nanotechnology research in 2003 and has committed US$3.7 billion for 2005-2008). Australia risks falling behind if a similar organisation is not set up here, especially since to be competitive we will need to target our limited funds to specific areas. A positive example is the establishment, through the Commonwealth Government's Major National Research Facilities program, of the Nanostructural Analysis Network Organisation (NANO) to provide the peak Australian facility for nanometric analysis of the structure and chemistry of physical and biological materials.

The Australian Bureau of Statistics (ABS) has recently included nanotechnology as a category under its classification system, so there is now some data available on

Australian expenditure on nanotechnology in the financial year 2000-2001 (published in 2002). The data indicates that total spending for 2000-2001 on nanotechnology was A$1,515,000, consisting of $582,000 from CSIRO Nanotechnology and $933,000 from the higher education sector. This data will be an underestimate, as the emerging and cross-disciplinary nature of the field means that most spending is being reported under more traditional categories. However, as nanotechnology becomes more established this data source will become a more meaningful reflection of money spent.

Stephen Walker from the ARC has compiled a list of ARC-funded projects commencing in 2002 and in 2003, where the string 'nano' is in the project title or the project summary. The data is summarised in Table 4. A total of **A$53,013,909** has been allocated for these projects over their project lives, from 2002-2007.

Table 4 – ARC funding for nanotechnology projects, commencing 2002 and 2003

	2002	2003	2004	2005	2006	2007
Projects	2,451,602	10,513,872	9,779,102	7,601,780	2,543,664	718,262
Infrastructure and equipment	1,912,000	3,384,342	-	-	-	-
Federation Fellowships and CSIRO postdocs	2,250,000	2,314,345	2,314,345	2,314,345	2,250,000	2,250,000
International exchanges/ collaborations	144,700	151,060	117,590	2,900	-	-
Total	**$6,758,302**	**$16,363,619**	**$12,211,037**	**$9,919,025**	**$4,793,664**	**$2,968,262**

(Note: The funding for 2002 and 2003 can be considered final, but more money will be allocated in subsequent funding rounds to be spent in 2004-2007 and beyond.)

State governments are also funding nanotechnology infrastructure in their states. For example, the Victorian Government has committed A$12 million to 'Nanotechnology Victoria' for the period 2003-2005, to invest in nanoscience infrastructure, research programs and commercialisation activities; and the Queensland Government has committed A$20 million to establish the A$50 million Institute for Bioengineering and Nanotechnology.

3.5 Undergraduate nanotechnology courses in Australia

The following information has been obtained from documentation prepared for a Course Evaluation Committee for a proposed Bachelor's degree in nanotechnology at the University of Wollongong. Use of this material for the Nanotechnology Benchmarking Project has been cleared with Dr Geoff Spinks at the University of Wollongong.

Most Australian universities include education in nanoscience and nanotechnology as part of their BSc and BE undergraduate courses, as well as postgraduate studies in nanotechnology. Specific undergraduate nanotechnology courses are now offered by the University of New South Wales, the University of Technology Sydney, Flinders

University, and are planned for the University of Wollongong, the University of Western Sydney and Monash University. All courses have varying numbers of elective subjects and usually one specialist nanotechnology subject in each year of study. Each of the courses is slightly distinctive in its emphasis:

- Flinders A: Chemistry/Biology
- Flinders B: Physics
- University of New South Wales: Physics/Chemistry/Biology
- University of Wollongong: Materials/Chemistry.

Details of other courses offered at the University of Technology Sydney, Monash University and the University of Western Sydney were not fully available for the purposes of this summary.

Table 5 - Course comparison table. Number of subjects offered in each discipline area (numbers in parentheses are elective subjects)

University	Materials	Chem	Math	Physics	Biol	Eng	Nano	Other
Wollongong - 4-year (4x48cp / 6 electives)	6.5 (4)	7 (4)	2 (1)	3.5 (3)	(3)	(4)	4	
Wollongong - 3-year (3x48cp / 6 electives)	4 (4)	7 (4)	2 (1)	3 (3)	(3)	(4)	3	
UNSW (4x48 cp / 5.5 electives)	2 (4)	4.5 (2)	2	5.5 (1.5)	3 (2.5)	(0.5)	4.5	2 (0.5)
UTS (3 or 4 x48 cp / yrs 2 & 3 still to be detailed)	2	3	3	3	1		2	
Flinders A (4x36 cp / 3 electives)	(1)	8 (2)	2	3	6	1	4	4 (1)
Flinders B (4x36 cp /3 electives)	(1)	3	9	10 (4)	0	1	4	4

3.6 Results of leadership survey

The leading Australian researchers identified in the bibliometric analysis were sent a copy of the preliminary bibliometric results, along with a survey asking them to:

- identify ten world leaders in nanotechnology;
- identify any leading Australian nanotechnology researchers NOT identified in Appendix 2;
- rate their impression of how Australia stands in nanotechnology (and its various sub-fields and topics) now and in the future;
- identify the 'tools' they use for nanotechnology research, and the tools they would like to have access to;
- provide any general comments or feedback.

From the 94 surveys sent out, 38 responses were received.

