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WORKING PAPER

NANOTECHNOLOGY ADVANCES IN EUROPE

Scientific and Technological Options Assessment Series

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NANOTECHNOLOGY ADVANCES IN EUROPE

Dr. S. Dunn and Prof. R.W. Whatmore (University of Cranfield, UK)
in cooperation with G. Chambers

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Options Brief & Executive Summary

1. The lack of undergraduates taking all science and engineering subjects is a major concern. More effort should be made to encourage young people to enter science and engineering.
2. More money should be set aside for networking, publicising the networking opportunities and making the information about current networks more accessible.
3. A framework to allow the continuation of small research activities should be made more readily available.
4. A greater focus on the funding of strategic developments would be beneficial.
5. An increase in the number of avenues to raise public awareness about nanotechnology advances and the way it is impacting (currently and in the future) on their lives.
6. A framework to allow young researchers the opportunity to focus on their research activities would be very desirable.

A more clearly defined academic career structure with remuneration commensurate with industry would be beneficial.

Summary

Nanotechnology is currently an area of research focus in most developed nations. The effort in research and development in Europe is the largest, in terms of publications, in the world. The research conducted in Europe covers all of the main nanotechnology research areas and varies from country to country, due mainly to the historical manufacturing base.

The issues raised concern the lack of availability of suitable staff and students, a lack of accessible information about networking possibilities (for those new to the field) and concerns over the public perception of nanotechnology. The movement to larger research grants also concerns many as this is seen as potentially a move from emphasis on fundamental research to more short term goals. The generation of large collaborative centers of excellence concerns those who are not involved as they foresee the danger of politicisation, more difficulties in getting funding and further difficulties in getting staff. Funding for networking opportunities was criticised as being spread too thinly, though networking was described as adequate, by those who have been in the research field for a number of years.

The lack of suitable staff and students from within Europe is a major concern. The development of undergraduate and postgraduate training packages directed at nanotechnology was seen as beneficial, but the lack of funding for these initiatives was a concern.

The perception of nanotechnology by the general public was seen as dangerous for those conducting the research. Too much emphasis was placed on sensational reporting of nanotechnology that is unlikely to impact on people's lives in the near future, while nanotechnology with direct impact on people's lives was left largely unreported. The gap between the awareness and reporting of science in the US and Europe was a concern for some who felt that although they are conducting first class work there is little publicity for it in Europe.

Contents

Introduction

This report has been compiled after discussions either face to face, via the telephone or e-mail with a number of parties who are conducting nanotechnology research or are heavily involved in managing projects in nanotechnology related areas. Extra information was obtained from a review of recently published reports, texts or appropriate web sites. The opinions expressed by those consulted were that of the person being interviewed and not of the institution for which they work. Of those approached to contribute to this report a disappointing number refused to make comments, via telephone, email or letter.

The report aims to address three fundamental questions:

1. Where does Europe stand in the field of Nanotechnology research?
2. What are the major issues facing those conducting Nanotechnology research?
3. What do those conducting the research feel will happen in the future with regard to Nanotechnology?

It will also introduce the various topics/divisions of Nanotechnology after explaining some of the terminology involved.

Nanotechnology is a term that is being used more and more frequently to describe research where dimensions of the order of $1\text{-}100\text{x}10^{-9}$m where $1\text{x}10^{-9}$ m is a nm (or 1/20,000 of the diameter of a human hair) are critical. The research areas that are finding interest in nanotechnology range from mechanical engineering through to biotechnology, chemistry and physics. The activities that these broad fields of science and engineering cover are obviously very different, but in the context of nanotechnology a lot of the goals are relatively similar. The main drive is to control surfaces or structures with nanometric precision in order to produce new devices and/or fulfill a role/application that can not currently be completed. These various fields of research are coming together, increasingly in multidisciplinary groups to tackle the complex difficulties that are being encountered.

The future developments of nanotechnology, which are being embraced by multidisciplinary groups, are believed by many to be vital to see nanotechnology develop into areas that have a high probability of impacting in a positive way on a large number of people's lives.

1. Overall outlook

1.1. What is Nanotechnology?

Nanotechnology has been variously described and defined since the phrase was first used by Japanese scientists in the last century. This was after the pioneering talk given by Prof. Feynman, who is generally heralded as the initiator of the Nanotechnology revolution when, in 1959, he delivered his speech; "Plenty of room at the bottom". In this he stated; "The principles of physics, as far as I can see, do not speak against the possibility of manoeuvring things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice it has not been done because we are too big".

Nanotechnology was described by those contacted to complete this report as falling into two broad categories-Black nanotechnology and White nanotechnology. Black nanotechnology is the manipulation of atoms or molecules to produce devices such as single electron electronic devices. These are components that use a single electron to determine the on or off state for binary logic gate black nanotechnology also includes nanometrology-the classification of surfaces with resolutions in the order of 0.5-2nm. The size range of 0.5 to 2 nm can be thought of as on the order of the size of a large molecule or a cluster of a few tens of atoms. The control and manipulation of substances at this scale, the famous picture of a quantum corral which can be found at www.almaden.ibm.com/vis/stm/images/stm15.jpg, shows that the manipulation and precise positioning of individual atoms is possible. The image shows individual iron atoms that where positioned on a copper surface to generate a corral of electrons with atomic precision. This form of extreme nanotechnology is opening the doors to a more fundamental understanding of physics that is important for the next generation of nanoelectronics (nanoelectronics are electronic devices made on the nanometer scale rather than micrometer scale, such as today's microprocessors which are known as microelectronics). There are many other examples of black nanotechnology that exist. The dimensions of concern for black nanotechnology are generally in the range of 1-20nm.

White nanotechnology covers a far broader group of technologies and research activities. Here the range of dimensions that are of interest range from 10nm up to 80-150nm. There is naturally some cross over between the black and white areas of nanotechnology. An example of which is the development of quantum dot arrays from reactively grown CdSe nanoparticles. The CdSe nanoparticles can be made with good reproducibility; however the assembly of these particles on surfaces and subsequent addressing to obtain a user interfaced device is very difficult. The prime difficulty in defining nanotechnology stems from the very diverse activities that fit into a size range that is *nanometric* and the cross over from bottom up technology (where systems are grown by self assembly or by the rearrangement of individual atoms) to top down assembly (techniques such as the further reduction in line widths of photolithographic techniques) which are currently approaching nanometric sizes. There are also a number of technologies that cross over between bottom up and top down approaches, these further complicate the picture and make a definitive of nanotechnology very difficult to produce.

Currently nanotechnology encompasses research that is being conducted in a number of distinct areas. It has proved difficult to determine a definitive list so I have used the list provided by the Engineering and Physical Sciences Research Council (EPSRC) in the UK as a guide:

- **Extreme nanotechnology**: areas of research that include
    - Self-assembly (the ability to cover large areas (100's of $\mu\mathbf{m}^2$) of surfaces with identical arrays of molecules in the absence of external control);

  - Molecular manipulation (the manipulation and movement of single, or small clusters of molecules);
  - Single molecule devices (devices or components that are made from single molecules through direct manipulation or self assembly) and;
  - Supramolecular systems (systems that consist of components that are molecules in their own right, an example would be DNA).

- **Nanofabrication**: covering a range of enabling technologies
  - Primarily focused towards the further reduction in microelectronics towards nanoelectronics (these include photolithographic techniques such as LIGA and the further development of ‘soft lithography’).

- **Metrology**: the ability to measure to nanometer precision.

- **Nanostructured materials**:
  - Nanocomposites (the incorporation of nanosized particles to compounds to produce a composite with a nanosized phase);
  - Fullerenes (nanosized carbon structures shaped like miniature footballs, also termed Buckyballs);
  - Nanotubes (nanosized carbon structures that are long tubes shaped like cigars, often termed Carbon Nanotubes (CNT));
  - Thin films (films that are 1-25 nm thick and constrain electrons so that they behave as a wave rather than a particle, this work is intimately tied with next generation electronics and communications) and;
  - Photonic crystals and fibres (crystals that can alter the path of light according to a predetermined parameter, for example bend light through 90º).