A wide variety of world leaders were identified (145 in total), indicating that there are few clearly established world leaders in this field, taken as a whole. As well as the 'emerging' nature of nanotechnology, this is also no doubt due to the multidisciplinary nature of nanotechnology, as each sub-field or topic has its own distinct leaders. Eleven of the 145 world leaders identified by Australian researchers were Australian.

Thirty of the world leaders identified were named more than once, so they were taken to be the main world leaders in nanotechnology as seen by Australian researchers. Two were Australian. The 30 world leaders were surveyed and asked to identify who they see as the world leaders, and asked to identify any leading Australian nanotechnology researchers whose work they were aware of. Ten replies were received. The world leaders who were named corresponded well with those named by the Australian researchers. Fifty-four different world leaders were identified, of which two were Australian. All of the world leaders surveyed struggled to list prominent Australian nanotechnology researchers. While this result suggests that Australia does not have many key players on the world nanotechnology stage, it is consistent with Australia's publication output of around 2 per cent of world science publications.

The leading Australian researchers were asked to rate where they see Australia's standing in nanotechnology (and its sub-fields or topics) now, and in the future, using the following scale:

Research leadership. Defining the direction taken by the research frontier, ie 'the best of the best'.
Research excellence. Possessing the capability to play a leading role in advancing the research frontier, even if not currently setting the overall direction, ie, 'the best'.
Research competence. The capability to monitor and fully understand the advances being made, with the option to move to research excellence with a modest increase in investment, ie, 'the competent'.
Research tracking. Possessing the capability to monitor and understand the advances being made, but with insufficient capability to move to research excellence without significant investment, ie, 'watching from the side-lines'.

On average, Australian researchers saw Australia sitting at the 'research competence' level, with the impression that Australia is moving towards, but not reaching, the 'research excellence' level in nanotechnology over the next 5-20 years. The results were similar for each of the main sub-fields (nanomaterials, nanobiotechnology and nanoelectronics/photonics). These results reflect Australia's position as having a good base of nanotechnology expertise, but currently without the resources to play a major role in advancing the research frontier. The survey findings are also consistent with the results of the bibliometric analysis that show Australia's nanotechnology research outputs are struggling to keep up with the rest of the world.

When the Australian researchers were asked to identify any leading Australian researchers not identified in the bibliometric analysis, only a few names were suggested. Upon further investigation, most of these names were absent from the bibliometric analysis due to the researchers having done most of their work overseas, or because the researchers were working in a commercial environment where much of their research was not published in journals. This result suggests that the keywords used did in fact pick up the majority of nanotechnology publications and researchers. Therefore, it was concluded that the keywords were acceptable.

The leading Australian researchers were also asked to identify the 'tools' they used for nanotechnology research, and the tools they would like to use but do not currently have access to. With this information, a 'register' of nanotechnology equipment in Australia could be set up to assist in the sharing of infrastructure in Australia. It is hoped that the results can be used as a starting point upon which to build a more complete register. The most commonly listed tool that researchers would like to use but do not currently have access to was a synchrotron. This should be remedied in the near future when the Australian synchrotron facility is completed.

3.7 Discussion, conclusions and summary

Australia produced 1.41 per cent of the world's nanotechnology publications from 1980-2003 and 1.49 per cent from 1998-2003. This is lower than for science as a whole, where Australia produced 2.0-2.4 per cent of the world's science publications between 1990-99 (see Section 3.2.3). The number of Australian nanotechnology publications has increased fairly steadily each year since 'taking off' around 1990 (see Figure 1).

A citation analysis of Australian nanotechnology publications indicates that Australian nanotechnology papers are being published in relatively high impact journals, and are receiving a higher than average citation rate in those journals. This is to be expected in an emerging field such as nanotechnology that is generating interest in the scientific community. However, we cannot determine whether Australian nanotechnology papers are higher impact than the world average nanotechnology papers (see Section 3.2.4).

The percentage of world science publications relating to nanotechnology has been increasing linearly since 1990, indicating that nanotechnology is rapidly becoming an important area of research throughout the world. The percentage of Australian science publications containing nanotechnology is also increasing, indicating that nanotechnology is becoming an important area of research in Australia. However, it appears that this increase is less rapid than for the world as a whole. Australia's share of world nanotechnology publications peaked in the mid to late 1990s but has decreased a little since then, suggesting that while Australia's nanotechnology capability is increasing, we have not been keeping pace with the rest of the world in the past 5 years (see Figure 2).

From an analysis of the publication outputs of leading nanotechnology countries', nanotechnology represents a larger portion of each country's science publications in 2002 compared with over the last 10 years, indicating the increasing interest in nanotechnology. Nanotechnology appears to be a smaller sector of science in Australia compared with most other leading nations. In contrast, nanotechnology represents a larger sector of science in the leading Asian countries or regions compared with the world average (see Section 3.2.5, Figure 6).

The percentage of Australian nanotechnology publications with international collaboration has been generally increasing since 1990. Australian nanotechnology publications have a higher level of international collaboration than for Australian science as a whole. The rate of collaboration with Asia is increasing, increasing slightly with Europe, steady with North America, and declining with England (see Section 3.2.6, Figures 7 and 8).

Australia appears to have at least some collaboration with most of the worlds leading nanotechnology research institutions (see Section 3.2.7, Table 1).

Australia's publication outputs are consistent across the major nanotechnology sub-fields and key topics, indicating a broad level of expertise in all areas of nanotechnology (see Sections 3.2.8 and 3.2.9).

Australia ranks 7th in the world (excluding the USA) in US nanotechnology patents, based on a number of different ranking criteria, not just absolute number of nanotechnology patents (where we rank 9th) (see Section 3.3).

Australia has no formal national nanotechnology initiative, although an informal network is currently in the process of developing a formal structure. Other countries have formal national nanotechnology initiatives that not only pour (in some cases) large amounts of money into nanotechnology R&D, but also serve to focus and direct the national effort. Australia risks falling behind if a similar organisation is not set up here. However, there is Commonwealth Government investment in Australian nanotechnology research from the Australian Research Council (ARC) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), plus funding from state governments. Various ARC-funded nanotechnology projects which commenced in 2002 and 2003 have been allocated a total of A$53,013,909 over their project lives (see Section 3.4).

While nanotechnology is taught in most universities as a part of a BSc or BE degree, there are now some specific nanotechnology degrees. Flinders University in South Australia created the world's first Bachelor of Nanotechnology degree, and nanotechnology degrees are now offered by the University of New South Wales, the University of Technology Sydney and Flinders University and are planned for the University of Wollongong, the University of Western Sydney and Monash University (see Section 3.5).

The benchmarking results were 'peer reviewed' by sending preliminary results to leading Australian nanotechnology researchers for comment, along with a survey aimed at identifying world-leading researchers in the field, who subsequently were also surveyed. While the size of the sample was small, the survey confirmed that Australia has a small number of 'world leaders' in nanotechnology, but in some sub-fields the international researchers found it difficult to name Australian researchers. This is consistent with the bibliometric result that Australia's involvement in nanotechnology is not keeping up with the rest of the world (see Section 3.6).

Summary

Australian nanotechnology researchers are producing high-quality work across all areas of nanotechnology, but there is evidence that we are not advancing our capabilities as quickly as the rest of the world.

4 Assessment of benchmarking methodology

The benchmarking methodology outlined in Section 2 has been successfully applied to benchmarking Australia's nanotechnology capability.

Preliminary results from the benchmarking exercise have been well received, with a wide range of people having had the opportunity to provide feedback on the methodology and the results, including:

- expert steering committee involvement;
- more than 100 Australian and overseas nanotechnology researchers have had an opportunity to comment via a survey;
- preliminary results from the benchmarking exercise were presented at the Sir Mark Oliphant Conference, 'Scaling down to a nano-materials world', in Melbourne on 1-4 December 2003, where Australian and international participants took the opportunity to provide feedback.

In most cases, the feedback received has validated the findings from the benchmarking methodology.

Of particular value was the bibliometric analysis that was performed. The effectiveness of this analysis hinged on developing an appropriate set of keywords and phrases. This was done in an iterative process in consultation with experts in the field, and validated by surveying key Australian researchers to see if their experience agreed with the results. The bibliometric analysis provided a rich source of data with which to assess Australia's nanotechnology research outputs.

Surveying the leading Australian nanotechnology researchers proved to be useful in validating the results of the bibliometric analysis. However, the international virtual congress methodology adapted from the one used by COSEPUP was of less value, principally because of the small sample of international replies received. It may have been able to improve this part of the study by approaching more international experts, although the relatively small size of Australia's population and corresponding research effort means that it cannot be expected to have a large number of prominent researchers on a world scale.

Appendix 1 – Nanotechnology keywords

Search string 1

nanoa* OR nanob* OR nanoc* OR nanod* OR nanoe* OR nanof* OR nanog* OR nanoh* OR nanoi* OR nanoj* OR nanok* OR nanol* OR (nanom* not nanomol*) OR nanon* OR nanoo* OR nanop* OR nanoq* OR nanor* OR (nanos* not nanosec*) OR nanot* OR nanou* OR nanov* OR nanow* OR nanox* OR nanoy* OR nanoz* OR nano

Search string 2

atom* force microscop* OR tunnel* microscop* OR scanning probe microscop* OR scanning force microscop*

Search string 3

self assembl* OR self organized growth OR self organised growth OR molecul* assembl* OR positional assembl* OR molecular wire* OR molecular switch* OR single molecule* OR single atom* OR molecular manipulation OR molecular engineering OR molecular motor* OR molecular beacon*

Search string 4

quantum dot* OR quantum array* OR quantum device* OR quantum wire* OR quantum computer* OR quantum well* OR coulomb blockade* OR langmuir blodgett OR atom* manipulat* OR atom* scale OR single electron* tunnel* OR electron beam lithography OR quantum cellular automat* OR ultraviolet lithograph* OR PDMS stamp OR soft lithography OR surface acoustic wave* OR focused ion beam* OR focussed ion beam* OR quantum ratchet* OR DNA comput* OR NEMS OR MEMS OR molecular electronics OR resonant tunnel* OR single electron logic OR single electron transistor* OR (photonic AND bandgap AND crystal*) OR quantum size effect* OR spintronic* OR molecular comput* OR ballistic transport* OR low dimensional structure* OR qubit*