- **Functional nanotechnology**:
  - Nanoelectronics (the further development of microelectronics to use feature sizes that are in the order of 100 nm, this reduction in feature size increases the speed at which the device can work and increases the density of devices that can be produced);
  - Photonics (as described above in photonic crystals, but in this case more appropriate to fully integrated systems);
  - Bio-electronics (the use of biological molecules to in-electronic devices either as sensors or actuators or electronic components such as diodes) and;
  - Drug delivery (developing encapsulation or production techniques for drugs that allow slow release or the drug to enter the body by altering only the size of the drug particle).

- **Nanomechanical devices**:
  - Next generation microsystems (the development Nanomechanical systems, these are systems that integrate sensing, actuation and user interface connections in a single device) and;
  - True nanogeneration systems (self assembly systems that can be preprogrammed to produce a structure or device of predetermined shape or functionality from certain raw materials).

- **Molecular nanotechnology**:
    - Biological nanotechnology (the interaction and impact of biological systems on nanotechnology life, as we know it, are just self replicating supramolecules);
    - Membranes (biological membranes act as catalysts or filters with very high precision);
    - Molecular recognition (the recognition of certain molecules is very specific in biological systems and would be very desirable in synthetic systems) and;
    - Sensors (the ability to detect specific molecules, similar to molecular recognition).

- **Nanoclusters**:
    - colloidal systems (generally particles of metal held in a liquid suspension, the size of the particles varies from 2-50nm, though larger systems can exist);
    - particulate technology (the generation of particles of metal oxides/carbides etc through various techniques such as laser ablation or controlled burning) and;
    - nanophase ceramic components (the production of bulk materials from components that are in the nanophase, the resulting structures have enhanced properties over materials produced by traditional techniques).

A more thorough description of applications and implications of the topics above can be found in the sections dedicated to discussing the research activities with in Europe in the specific areas.

The very broad definition of nanotechnology as used in the US can be found at www.nano.gov/omb_nifty50.htm, this is a common definition used by some authors and omits to highlight the various activities that occur under the broad heading of nanotechnology. I have used the definition of nanotechnology given above in order to show the large variety of activities that are being undertaken and show the reader some of the possible implications and applications of nanotechnology that can be associated with the research area.

1.2. Where is Nanotechnology going?

This is a question that is frequently asked by a variety of people ranging from those conducting the research to those who involved with the popular press/media and also scientific press. It is also a question that isn't very easy to answer and it would appear from discussions with those conducting Nanotechnology research that the directions are specific to the nature of the work that is being conducted at the various research establishments. The future directions of the research will be addressed in sections that are specific to the research area of nanotechnology, rather than as a general discussion. This section will concentrate on the more general aspects concerning the direction of nanotechnology, the feel from those conducting the work and impact on press exposure.

One of the more surprising comments that has come from the people approached to complete this report is that the views of Nanotechnology disseminated by the ‘popular press’ is regarded as a double edged sword. It is seen that there are benefits to having the technology relayed to the general public, it increases awareness and the *potential* of the technology. This has a direct effect in that the level of funding is increased for research that carries a Nanotechnology tag. However, it is felt that (for many future developments) as some of the reporting does not give realistic timescales, in some cases the timescales are thought to be overoptimistic. Consequently the support from the general public is likely to wane over a period of time. In other cases the timescales are large (in excess of 10-20 years) for significant progress to be made so that the general public may become disillusioned by seeing no changes in the near future. This sort of reporting is therefore seen as negative for those who are conducting the research.
The more general applications of nanotechnology that are impinging on peoples lives today, for example nanoparticles incorporated in sunscreen, are not seen as great leaps forward as the technology (i.e. sunscreen) has been available in some form to the layman for many years. This is felt to be a concern by many as nanotechnology is a relatively young field of science that is developing enabling technology (skills and techniques that enable another operations or developments) to enable future developments that will potentially impact on the lives of many as well as technology that is and will directly affect peoples lives. Unfortunately the development of these enabling technologies and some of the more substantial though not so ‘lively’ developments in nanotechnology (such as nanoparticle synthesis, the development of new nanocomposites polymers with improved properties) is not as well reported as the exotic claims. An example of well reported exotic nanotechnology is nanosubmarines that will be able to complete surgery *in-vivo*, a technology that will some day come to fruition (estimated variously at 25-100 years) but the time period and the financial cost of doing so are very high. The likely benefits are such that it seems unlikely to happen in the near future. As this is the overwhelming concept of nanotechnology to most members of the public then the dangers of this publicity are apparent.

A further issue is that many research groups that were previously doing Nanotechnology under another guise, such as molecular electronics (which crosses the boundaries of both extreme nanotechnology and molecular nanotechnology), have now named themselves Nano….. in order to appear more ‘current’ when applying for funding. This has the effect of spreading the funding more thinly throughout a larger number of research groups and increases the difficulties in getting funded.

On a broader note there was a concern among some of those interviewed that within Europe we are not very good at publicising our achievements. In the US leading Newspapers carry articles hailing the achievements made within the research and development arena, while in Europe we are more reserved and tend not to shout about the achievements quite so loudly. A search of the WWW using Google.com and the search term Nanotechnology retrieves US/Japanese led publications/sites but lacks any significant publications/sites that are European based (with the exception of the

Institute of Nanotechnology and Cordis site) for the first three pages (30 hits). Using a more specific search term like Nanowire on Google.com would lead the casual observer to believe very little nanowire type research is being conducted in Europe as the first hit for a European group is the mpi-stuttgart.mpg.de site, found on the third page. However, this is not the case as work on nanowire type structures is being conducted in laboratories all over Europe. While the lack of 'advertising' or publicity does not affect the quality or volume of research that is being conducted, it does make some researchers feel that although they are conducting first class work there may be benefits in working in higher profile environments. These high profile environments also tend to appear to be more highly supported.

The level of understanding of the potential impacts of nanotechnology among even high level decision makers has also been tainted by the opinions of the popular press. There have been occasions recently where senior officials have visited laboratories in order to gain an overview of nanotechnology activities and have left disappointed when they have found no research being conducted on nanobots (nanosized robots) and smart nanomaterials. This misconception that nanotechnology research is purely conducted along such lines is potentially very damaging.

As a final point in the overview of where nanotechnology is going, it was felt by a number of people contacted that nanotechnology in the format it is today will not exist in the medium term, over 5 -7 years. After this period it was felt that people would move away from the term and hence association with nanotechnology to be other names. There was no specific name that the researchers felt would be used but it was felt that nanotechnology may become something that only a few specialist groups or researchers would embrace after this period of time. The reasons for this can be found in the discussion above. Nanotechnology is a very 'current' field of research, which is rightly due to the various ways in which it could enrich lives, generating a significant amount of interest in sponsoring bodies both governmental and industrial. However, if some of the targets that have been set appear to fail than the level of funding will undoubtedly reduce and with it the number of groups conducting nanotechnology research. Although some of the specific targets may not be met, it is clear that the new science and engineering learned from undertaking the work will be crucial for the further development in key areas such as pharmaceuticals/biomedical, structural materials and environmental issues, areas that have a very specific impact on the way in which people lead their lives.

1.3. Nanotechnology research, expenditure and directions out with Europe

A report indicating the predicted expenditure (financial year (FY), 2002) and the expenditure (FY, 2001) on Nanotechnology and Nanotechnology related research activities in Japan as well as the future directions of research and development (R+D) on Nanotechnology, has recently been published. There is inherent difficulty in producing accurate data concerning expenditure and R+D on Nanotechnology research owing to the broad spectrum of research that is being conducted and the lack of a universal definition describing exactly what nanotechnology research is.

Unfortunately the report covering the same detailed information for the US over the same period has yet to be made public. What is generally known from the US is that:

> President Bush is seeking a significant increase in funding for nanotechnology research. The budget he sent to Congress last week requests 17% more, or $679 million, for the federal National Nanotechnology Initiative, which funds university grants.
>
> David M. Ewalt,
> www.informationweek.com/story/IWK20020208S0027, Feb 2002

which indicates the importance of the Nanotechnology initiative to the US government. The trends in Nanotechnology funding can be seen from looking at Table 1, there is a general increase in the funding levels for Nanotechnology in the US. It is also clear that the anticipated impact of peoples lives has moved into new areas, with the increase in expenditure for the Dept. of Justice and Environmental Protection Agency. The discrepancy between the figure of $679 million above and the figure of $518 million is due to the increase in funds applied for by Congress after the publication of initial data by the National Science Foundation.

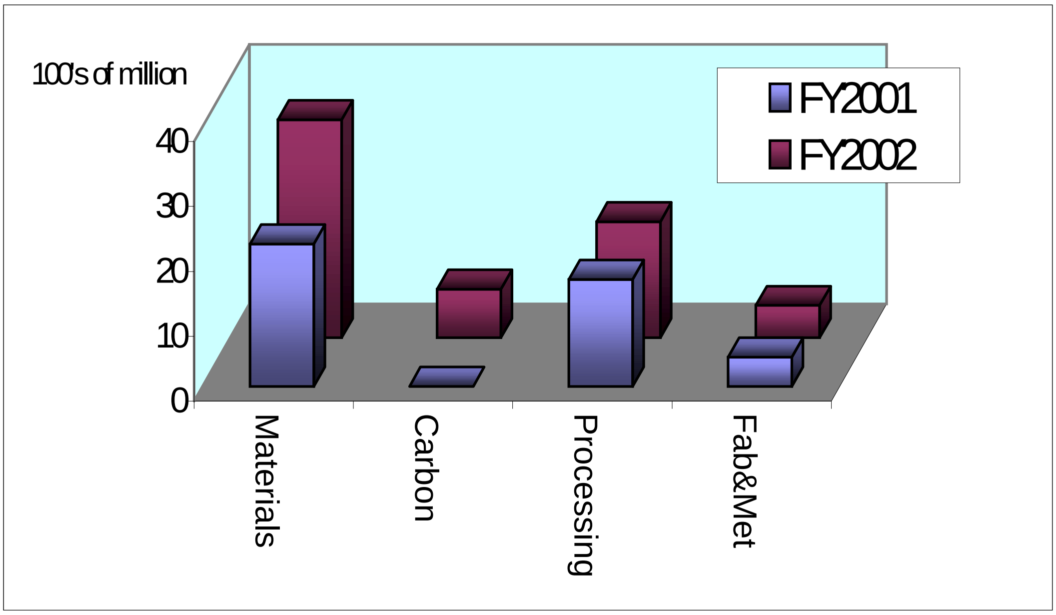
Table 1: Expenditure on Nanotechnology related research in the US, figures are $millions.

Agency/Gov. Department	FY 2000	FY 2001	FY 2002 (predicted)
Dept of Defence	70	110	133
Dept of Energy	58	93	97
Dept of Justice	0	0	1.4
Environmental ProtectionAgency	0	0	5
NASA	5	20	46
National Institutes of Health	32	39	45
National Institute of Standards and Technology	8	10	17.5
National Science Foundation	97	150	174
Totals	**270**	**422**	**518.9**

Source Nanotech, the tiny revolution, CMP Cientifica, Nov 2001.

From the Nanotechnology in Japan-Update January 2002 report compiled by Ivan Meakin of the British Embassy in Japan it is clear that Nanotechnology research is also highly supported in Japan. A total of 60.6 billion Yen or 538 million Euros (Exchange rate of 1 EUR = 112.678 JPY has been applied.) were allocated to Nanotechnology research for the FY 2001. Of the key changes that are in place for the FY 2002 is the increase in funding for research and developmentof carbon based materials. This is shown in Figure 1, where the additional funds for Nanoscale carbon research come under the broad heading of the Materials Nanotechnology project and is intended to allow the mass production of carbon nanotube and fullerene products and with funding coming from METI (the Ministry of Economic and Trade Industry). The applications and descriptions of these materials/products will be more fully discussed later in the report.

Figure 1: Nanotechnology funding in Japan



In Japan there is an increase in the development of Nanotechnology consortia and a drive to see some technologies pushed into mass production. This is being led by the desire to see Nanoscale carbon products pushed into production. The private sector in Japan is investing heavily in Nanotechnology type initiatives. This is mainly in response to the predicted market for nanotechnology based/type products reaching £154 billion by 2010. A further reason for the heavy investment, by Japan in nanotechnology initiatives, is that a recent survey (completed by Mitsubishi Research Institute) showed that Japan was falling behind in research being conducted in the life sciences, among others. As such an increased level of funding for these areas has been agreed.

1.4. Funding concerns

There is a concern that with the increase in size of the projects the ‘small person in the lab’ will find it increasingly difficult to get funding for projects as the average cost of funded project increases. This is particularly in response to the likely increase in project funding for Framework VI and the trend for some national bodies to fund larger projects. This is of particular concern for nanotechnology research as it is dependent on the development of some key technologies and is not following any ‘roadmap’. A ‘roadmap’ is a plan or route by which the development of a research sector is likely to develop for a given period of time. The classic example is that of the microelectronics industry, where the ‘roadmap’ has been closely followed for around 35 years (Moore’s law). Although the microelectronics roadmap has been closely followed significant leaps have been brought about when new unforeseen technology has been implemented. It is for this reason that no ‘roadmap’ exists for nanotechnology, the science and engineering is so broad and diverse that new discoveries are constantly having impacts on the way in which the science is being conducted. These discoveries are not centered just in the big research laboratories but occurring throughout all universities and research institutions concerned with nanotechnology.

The increase in the number of high profile and high prestige collaborations that are being funded is a cause for concern to both established laboratories and those beginning to develop research groups who are not involved in these collaborations. This perceived 'politicisation' of nanotechnology research where large sums of money and kudos are associated with a small number of collaborative research groups, tackling a large number of activities, makes it more difficult for those 'not in the in crowd' to get the funding required to complete research. As important and of a more pressing concern is the difficulty in finding suitably qualified staff who are drawn to more prosperous/high profile institutions within the collaborations.

A further concern is that with large projects, such as those proposed in Framework VI, the focus for the research will be led by the 'leading partners'. If the leading partners are large industrial concerns, as seems likely due to limited number of University research groups capable of running such projects, then the focus for the completion of work and the work undertaken could be of the short-medium term rather than long term. Without further improvements in understanding some of the fundamental issues (only tackled in long term research projects) Nanotechnology may not flourish as rapidly as it could. This could lead to some of the more important changes that could possibly affect society not happening as efficiently as they otherwise might. If the project is being managed by a dedicated project management team or organization dedicated to running that project then it is up to the project managers to ensure that the project is not driven by the larger partners.

A number of the academics approached indicated that there was a concern with the level of funding available for big strategic developments. It was seen as vital, in order to maintain a leading role in Nanotechnology research, that an overall perspective approach be taken on some issues. Some examples of which are the development of a high power computing facility to further enhance the modeling capability within Europe, the availability of funds to build new laboratories, etc. Only one of the academics stated categorically that there was no concern with getting funding to complete large strategic initiatives, and they are working in a very industry led field and use a significant proportion (70%) of industry money to support their work.

When asked directly if there were any problems in setting up the research laboratories there was a split between those who are running established laboratories (established) and those who are at the initial stages of developing their research (developing). The established groups in general had some difficulty in developing their activities, while the developing groups are finding it slightly easier to get established. The issue breaks down into two main areas, the first is funding; it appears that there is more funding available today for people conducting Nanotechnology type work (the injections of funding towards nanotechnology are having a positive effect), in the past (3-5 years ago) it was difficult to get funding. The second issue is space: it has been difficult to convince Universities and organizations to give up valuable space to the new unproved research areas. Some of the issues concerning space and institution politics are still current and causing a concern for a number of those contacted. The issues of difficulties with networking and general expansion into new areas through cooperation are dealt with later.

The lack of direct funding for young researchers from the EU was raised as an issue. Schemes exist at national levels to support talented young (less than 35-40) researchers to enable them to concentrate on their chosen research field. Within the EU framework no such scheme is available, or not known to those who are conducting the nanotechnology research. The scheme would be advantageous as it would encourage talented young researchers to remain within Europe as they will be directing their own research path.

A common comment was that the bureaucracy that holds back payment for up to six months after signing documentation is not helpful when developing networks or recruiting new staff. The major issue that faces most Nanotechnology researchers is the lack of suitable staff and students to complete the work that is required.