Search string 5

porous silicon OR supramolecular chemistry OR fulleren* OR colloid* particle* OR organometallic catalysis OR molecular catalys* OR organic catalys*

Search string 6

biomim* OR molecular membrane* OR synthetic membrane* OR modified virus* OR encapsulat* AND virus* OR molecular template* OR molecular recognition OR synthetic receptor* OR biocompatible membrane* OR biocompatible surface modification* OR S-layer* OR biosensor* OR lab on a chip OR biochip* OR molecul* channel* OR drug carrier* OR rational drug design OR (ion* channel* AND (synthetic OR device* OR screen* OR HTS OR diagnostic* OR sensor OR sensors OR implant* OR switch*))

Search string 7

(drug delivery OR drug action OR drug targeting OR gene therapy OR gene delivery) AND (polymer OR polymers OR particle* OR encapsul* OR conjugate OR molecular cage* OR fulleren* OR clath*)

site-specific AND (gene therapy OR drug delivery or drug action OR gene delivery)

(immobiliz* OR immobilis*) AND (DNA OR template* OR primer* OR oligonucleotide* OR polynucleotide*)

surface modification AND (molecular layer* OR multilayer* OR layer-by-layer)

(patterns OR patterning) AND (organized assembl* OR organised assembl* OR biocompatib* OR bloodcompatib* OR blood compatib* OR cellseeding OR cell seeding OR cell therapy OR tissue repair OR extracellular matrix OR tissue engineering OR immunosensor* OR cell adhesion)

Search string 8

(polymer OR polymers) AND (protein* OR antibod* OR enzyme* OR DNA OR RNA OR polynucleotide* OR virus*)

Search String 9

molecular siev* OR mesopor* OR ultrathin film* OR ultra thin film* OR thin solid films OR (thin film* and micropor*) OR artificial muscle* OR

((one dimensional OR 1D OR two dimensional OR 2D) and (structure or semiconductor))

Appendix 2 - Australian researchers active in nanotechnology, 1997-current

Table 2.1 – Top publishing Australian nanotechnology authors

The table lists researchers with an Australian institutional address who have 15 or more 'nanotechnology' publications published in the period January 1997 to May 2003.

The researchers are listed in order of highest number of nanotechnology publications.

The 'Research topics' are those identified from the authors' nanotechnology publications where five or more of their papers relate to the topic.

The institutional addresses were current as of May 2003.

Only papers with 'Australia' in the address field are counted, so publications produced by researchers while working in overseas institutions are not counted (unless co-authored with a researcher at an Australian institution).

Authors	Address	Research topics
Jagadish, C.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	quantum dots, quantum structures, semiconductors
Tan, H.H.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	quantum structures, semiconductors
Wallace, G.G.	Univ Wollongong, Intelligent Polymer Res Inst	biosensors, catalysis, medicine, nanocomposites, nanotubes
McCormick, P.G.	Univ Western Australia, Res Ctr Adv Mineral & Mat Proc	nanocomposites, nanoparticles, semiconductors
Zou, J.	Univ Sydney, Key Ctr Microscopy & Microanal	quantum dots, quantum structures
Mulvaney, P.	Univ Melbourne, Sch Chem, Nanotechnol Lab	nanocomposites, nanoparticles, quantum dots, semiconductors, self assembly
Gooding, J.J.	UNSW, Sch Chem Sci	biosensors, self assembly
Lu, G.Q.	Univ Queensland, Dept Chem Engn, NanoMat Ctr	catalysis, energy storage and distribution, nanocomposites
Williams, J.S.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	nanoparticles, nanotubes, semiconductors
Clark, R.G.	UNSW, Sch Phys, Ctr Quantum Comp Technol	quantum structures, semiconductors
Biggs, S.	Univ Newcastle, Sch Biol & Chem Sci	nanocomposites, nanoparticles
Swain, M.V.	Univ Sydney, Biomat Sci Res Unit	nanocomposites, semiconductors
Lu, W.	Univ Wollongong, Intelligent Polymer Res Inst	quantum structures
Gal, M.	UNSW, Sch Phys	quantum dots, quantum structures, semiconductors
Milburn, G.J.	Univ Queensland, Ctr Quantum Comp	quantum dots
Do, D.D.	Univ Queensland, Dept Chem Engn	catalysis, quantum structures
Dou, S.X.	Univ Wollongong, Inst Superconduct & Elect Mat	energy storage and distribution, nanocomposites, nanoparticles
Newbury, R.	UNSW, Sch Phys	quantum dots, quantum structures, semiconductors