1.5. The major issue

The major issue that faces researchers conducting nanotechnology research comes from the lack of suitable students or postdoctoral staff available. The regulations imposed by a number of the sponsoring bodies (including the EU and some local Country Government contracts) for the completion of the project prohibit the use of staff/students from outside Europe. Only one of those that were contacted to complete this report said that they had no difficulty in finding suitable recruits, all others said it was one their major concerns. There was no difficulty in finding people to complete the work from countries such as India and China, but from within Europe there was a major problem. The issue is most acute when trying to find students/staff to complete very novel research as the potential rewards are not seen as very high. The problem does not seem so acute in the US where recruits into novel research areas are often rewarded when a ‘spin off’ company evolves or positions outside of academia are obtained.

The lack of suitable people appears to stem from the lack of school leavers and undergraduates who see science and engineering as a suitable option for a career. The reasons for this are well discussed elsewhere but originate in low salaries, long hours and low rewards when working in the academic sector. When in the industrial sector it is more an issue of the lack of kudos associated with many of the science and engineering positions and the lack of perceived promotion possibilities. Without addressing these issues the lack of enthusiastic and capable students coming through to complete PhD level qualifications will become an ever increasing concern for senior research scientists and engineers seeking to recruit.

Within Europe there is a push to increase the status and rewards of school teachers and other public sector workers, however, there is no analogous drive to make the rewards for remaining in academia a good option when compared to industry or moving to other regions to complete research. This leads to many key people leaving Europe in search of higher rewards. The overall effect of this is that few young people see academia as good career option which reduces the numbers of people taking further degrees.

Of those contacted none had a solution to the problem of increasing the number of suitable applicants for PhD, post-doctoral or senior positions. This lack of foresight for a potential solution to the problem was also raised as a concern in itself, it seems that this issue must be tackled by high level initiatives if it is to be resolved.

1.6. Research output

The research output from Europe and other major global players has been determined by conducting a search on the ISI web of Science web site (which can be found at http://wos.mimas.ac.uk/). The search was completed in a variety of ways in order to deliver a range of information. Any duplication in the number of hits for a given search term is likely to be found equally through all the countries searched so the figures are likely to provide a good qualitative guide to the number of publications but should not be taken as a definitive quantitative count. The search was performed over the period 10th January to 14th January 2002, and is likely to yield different results if performed in the same way today as the database may have been updated. The search was limited to the years 2000 and 2001. The search terms used and the number of hits found for each search term are shown in Tables 2 and 3. The search terms were evaluated from the Keywords, Abstract or Title of the publication. For example when searching with the term **nano*** the search engine searches for all publications with nanotechnology, nanocystals etc in the abstract, keywords and title of publications held on the database from 2000 and 2001. By adding in the term **USA** in the authors affiliation the search is narrowed to publications with **nano*** in the abstract, keywords or title and the authors affiliation as being **USA**. Table 3, shows the research activities of France and Germany compared in terms of the search terms listed. France and Germany were chosen as they are the leading countries within Europe (excluding Russia) in terms of nanotechnology publications.

The results of the search are shown graphically in Figures 2 and 3 and indicate that if measured on the output of refereed publications Europe, as a single entity, has the leading global position. When the details are broken down into individual countries then the US leads with Russia, Japan, Germany and China (in that order) following. The output from France and the UK follows but is ca.70% and ca.50%, respectively, of the German output.

Table 2: The results of search performed using on http://wos.mimas.ac.uk using the Boolean term Nano* in the abstract or title of the article and adding the specific country that author is from.

Search term	Number of hits for the term
Nano*	27865
Nano* + USA	7954
Nano* + Russia	3647
Nano* + Japan	3491
Nano* + Belgium	318
Nano* + France	2224

Nano* + GB or United Kingdom or England or Scotland or Wales	1584
Nano* + Greece	163
Nano* + Netherlands	515
Nano* + Lux*	6
Nano* + Italy	976
Nano* + Spain	791
Nano* + Portugal	99
Nano* + Switzerland	640
Nano* + Denmark	200
Nano* + Sweden	435
Nano* + Finland	152
Nano* + Norway	39
Nano* + Germany	3263
Nano* + Korea	912
Nano* + China	3135
Nano* + India	688

Table 3: The results of search performed using on http://wos.mimas.ac.uk using the Boolean term as indicated in the abstract or title of the article and adding the specific country that author is from. A comparison of the research output in the form of published scientific papers for France and Germany over the period 2000-2001.

Search term	Hits for France, in country of author	Hits for Germany, in country of author
Nanocrystals	569	171
Nanoparticles	538	405
Nanowire*	80	41
Nanoassembly	1	0
Nanocomposites	108	131
Nanotubes	208	161
Nanosized	74	59
Nanorods	16	5
Nanocavity	12	2
Nanoindentation	60	38
Nanofiltration	28	47
Nanostructured devices	571	301
Nanolithography	33	12
Nanofabric	21	15
Nano* + Bio*	249	167
Nano* + Med*	19	213
Nano* + Drug	109	63
Nano* + Quantum	365	182

Figure 2: Refereed publications using the search term Nano* and associated country of origin for the authors affiliation.

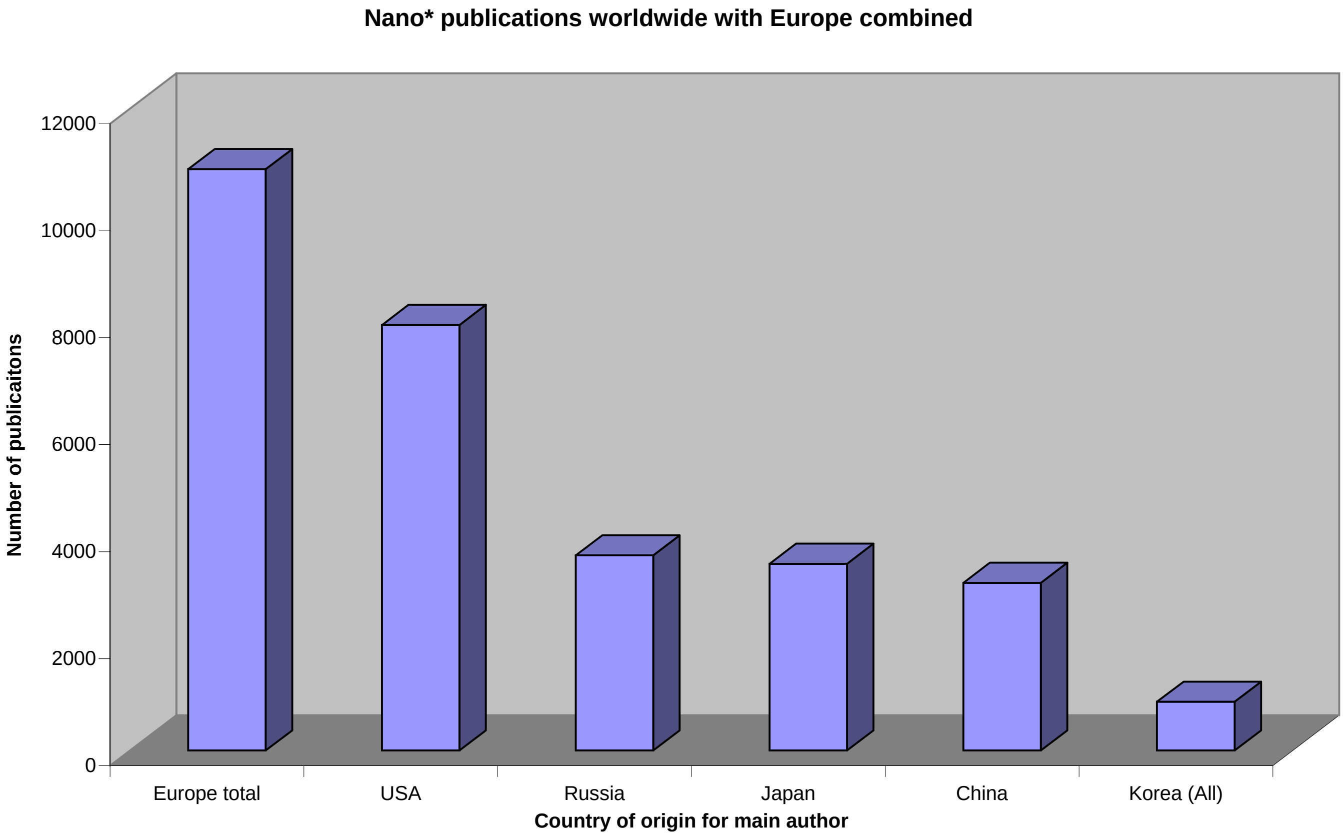
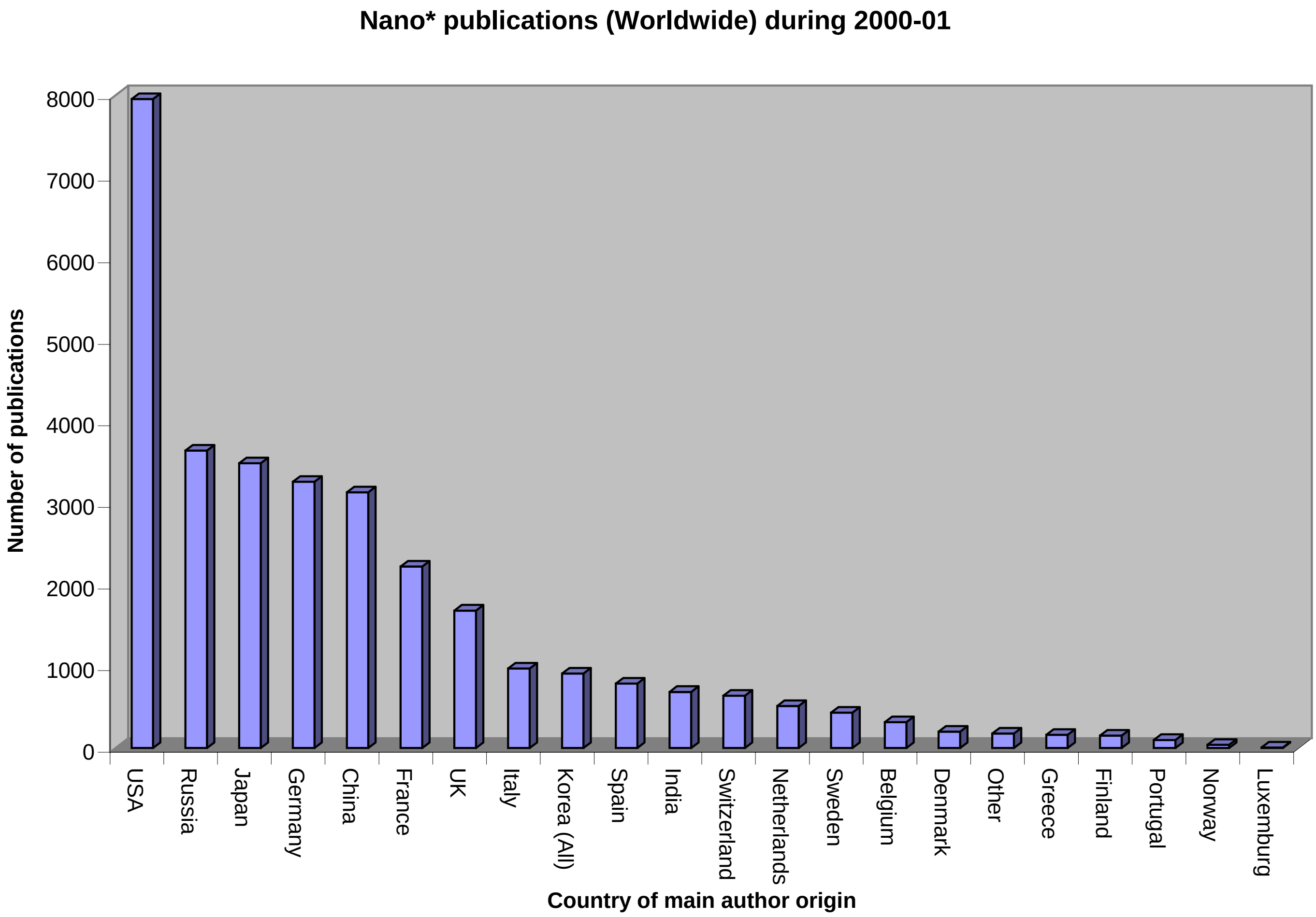


Figure 3: Output of refereed papers using the search term Nano*, found in Keywords, Abstract or Title, with break down on country of affiliation for authors.



A breakdown of the publications during the years 2000 and 2001 from France and Germany by topic from the abstract, keywords or the title is shown in Figure 4. From this the focuses of research in the two countries can be seen. The number iof publications have been normalised to represent a percentage of the published papers to remove any discrepancies due to the larger number of publications coming out of Germany. There are only two main topic areas of nanotechnology research in which there is a significant difference between France and Germany. These are Nanocrystals, a field where Germany is publishing a significant number of articles and Nano/Medical where France is publishing a larger number of articles. There is no clear indication as to why these differences may exist, other than for historical reasons.

Figure 4: Refereed publications from France and Germany over the period 2000-2001 broken down by topic of the publication from the abstract or title.