Sanders, B.C.	Macquarie Univ, Dept Phys, Ctr Quantum Comp Technol	quantum structures, semiconductors
Bhatia, S.K.	Univ Queensland, Dept Chem Engn	catalysis
Griesser, H.J.	CSIRO Mol Sci	medicine, nanocomposites, self assembly
Elliman, R.G.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	nanoparticles, semiconductors
Hibbert, D.B.	UNSW, Sch Chem	biosensors, self assembly
Goldys, E.M.	Macquarie Univ, Div Informat & Commun Sci/ Semicond Sci & Technol Labs	quantum dots, quantum structures, semiconductors, self assembly
Micolich, A.P.	UNSW, Sch Phys or Univ Oregon, Dept Phys, Inst Sci Mat, USA	quantum dots, quantum structures, semiconductors
Shen, S.C.	?	quantum structures
Mau, A.W.H.	CSIRO, Div Mol Sci	fullerenes, medicine, nanotubes, nanocomposites
Liu, H.K.	Univ Wollongong, Inst Superconduct & Elect Mat	energy storage and distribution, nanoparticles
Attard P.	Univ S Australia, Ian Wark Res Inst	nanoparticles
Dzurak, A.S.	UNSW, Ctr Quantum Comp Technol	quantum structures, semiconductors
Bursill, L.A.	Univ Melbourne, Sch Phys	fullerenes, nanoparticles, nanotubes
Zhu, H.Y.	Univ Queensland, Ctr Microscopy & Microanal, Dept Chem Engn/ NanoMat Ctr	catalysis, energy storage and distribution, nanocomposites, nanoparticles
Prawer, S.	Univ Melbourne, Sch Phys	fullerenes, nanoparticles
Deenapanray, P.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	
Fu, L.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	quantum structures
Tsuzuki, T.	Adv Nano Technol Pty Ltd, or Univ Western Australia, Res Ctr Adv Mineral & Mat Proc	nanoparticles
Liao, X.Z.	Univ Sydney, Key Ctr Microscopy & Microanal	quantum dots, quantum structures
Jamieson, D.N.	Univ Melbourne, Special Res Ctr Quantum Comp Technol, Sch Phys	
Simmons, M.Y.	UNSW, Sch Phys	quantum structures
Nicolau, D.V.	Ind Res Inst Swinburne	biosensors
Luther-Davies	ANU, Res Sch Phys Sci & Eng	
Grieser, F.	Univ Melbourne, Sch Chem, Particulate Fluids Proc Ctr,	nanocomposites, nanoparticles, semiconductors, self assembly
Catimel, B.	Royal Melb Hosp, Ludwig Inst Canc Res	biosensors, medicine
Calka, A.	Univ Wollongong, Fac Engn	nanocomposites, nanoparticles
Cadogan, J.M.	UNSW, Sch Phys	nanoparticles
White, J.W.	ANU, Res Sch Chem	catalysis, dendrimers and supramolecular chemistry, fullerenes
Wlodarski, W.	RMIT Univ, Sch Elect & Comp Engn,	nanocomposites
Wong-Leung	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	semiconductors
Chen, Y.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	catalysis, energy storage and distribution, nanoparticles, nanotubes

Total = 49

Table 2.2 – Top recent publishing Australian nanotechnology authors

The table lists researchers with an Australian institutional address not already listed in Table 2.1 who have six or more 'nanotechnology' publications published in the period January 2002 to May 2003.

The researchers are listed in order of highest number of nanotechnology publications.

The 'Research topics' are those identified from the author's nanotechnology publications where five or more of their papers relate to the topic.

The institutional addresses were current as of May 2003.

Only papers with 'Australia' in the address field are counted, so publications produced by researchers while working in overseas institutions are not counted (unless co-authored with a researcher at an Australian institution).

Author	Address	Research Topics
Cheng, Y.B.	Monash Univ, Sch Phys & Mat Engn	nanocomposites
Clare, B.W.	Univ Western Australia, Sch Biomed & Chem Sci	fullerenes
Kepert, D.L.	Univ Sydney, Sch Chem	fullerenes
Nielsen, M.A.	Univ Queensland, Ctr Quantum Comp Technol	
Green, M.A.	UNSW, Photovolta Special Res Ctr	energy storage and distribution, semiconds
Hamilton, A.R.	UNSW, Sch Phys	
Zhang, L.C.	Univ Sydney, Sch Aerosp Mech & Mechatron Engn	
Shapter, J.G.	Flinders Uni S Aust, Sch Chem Phys & Earth Sci	biosensors, self assembly
Meagher, L.	CSIRO Mol Sci, Ian Wark Labs	medicine
Munroe, P.	UNSW, Electron Microscope Unit	nanocomposites, semiconductors
Wang, X.G.	Macquarie Univ, Dept Phys	
Hill, A.J.	CSIRO, Mfg Sci & Technol,	nanocomposites
Hollenberg, L.C.	University of Melbourne	
Bartlett, J.R.	Australian Nucl Sci & Technol Org, Div Mat	nanoparticles
Myhra, S.	Griffith Univ, Sch Sci	
Bradby, J.E.	ANU, Res Sch Phys Sci & Eng, Dept Elec Mat Eng	semiconductors
Sader, J.E	Univ Melbourne, Dept Math & Stat	
Crossley, M.J.	Univ Sydney, Sch Chem	dendrimers and supramolecular chemistry
Caruso, F.	Univ Melbourne, Dept Chem & Biomol Engn	biosensors, medicine, nanocomposites, self assembly

Total = 19

Table 2.3 – Overseas researchers collaborating with Australians on nanotechnology publications

The table lists researchers who do not currently have an Australian institutional address, but who have 15 or more 'nanotechnology' publications which contain an Australian institutional address published over the period January 1997 to May 2003. In most cases the researcher has worked in Australia but has since moved overseas, but in some cases the researcher is simply collaborating regularly with Australian researchers on nanotechnology publications.