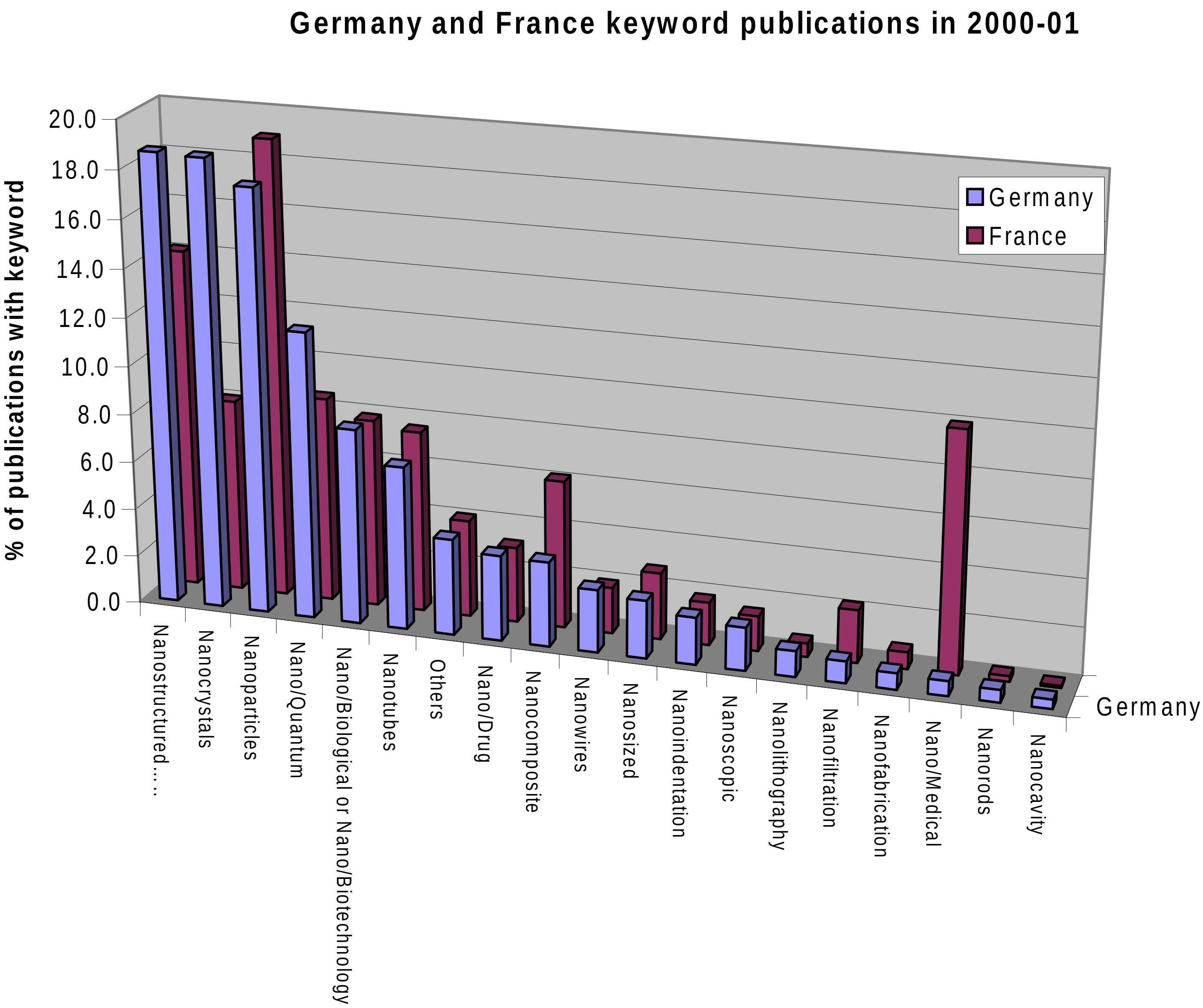
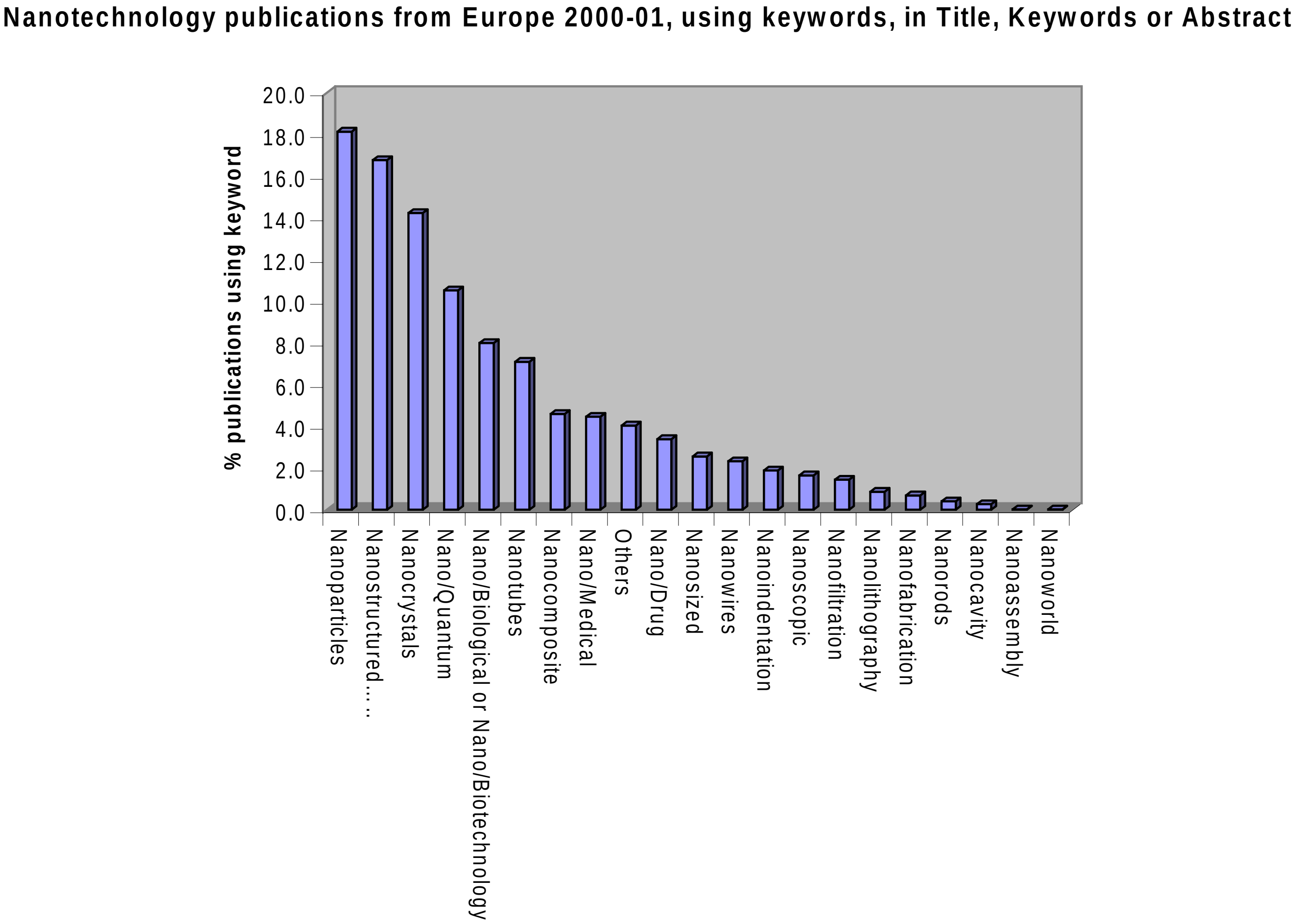


Figure 5 shows the resulting publications from all of Europe in terms of research activities found in the Keywords, Abstract or Title. The graph shows that the majority of publications from Europe are in the fields of Nanoparticle technology and the use of these nanoparticles to generate new nanostructured materials.

Figure 5: Publications from Europe during 2000-2001 sorted by research activity found in Keywords, Abstract or Title of the publication. The graph shows that the research output of Europe is concentrated around generating new nanosized materials the productions of nanostructured systems.



1.7. Mobility and interdisciplinary research activities

As may be discerned from the introductory text nanotechnology is a very interdisciplinary/multidisciplinary field. The range of activities that are being undertaken and classed as Nanotechnology cover traditional research areas such as chemistry and physics through to activities that involve many newer techniques such as biotechnology and gene sequencing. A growing number of research groups consist of scientists and engineers with a vast range of first degree specialisations that are now working together as one unit. Of those questioned to complete this survey it was considered vital among nearly all that interdisciplinary activities are encouraged. It was felt important to break down barriers between the various scientific communities in order that each community could learn from the others. The lack of interdisciplinary training at undergraduate level was a concern and considered short sighted, it is hoped that more could be done to increase interdisciplinarity at an earlier stage in the development of potential staff.

A comment that was made quite frequently was that when drafting an interdisciplinary proposal it was difficult to find the right body to support the work. One example that was given was that in the UK funding is given out by the various research councils, of which the EPSRC is one. During the completion of the proposal the authors are asked to choose into which stream, such as materials, etc the proposal should be entered. The proposal is then refereed; the problem is that if the proposal is truly interdisciplinary then the referees chosen might not be suitable as their specialism may lie outside of a large proportion of the proposed work. In these cases the proposal may be rejected and not get funding. The problem does not lie with the referee more with the procedure of selecting referees from very specific academic backgrounds. However, some interviewees also stated that the problems have been abating in the last few years and it may be that as more referees are available who are conducting interdisciplinary research the problem will be removed.

Due to the nature of Nanotechnology research some of the equipment is not only expensive but demanding in terms of technician and training time. The initiatives by the EU and Governmental bodies to allow movement of personnel throughout Europe are helping to ensure that the necessary equipment is available to those who need it. In particular the COST and Phantoms initiatives are seen as excellent, though under funded, ways to ‘network’ with people who have access to equipment that is required. In some cases it was mentioned that results can be generated in a matter of 48 hours, as the sample can be sent by courier, analysed and the results published on an intranet site. This kind of cooperation is allowing certain groups to extend the capabilities beyond the resources with in their own University. In general the ability of researchers to move around Europe is seen as adequate.

A concern that was raised by some of those approached was that the networks that are set up to provide support for interdisciplinary research in Europe are difficult to break into. Once in, the networks appear to work effectively though some people commented that there are too many meetings with little focus on delivering results. The first stage, after developing a new laboratory, of getting your ‘foot in the door’ of a network appears to be quite difficult. When pressed on these issues the reply was that it was difficult to find clear and concise information about the networks that are currently running. After these initial difficulties the more experienced researchers approached indicated that transferring from one network to another and generating contacts in a new network was relatively simple.

1.8. Funding sources

When interviewed, the interviewees where specifically asked about the main sources of their funding. These ranged from national funding sources to the EU framework programs (such as Framework V, FW V) with a large number of interviewees stating that significant proportions of their income came from industrial sources. The exact divisions between the sources of funding did not have any significant trend, except that it was more common for large amounts of industrial support to come from industries that are associated with high risk research, such as the microelectronics industry. The amount of income generated through industrial partnerships was considered to highlight the importance of nanotechnology as a research field.

A break down for the sources of funding for individual contributors can be found in Appendix 2.

1.9. Interviewees opinions on where Nanotechnology will benefit society

Those contacted where asked to give their opinions on what areas of Nanotechnology research were likely to have a major impact on society. They were specifically asked to include areas of research that were not their specialism when considering the question. The majority of those contacted said that they believed that alteration of material properties through the introduction of nanoscale components was a most likely use of nanotechnology to impact on society. The examples of applications are; nanocomposites systems for improved polymers, cutting tools, self cleaning paints, pigments, optical components for telecommunications, Nanoscale carbon chemistry (CNT, buckyballs) catalysis and developing corrosion resistant materials.

The further reduction in microelectronics through ‘nano-inside’ technologies was also seen as a very likely area of high impact for society, this is the concept of using Nanolithography (the production of electronic components with nanometric resolution) to produce nanoelectronic components within a standard microelectronic device. An improvement in the ability to model systems at the Nanoscale is leading the way to design structures with specific properties and this allied with the experimental improvements in controlling the way systems grow will allow the further improvement of material properties, such as ductility. The last area of nanotechnology that was seen as significant for adding quality to society was that of drug delivery and bio/nanotechnology. This area of research was highlighted most commonly, by those not in the field, as likely to have a significant impact on society. The concept of nanomachines and smart nanostructures was seen as ‘hype’ by most people interviewed and not likely to make an impact on society for a significant period of time and only after very significant investment.

1.10. Nanotechnology related education packages

A number of Universities within Europe are now offering nanotechnology ‘modules’ as part of the undergraduate training package. This is a very positive move as it means that the students are getting exposed to nanotechnology and nanotechnology terminology and constraints at an early stage of their education. The complexity and diversity of nanotechnology means that many believe it will not be possible to offer a degree in nanotechnology and that the best solution is to offer modules and projects that are related to nanotechnology. It is also now possible to complete a masters level training course in nanotechnology at Universities in the UK and Germany. These courses range from those that are dedicated to developing a full understanding of the fundamentals of nanotechnology to those that are ‘applications’ and industrially led. These courses are likely to further improve the standing of Europe in the field of nanotechnology as the graduates work through the career ladder. Funding for similar courses and qualifications would be beneficial.

2. Focus on nanotechnology research activities in Europe: Research conducted by interviewees

The loose terms used to cover nanotechnology in the introduction section will be used as the outline for a more detailed review of nanotechnology research in Europe that the interviewees are currently completing. Appendix 3 shows a break down of the areas of nanotechnology research individual researchers are conducting. It is clear from examining Appendix 3, that those researchers contacted are all conducting work in a number of nanotechnology areas. This highlights the multidisciplinary nature of nanotechnology type research. As projects progress from one initial idea there is a rapid expansion in the possible applications and uses of the technology which requires further research in a number of different research areas. The large proportion of research activities, outlined by those interviewed, was seen to either having a direct application (application led), as likely to have an impact on people lives or was described as 'fundamental' to improving the understanding required to make an impact on people lives. The research is therefore directed in avenues where most benefit can be achieved for society. The break-down and division was made by the author of the report and follows the outline given earlier. A more thorough analysis of the projects being undertaken by those contacted follows. The close relationship between a number of the research areas is highlighted by the level of collaboration that is undertaken by the research groups.

2.1. Extreme Nanotechnology

Extreme nanotechnology research is being carried out in a number of guises throughout Europe. Of those contacted to complete this report, 6 are completing research that can be termed as Extreme nanotechnology. The activities range from those researchers who are focusing on long range self assembly systems, to those who are concentrating on developing systems that use single molecules to perform the tasks usually associated with electronic components. A number of research groups conducting extreme nanotechnology are also involved with nanocluster development; this is because the development of nanoclusters is often a precursor to extreme nanotechnology. Quantum computation research is also being conducted in Europe.

The future directions of extreme nanotechnology are believed to be using the technology of self assembled monolayers (SAM) to produce long range ordered systems that are identical. These systems are believed by many to be a first step to producing nanoelectronics systems. The ability to control the evolution of active surfaces by the selected movement of individual molecules or atoms is allowing a further understanding in the fundamental principles that govern the way matter behaves, this understanding could be used to further enhance materials properties.

2.2. Nanofabrication

A number of respondents are conducting research in the area of Nanofabrication. These groups are most heavily funded by industry and have a very application based research portfolio. The research being conduced by these groups focuses on the further miniaturisation of microelectronic components and covers a range of enabling technologies such as e-beam lithography, soft lithography and integration issues. The groups also stated that they had the least difficulty in finding suitable staff, although staff issues are a concern for some.

The future directions of nanofabrication are believed to come from the interface of SAM technology and soft lithography (best described as nanoscale printing of a pattern) to produce a system that can generate reproducible images with feature sizes of 30-80nm. A further direction is the introduction of organic molecules to complete the tasks of electronic components and the introduction of CNT's into electronic circuits. The use of other lithographic processes to develop systems with feature sized in the order of 30-80nm is also believed to be important for future developments. Some believe the technology that will be responsible for the production of nanoelectronics devices is currently not available and will be discovered through the current research that is being conducted.

2.3. Metrology

None of those who replied are conducting Nanoscale metrology. A significant amount of work is being carried in Europe at the Danish Technical University and well as the spin off company DTM, and also at NPL in the UK. Other research and national institutions are also conducting research in the field of nanometrology.

The future of nanometrology lies in determining standards for use at the nanometric scale. These include determining standards for translation in the x, y and z axis that are traceable as well as force standards for nano Newton forces. A series of standards that can be used readily within the laboratory are also required.

2.4. Nanostructured materials

A number of groups that were contacted are completing work in the field of nanostructured materials. The research focuses on further developing the fundamental understanding through modeling to developing new techniques for producing Nanoscale powders and nanophase composites. Groups that are conducting work in nanostructured materials are also heavily involved in nanocluster research, the production of a nanocluster is often a precursor for the production of the nanostructured material. A number of European companies are also involved in the production of nanostructured materials. A growing interest in activities concerned with nanostructured carbon was highlighted.

The future directions of nanostructured materials research appears to lie in the direction of closer collaboration between those conducting modeling research and those producing nanostructured materials. The enhancements made in the synthetic techniques for producing nanoclusters is rapidly feeding into the nanostructured materials arena, this is mainly due to the close relationship between the two research activities. With potential markets estimated to be $11 billion by 2010 there is a significant drive for the technology to come to market.

2.5. Functional nanotechnology

Functional nanotechnology includes those who are conducting research in the area of drug delivery. The areas of research being conducted by those who responded vary from the development of novel drug delivery systems to developing new systems for the diagnosis of illness through DNA/RNA template analysis. Difficulties in finding funding and staff in these areas was highlighted by the respondents.

The development of safer and more efficient drugs and drug delivery systems is the current driving force in functional nanotechnology. These developments are seen by many as very likely to improve the quality of life for a large number of people. The techniques that being evaluated in order to deliver drugs more safely include the use of nanoscale carbon technology, coating nanoparticles of drug with biodegradable polymer micelles and the generation of drug molecules as nanoparticles. The ability to tag a molecule and follow it’s path through a living system is also likely to have an impact on the research direction in the near future.

2.6. Nanomechanical devices

None of those who replied were classified as conducting research in Nanomechanical devices, although some of the groups conducting work in nanofabrication and extreme nanotechnology may well have projects that broach into the area of nanomechanical devices. There is research being conducted in Europe on Nanomechanical devices notably at IBM in Switzerland and University of Basel and at other centers.

The ability to use biological energy as a source of energy for Nanomechanical devices is likely to be a significant driving force in the future directions for nanomechanical devices. The future for nanomechanical devices seems to fall down two paths; the first is the ability to sense and then actuate on a stimulation of nanoscale. For example, the interaction of a single particle or small clusters of particles with an active surface. This is already being done and further developments on this research are likely to have a high impact on society. The second area is that of nanogeneration systems this, as explained earlier, is believed to be less likely to have an impact on society in the short term. The number of groups that are conducting research in this area in Europe is very small.

2.7. Molecular nanotechnology

Of those interviewed only one researcher was conducting research that was in the molecular nanotechnology. There is a reasonable amount of research being conducted in Europe on Molecular nanotechnology, at institutions based in most of the European countries.

The future of molecular technology lies in the further understanding of how molecules interact and ways to control the interaction. The transport of individual molecules across boundaries or barriers is also regarded as a topic that will be investigated in the near future.

2.8. Nanoclusters

A significant number of respondents claimed to be conducting research in the area of nanoclusters, both using colloidal and dry synthetic techniques. Most of those who are conducting nanocluster research are also interested in the potential applications of the nanocluster and also conduct research in areas such as extreme nanotechnology and nanostructured materials.