The researchers are listed in order of highest number of nanotechnology publications.

The 'Research topics' are those identified from the author's nanotechnology publications where five or more of their papers relate to the topic.

The institutional addresses were current as of May 2003.

Authors	Address	Topics
Dai, L.M.	University of Akron, Polymer Engineering Ohio USA (formerly at CSIRO Mol Sci)	catalysis, fullerenes, medicine, self assembly, dendrimers and supramolecular chemistry, nanocomposites, nanotubes
Raston, C.L.	Univ Leeds, Dept Chem, Leeds, England (formerly at Monash Univ, Dept Chem)	dendrimers and supramolecular chemistry, fullerenes, self assembly
Cockayne, D.J.H.	Univ Oxford, Dept Mat, Oxford, England (formerly at Univ Sydney, Key Ctr Microscopy & Microanal)	quantum dots, quantum structures
Leon, R.	CALTECH, Jet Prop Lab, USA (formely at ANU, Res Sch Phys Sci)	quantum dots, quantum structures, semiconductors
Taylor, R.P.	Univ Oregon, Dept Phys, USA (formerly at UNSW, Sch Phys)	quantum dots, quantum structures, semiconductors
Liu, X.Q.	Chinese Acad Sci, Shanghai Inst Tech Phys	quantum structures
Micolich, A.P.	UNSW, Sch Phys or Univ Oregon, Dept Phys, Inst Sci Mat, USA	quantum dots, quantum structures, semiconductors
Ritchie, D.A.	Univ Cambridge, Cavendish Lab, Cambridge, England	quantum dots, quantum structures, semiconductors
Linke, H.	Univ Oregon, Dept Phys, USA	quantum dots, quantum structures, semiconductors
Hardie, M.J.	Univ Leeds, Sch Chem, England (formerly Monash Univ, Dept Chem)	self assembly
Huang, S.M.	Duke Univ, Dept Chem, Durham, USA (formerly CSIRO Mol Sci)	nanotubes

Total = 11

Table 2.4 – Other prominent Australian nanotechnology researchers

The following researchers were identified from patent literature, expert steering committee recommendations, or recommended by leading Australian researchers as being prominent Australian nanotechnology researchers.

Name	Address
Cornell, B.A.	Ambri Pty Ltd
Drummond, C.J.	Cap-XX Pty Ltd
Trau, M.	Univ Queensland, Ctr Nanotechnology & Biomaterials
Hyde, S.T.	ANU, Res Sch Phys Sci & Engn
Rode, A.	ANU, Res Sch Phys Sci & Engn
Gadd, G.E.	Australian Nuclear Science and Technology Organisation,
Lamb, R.N.	UNSW, Sch Chem, Surface Sci & Technol Ctr
Mai, Y.	Univ Sydney, Ctr Adv Mat Technol, Dept Mech & Mechatron Eng
MacKenzie, D.	Univ Sydney, Sch Phys
Ringer, S.	Univ Sydney, Also Exec Director of NANO MNRF
Faraone, L.	Univ Western Australia, Dept Elect Engn & Elect
Muddle, B.	Monash Univ, Sch Phys & Mat Engn
MacKinnon, I.	Univ Queensland, NanoChem Ltd / Ctr Microscopy & Microanal
Dunlop, G.	Univ Queensland, CRC CAST Metals Manufacturing
Braach-Maksvytis, V.	General Manager, CSIRO Global Aid, also Co-Director, CSIRO Nanotechnology
Turney, T.W.	CSIRO, Div Mfg Sci & Technol
Wilkins, S.	CSIRO Manufacturing & Infrastructure Technology
Riley, J.	La Trobe Univ,Fac Sci & Technol, Sch Phys
Cortie, M.	UTS Sydney, Dir, Inst Of Nanoscale Technology
Martin, D.	UTS Sydney, Inst Of Nanoscale Technology
Smart, R.S.	Univ S Australia, Ian Wark Res Inst, Adelaide
Gu, M.	Swinburne Univ Technol, Sch Biophys Sci & Elect Engn, Ctr Microphoton
Holmes, A.B.	Univ Cambridge, UK (will start Federation Fellowship in 2003)
Meredith, P.	Univ Queensland
McKenzie, R.	Univ Queensland
Neilson, D.	University of New South Wales
King, B.V.	University of Newcastle
Dastoor, P.C.	University of Newcastle
O'Connor, D.J.	University of Newcastle
Stampfl, C.	University of Sydney (new Federation Fellow)
Foley, C.	CSIRO Telecommunications & Ind Phys,
Usher, B.	LaTrobe, Dept Electronic Eng
Voelcker, N.	Flinders Univ, School of Chemistry, Physics and Earth Sciences
Kane-Maguire, L.	Univ Wollongong, Intelligent Polymer Res Inst

Table 2.5 – Leading Australian nanotechnology researchers by citation rate

The table lists Australian researchers with more than 10 'nanotechnology' publications (for the period 1980 to July 2002), where the average citation rate for their papers is more than double the 'expected' citation rates for the journals in which they are published.