The ability to synthesise small clusters of atoms and then disperse them onto a surface is an essential first step in many extreme nanotechnology applications and also for the production of nanostructured materials. The further understanding of how to produce nanoclusters and control the size distribution is a pressing need for need materials to be produced. There is a significant market force driving the generation of nanocluster research and a large number of nanotechnology ‘start ups’ are targeting the nanocluster market.

3. Conclusions

The conclusions that can drawn from this report are that Europe is conducting a broad range of nanotechnology research initiatives. The very broad definition of nanotechnology that is used within Europe allows this wide range of activities to operate and is beneficial. There are concerns about the funding mechanisms and the move to larger projects which are seen to make it more difficult to perform nanotechnology on a small scale. With larger project consortia there is a danger that the long term issues of nanotechnology will be set aside in order to satisfy the more immediate concern. If the primary partner is industrial, as seems likely with large projects, this issue is likely to be a far more immediate concern. In this case then it will be detrimental to nanotechnology research as it requires some fundamental questions answered before significant progress can be made. A ‘glass ceiling’ could arise if short term goals are achieved without a thorough understanding of the mechanisms behind the processes. There is also a general feeling that the development of ‘centers of excellence’ is damaging for the nanotechnology community. These centers force the politicisation of the research area, make it difficult for others to obtain funds and staff and lead to conflicts that can cause the reduction in collaborative effort. The lack of funds available for large strategic projects was raised as a concern by a number of those interviewed.

The opportunities to network and interface with other researchers are seen as positive though difficult to break into. The information is available but only those who have the benefit of being involved in the networks know where best to find it and those who are just starting their research careers find it difficult to get clear and concise information. The level of funding for networking opportunities was described as insufficient.

The coverage of nanotechnology in the press was seen as potentially damaging by those completing nanotechnology research. A minority saw the coverage of at best neutral though most thought that the coverage highlighted aspects of nanotechnology that are unlikely to make an impact but were good ‘stories’. The result of this was that many researchers felt they would not be conducting research under the name of nanotechnology in a number of years. The increase in profile of nanotechnology, and associated increase in funding, has meant that a large number of people are using the name in order to obtain funds from the new nanotechnology initiatives.

The main issue facing researchers is the difficulty in finding suitable staff (at all levels, from students to lecturers) to take up the posts offered. Some of the difficulty comes from the fact that certain sponsors prohibit the employment of students from outside the EU, or home country on the contract. There are a significant number of applicants from outside Europe but very few from with-in Europe.

Europe is generating a significant number of publications in the area of nanotechnology. If Europe is taken as one overall region then it leads the world of publications covering the topic of nanotechnology.

The mobility of people through Europe was seen as adequate, and in some cases very good by those interviewed. A lack of structure for the development of young researchers was raised as a concern. A number of educational packages are now being developed in the areas of nanotechnology, these are aimed at both undergraduate and post graduate students.

Those who replied all stated that they believed nanotechnology had a major role in improving the quality of life of the general population in the immediate, short and long term future. The areas of impact ranged from improving the properties of materials (such as reducing the over weight of a car to improve fuel consumption) to altering the way in which drugs are administered.

Appendix 1

List of contributors (direct communication, or supplying documents used).

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Dr Marc Hou
Dr Guido Kicklebick
Dr Wolfgang Lacom
Dr Pierre Legagneux
Prof Mamoun Muhhamed
Dr Zorica Orel
Prof Richard Palmer
Dr Joerg Patscheider
Prof Mike Petty
Dr Paul Reip
Prof Saul Tender
Dr Dimitris Tsoukalas
Dr Helena Van Swygenhoven
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Appendix 2

Sources of financial support

			Primary Sources of funding	Country of Institution
Dr	Dolors	Baró	Spanish Government, EU FW V	Spain
Dr	Ramon	Compano	Not appropriate	Belgium/France
Dr	Debbie	Corker	EU FW V, other EU programs	UK
Dr	Emmanuel	Dubois	EU-Coordinator for SODAMOS program	France
Dr	Karen	Edler	Government agencies (EPSRC), Royal Society	
Prof	Juri	Estrin	DFG (Government of lower Saxony)	Germany
Dr	Martin	Garnett	Government agencies (EPSRC), EU FW V	UK
Dr	Jean-Charles	Guibert	Industry, State	France
Dr	Horst	Hahn	Government (DFG, BMBF, AvH, DAAD), industrial	Germany
Dr	Heinrich	Hofmann	National Research organisation, EU FW V	Germany
Dr	Marc	Hou	Federal Grant, IUAP (networks), French community government(nanotech network)	Belgium
Dr	Guido	Kicklebick	Austrain science foundation	Austria
Dr	Wolfgang	Lacom	Internal government funding	Germany
Dr	Pierre	Legagneux	EU FW V	France
Prof	Mamoun	Muhhamed	Faculty, Local Government, EU FW V	Finland
Dr	Zorica	Orel	Slovenian Ministry For Education and Science	Slovenia
Prof	Richard	Palmer	Government agencies (EPSRC), EU FW V	UK
Dr	Joerg	Patscheider	National Application orientated programs	Swiss
Prof	Mike	Petty	Government agencies (EPSRC), EU FW V	UK
Dr	Paul	Reip	Not appropriate	UK
Prof	Saul	Tender	Government agencies (EPSRC), EU FW V	UK
Dr	Dimitris	Tsoukalas	IST program	Greece
Dr	Helena	Van Swygenhoven	Swiss National Science Foundation	Swiss
Dr	Jurina	Wessels	No information supplied	Germany

Appendix 3: Research activity areas for those interviewed

Name			Areas of research
Dr	Dolors	Baró	Nanofabrication, Nanostructured
Dr	Ramon	Compano	Not appropriate
Dr	Debbie	Corker	Not appropriate
Dr	Emmanuel	Dubois	Nanofabrication
Dr	Karen	Edler	Nanostructured
Prof	Juri	Estrin	Nanostructured, Nanocluster
Dr	Martin	Garnett	Functional Nanotechnology, Nanoclusters
Dr	Jean-Charles	Guibert	Extreme Nanotechnology, Nanofabrication
Dr	Horst	Hahn	Nanostructured, Nanocluster
Dr	Heinrich	Hofmann	Extreme Nanotechnology, Nanostructured, Functional Nanotechnology
Dr	Marc	Hou	Extreme Nanotechnology, Nanostructured
Dr	Guido	Kicklebick	Extreme Nanotechnology, Nanoclusters
Dr	Wolfgang	Lacom	Nanostructured, Nanocluster
Dr	Pierre	Legagneux	Extreme Nanotechnology, Nanofabrication
Prof	Mamoun	Muhhamed	Nanostructured, Nanocluster, Extreme Nanotechnology
Dr	Zorica	Orel	Nanostructured
Prof	Richard	Palmer	Extreme Nanotechnology, Nanostructured
Dr	Joerg	Patscheider	Nanostructured, Nanocluster
Prof	Mike	Petty	Extreme Nanotechnology, Nanofabrication, Molecular nanotechnology
Dr	Paul	Reip	Nanostructured, Nanocluster
Prof	Saul	Tender	Functional Nanotechnology, Nanoclusters
Dr	Dimitris	Tsoukalas	Nanofabrication
Dr	Helena	Van Swygenhoven	Nanostructured, Extreme Nanotechnology
Dr	Jurina	Wessels	No information supplied

Appendix 4: WWW sources of Nanotechnology background and current information

The sites are listed alphabetically:

www. mp-cientifica.com/
www. uspen.com
www. ano.org.uk
www. ciam.com/nanotech/
www. malltimes.com/
www. yvex.com/nano/

This is not meant to be a comprehensive list of nanotechnology websites.

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3. *Nanotechnology in Japan: Latest trends in the private and public sector R+D Update*, Meakin, 2002
4. *The investors guide to Nanotechnology and Micromachines*, Fishbine, 2002
5. *Nanotech, the tiny revolution*, white paper, CMP Cientifica, Nov 2001
   Contains a good discussion on some possible applications of Nanotechnology and can be found at: http://www.cmp-cientifica.com/cientifica/frameworks/generic/public_users/NOR/NOR_White_Paper.pdf