Only papers with 'Australia' in the address field are counted, so publications produced by researchers while working in overseas institutions are not counted (unless co-authored with a researcher at an Australian institution).

Name	Average actual citations / Average expected citations
Swiegers G. F.	6.02
Chen Y.	5.40
Hawker C. J.	5.17
Zhao X. S.	4.58
Caruso F.	4.14
Senden T. J.	4.02
Atwood J. L.	4.01
Drummond C. J.	3.61
Liao X. Z.	3.39
Warr G. G.	3.32
Sader J. E.	3.22
Kane B. E.	3.22
Carnie S. L.	3.08
Barisci J. N.	3.02
Dai L. M.	2.90
Leon R.	2.75
Cockayne D. J. H.	2.73
Mulvaney P.	2.69
Lu G. Q.	2.62
Hibbert D. B.	2.57
Chan D. Y. C.	2.57
Zou J.	2.54
Spinks G. M.	2.50
Raston C. L.	2.44
Adeloju S. B.	2.39
White L. R.	2.39
Simmons M. Y.	2.36
Miao W. F.	2.36
Dance I.	2.34
Zhu H. Y.	2.33
Hardie M. J.	2.33
Lobo C.	2.32
Attard P.	2.29
Mau A. W. H.	2.23
Easton C. J.	2.22
Swain M. V.	2.20
Hush N. S.	2.18
Reimers J. R.	2.16
Munro W. J.	2.15
Tan H. H.	2.05
Pashley R. M.	2.02

Appendix 3 –Australian nanotechnology institutions

Institutions with 20 or more 'nanotechnology' publications	No. of nanotech publications
Australian Natl Univ, IAS, Res Sch Phys Sci & Engn	345
Univ New S Wales, Fac Sci & Technol, Sch Phys	230
CSIRO, Div Mol Sci	166
Univ New S Wales, Fac Sci & Technol, Sch Chem	140
Univ Sydney, Fac Sci, Sch Chem	132
Univ Melbourne, Fac Sci, Sch Chem	108
Australian Natl Univ, Ias, Res Sch Chem	106
Univ Melbourne, Fac Sci, Sch Phys	106
Univ Queensland, Fac Engn Phys Sci & Archit, Sch Engn	94
Univ Queensland, Fac Biol & Chem Sci, Sch Mol & Microbial Sci	88
Monash Univ, Fac Sci, Dept Chem	88
CSIRO, Div Telecommun & Ind Phys	76
Univ Queensland, Fac Engn Phys Sci & Archit, Sch Phys Sci	72
Univ S Australia, Ian Wark Res Inst	72
Univ Wollongong, Fac Engn, Intelligent Polymer Res Lab	71
Univ Wollongong, Fac Engn, Engn Phys Program	69
Macquarie Univ, Coll Sci & Tech, Div Inf & Commun Sci	65
Univ Western Australia, Fac Sci, Src Adv Mineral & Mat Proc	63
Univ Sydney, Key Ctr Microscopy & Microanal	57
CSIRO (Division unspecified)	54
Univ Melbourne, Fac Sci, Src Adv Mineral Prod	53
Univ Melbourne, Fac Sci, Sch Maths Sci	52
Aust Nuclear Sci & Technol Org	51
Univ Melbourne, Fac Med Dent & Hlth Sci, Sch Med	46
Ludwig Inst Canc Res	43
Australian Natl Univ, The Fac, Fac Sci	42
Univ New S Wales, Fac Engn, Sch Chem Engn & Ind Chem	39
Univ Sydney, Fac Engn, Dept Mech & Mechatron Engn	38
Monash Univ, Fac Med, Dept Biochem & Molec Biol	38
Monash Univ, Fac Engn, Dept Mat Engn	35
Univ Wollongong, Fac Engn, Inst Supercond & Electr Mat	34
CSIRO, Div Mfg Sci & Technol	34
Northern Territory Univ, Fac Sci Inf Tech & Educ	33
Univ New S Wales, Fac Sci & Technol, Sch Mat Sci & Engn	32
Flinders Univ, Fac Sci & Engn, Sch Chem Phys & Earth Sci	30
Queensland Univ Technol, Fac Sci, Sch Phys Sci	30
Univ Western Australia, Fac Sci, Dept Chem	30
CSIRO, Div Energy Technol	30
Univ Western Australia, Fac Sci, Dept Physics	29
Australian Natl Univ, Ias, John Curtin Sch Med Res	29
Royal Melbourne Inst Technol, Fac Appl Sci, Dept Appl Phys	29
Univ Adelaide, Fac Sci, Dept Chem	28
Univ Sydney, Fac Sci, Sch Phys	27
Macquarie Univ, Coll Sci & Tech, Div Environm & Life Sci	26

CSIRO, Div Plant Ind	25
Univ Queensland, Fac Hlth Sci, Ctr Microscopy & Microanal	25
Univ Sydney, Fac Sci, Dept Biochem	24
Griffith Univ, Fac Sci	24
Griffith Univ, Fac Sci, Sch Sci	24
Univ New S Wales, Fac Engn, Sch Elect Engn & Telecommun	24
Univ Newcastle, Fac Sci & Math, Sch Biol & Chem Sci	24
Univ New S Wales, Australian Def Force Acad, Sch Phys	23
Aust Nuclear Sci & Technol Org, Div Mat	22
Walter & Eliza Hall Inst Med Res	21
Telstra	21
Univ Technol Sydney, Fac Sci, Dept Chem Mat Sci & Forensic Sci	20

Australian companies working in nanotechnology
Adv Nano Technol Pty Ltd / Adv Powder Technol
Ambri Pty Ltd
Cap XX Pty Ltd
Artimech Pty Ltd
Micronisers Pty Ltd
Mimotopes Pty Ltd
MiniFAB (Aust) Pty Ltd
NABACUS Ltd
Nanochem Ltd / Nanochem Research Pty Ltd
nanomics UQ
Optiscan Imaging Limited
Panbio Ltd
PSivida Ltd
Quantum Precision Instruments Pty Ltd
Raustech Pty Ltd
Silverbrook Research
SOLA Optical Australia
Starpharma Pty Ltd
SureBeam Australia Pty Ltd
Vimed BioSciences Pty Ltd
Very Small Particle Company Pty Ltd;

Appendix 4 – Main journals where Australian nanotechnology papers are published

Impact factor = cites in 2002 to articles published in 2001 and 2000, divided by number of articles published in 2001 and 2000.

Or, **Impact factor** = cites to recent articles/number of recent articles.

Impact factor >4.567 = top 5 per cent of science journals

>3.00 = top 10 per cent

>2.00 = top 20 per cent

>1.00 = top 43 per cent

>0.844 = top 50 per cent

Journal/book title where Australian nanotechnology papers are published	No. of papers	Impact factor
Langmuir	176	3.248
Physical Review B	134	3.327
Applied Physics Letters	111	4.207
Journal of Applied Physics	100	2.281
Colloids and Surfaces a-Physicochemical and Engineering Aspects	74	1.35
Journal of Colloid and Interface Science	69	1.466
Nuclear Instruments & Methods in Physics Research Section B	58	1.158
Journal of Physical Chemistry B	54	3.611
Physical Review A	51	2.986
Australian Journal of Chemistry	43	0.647
Physical Review Letters	38	7.323
Journal of Biological Chemistry	37	6.696
Thin Solid Films	37	1.443
Abstracts of Papers of the American Chemical Society	36	n/a
Physica B	36	0.609
Chemical Communications	34	4.038
Journal of the Chemical Society-Faraday Transactions	34	n/a
Surface Science	34	2.14
Journal of the American Chemical Society	33	6.201
Journal of Magnetism and Magnetic Materials	30	1.046
Australian Journal of Physics	29	0.385
Journal of Physics-Condensed Matter	29	1.775
Analytica Chimica Acta	27	2.114
Applied Surface Science	27	1.295
Chemical Physics Letters	27	2.526
Journal of Physical Chemistry	26	2.756
Carbon	24	3.048
Journal of Materials Science	23	0.798
Electroanalysis	21	1.783
Macromolecules	21	3.751
Materials Science and Engineering A	21	1.107
Superlattices and Microstructures	21	0.876

International Journal of Modern Physics B	20	0.604
Journal of Alloys and Compounds	20	1.014
Journal of Chemical Physics	19	2.998
Microelectronics Journal	19	0.457
Analytical Biochemistry	18	2.37
Nature	18	30.432
Polymer	18	0.353
Synthetic Metals	18	1.187
Chemistry of Materials	17	3.967
Journal of Crystal Growth	17	1.529
Journal of Materials Science Letters	17	0.504
Journal of the Chemical Society-Chemical Communications	17	n/a
Scripta Materialia	17	1.168
Sensors and Actuators B-Chemical	17	1.893
Biochemistry	16	4.064
Journal of Physics D-Applied Physics	16	1.366
Physical Chemistry Chemical Physics	16	1.838
Journal of Materials Research	15	1.53
Physica E-Low-Dimensional Systems & Nanostructures	15	1.107
Physical Review E	15	2.397
Solid State Communications	15	1.671
Surface & Coatings Technology	15	1.267
Specific 'nano' journals:		
Nanotechnology	13	1.426
Nanostructured Materials	11	n/a
Journal of Nanoparticle Research	9	n/a
Journal of Nanoscience and Nanotechnology	8	1.734
Nano Letters	5	5.033

Appendix 5 – Australian nanotechnology publications with collaborations with other countries

COUNTRY	No. of collaborations
USA	454
England	266
Japan	171
Germany	137
Peoples Republic of China	114
Sweden	88
France	73
Canada	63
Italy	49
Singapore	38
New Zealand	37
Netherlands	35
South Korea	30
Russia	27
Poland	24
Israel	23
Denmark	20
Belgium	19
India	16
Spain	16
Taiwan	16
Switzerland	16
Finland	15
Czech Republic	14
Scotland	13
Mexico	10
Brazil	8
Austria	8
Indonesia	7
Thailand	6
Ireland	6
Hungary	6
Hong Kong	6
South Africa	6
Ukraine	5
Turkey	5
Wales	5