2016 National Research Infrastructure Roadmap
Capability Issues Paper

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RESPONSE FROM
AUSTRALIAN NATIONAL FABRICATION FACILITY

ANFF

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1. Executive Summary

The Australian National Fabrication Facility Pty Ltd (ANFF) is the governing body for an existing NCRIS facility providing researchers with access to infrastructure and expertise to support the fabrication of micro- and nano-scale devices and materials. ANFF resources are typically used by 2,700 researchers per annum, with access facilitated by 90 specialist technologists employed throughout the national network. ANFF facilities underpin the work of seven ARC Centres of Excellence and more than 10% of ARC-funded projects. Of order 20% of facility usage is by Australian industry. To date, ANFF has launched eight start-ups with another 23 ANFF-enabled projects currently rated as highly promising for commercialisation.

ANFF welcomes the opportunity to respond to the National Research Infrastructure Capability Issues Paper. This response represents the views of ANFF stakeholders, garnered through its Strategic Advisory Committee of Node Directors and its Board.

Key points are summarised as follows:

- The 2016 Roadmap should be firmly embedded in clear articulations of Australia's **research priorities and industry policy.**
- The fabrication of materials and devices on a micro- or nano-scale is a **fundamental capability** which impacts on all current national research priorities and the commercial opportunities which flow from them. It is an important component of six of the seven capability focus areas identified in the Issues Paper.
- The current ANFF facility has **capacity for expansion** to accommodate new technologies and emerging research requirements within its existing network of specialised laboratories.
- For continued success, fabrication facilities require funding for i) highly skilled **technical staff;** ii) scheduled **replacement of obsolescent equipment**; and iii) investment in **new and expanded capabilities** in response to emerging research priorities.
- Adequate **career pathways** for highly skilled technical staff need to be provided within (predominantly) university structures.
- Support for **Translational Science and Engineering** is a missing component in Australia's research infrastructure system. Expertise in systems engineering and integration as well as the provision of associated infrastructure are necessary in order to capture the commercial opportunities presented by Australia's scientific excellence.
- The establishment of **larger scale prototyping and testing facilities** is required in order to support commercialisation within Australia and enable possible new areas of manufacturing.
- ANFF's **Board with strong industry representation** is an effective governance structure that may serve as a model for future NCRIS facilities.

2. Background Comments

The NCRIS capability for Fabrication (The Australian National Fabrication Facility – **ANFF**) provides research infrastructure support for Australia's R&D activities in **Advanced Manufacturing** and for Practical Research Challenges faced in the following areas of National Science and Research Priorities[1]:

National Science and Research Priority	**Practical Research Challenge**
Food	Enhanced food production through novel technologies such as sensors, robotics, real-time data systems and traceability, all integrated into the full production chain.
Soil & Water	New and integrated national observing systems, technologies and modelling frameworks across the soil-water-marine systems.
Transport	Low emission fuels and technologies for domestic and global markets. Improved logistics, modelling and regulation: urban design, autonomous vehicles, electric transport, sensor technologies, real time data and spatial analysis.
Cybersecurity	Highly-secure and resilient communications and data acquisition, storage, retention and analysis for government, defence, business, transport systems, emergency and health services.
Energy	Low emission energy production from fossil fuels and other sources. New clean energy sources and storage technologies that are efficient, cost-effective and reliable.
Resources	Technologies to optimise yield through effective and efficient resource extraction, processing and waste management.
Environmental Change	Improved accuracy and precision in predicting and measuring the impact of environmental changes caused by climate and local factors.
Health	Effective technologies for individuals to manage their own health care, for example, using mobile apps, remote monitoring and online access to therapies. Contribution to new therapies (for example new cures for cancer), efficient pharmaceutical delivery and more precise diagnostic tools in the era of precision medicine.

The facilities provided by ANFF foster Australian research competence in the micro- and nano-technology sphere that will dominate manufacturing and technological processes in the future because of the lower cost of materials, increased functionality and the opportunity to interact effectively with the biological and natural worlds. They exist to allow the fabrication of complex structures at the cutting edge of materials science, nano-electronics and nano-photonics, nano-medicine interventions, and exciting developments in areas as diverse as quantum computing, highly efficient solar cells, resilient sensors, water treatment, energy storage, medical advances in new treatments, and diagnostics and disease prevention. Through ANFF, researchers can produce structures to test new physical and chemical theories, demonstrate hitherto unmeasurable

[1] http://www.science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx

phenomena and build prototypes of new devices able to launch products on the road to successful commercial development.

ANFF's fabrication systems are designed to sustain Australia's industrial and scientific presence in a world that is predicted to be dominated by emergent trends such as those illustrated in Table 1.

Table 1. Anticipated new products and services[2,3,4,5,6]

Totally networked communications environment (5G technology)	Continuous health monitoring
Clinical medical advances using nanostructured materials	3D printed organs including laboratory bench-top brain
Ready mass data handling via cloud	Robots for assisting the elderly
Advanced materials and computer engineered structures	Microchip implants in body and human brain
Electric, driverless cars	$1,000 computer with computing capacity of human brain
Fuels from CO_2	IT and genetically-enabled agriculture
Biofuels competitive in price with fossil fuels by genetic engineering	Cold storage and better food supply chains
Cheap batteries for efficient energy storage	Augmented reality in mobile and fixed displays
Smart clothes and wearable devices	Universal language translation in mobile phone
Mass produced housing	Wholly flexible electronics and flexible screens via ultra-thin organic light emitting diodes

Overlying these new products and services lies the concept of the ***Internet of Things*** (IoT) that embodies[7,8]: "networking of physical devices, vehicles, buildings and other items—embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data". IoT is presently dominating futurist thinking in Europe and the United States and heralds the need to develop many of the new components of the system.

ANFF currently supports the research infrastructure needs of 2,700 Australian researchers through its eight nodes, each with a distinct set of fabrication capabilities. Projects supported represent in excess of 10% of those currently funded under the Australian Research Council's Discovery and Linkage Grant schemes. ANFF also provides backing for 7 of the 25 current ARC Centres of Excellence. Through its 90 specialist technical staff, ANFF provides expert technical fabrication support to researchers and to industrial R&D personnel who consume 20% of its operational hours.

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[2] Bain and Company, (2011), *The Great Eight: Trillion Dollar Growth Trends to 2020*, http://www.bain.com/Images/BAIN_BRIEF_8MacroTrends.pdf

[3] The Future World, 2015, *Technology 2020: Commercial World*, http://thefuturescompany.com/

[4] Singh, S. (2013), *The 10 Social and Tech Trends That Could Shape the Next Decade*, http://www.forbes.com/sites/sarwantsingh/2014/05/12/the-top-10-mega-trends-of-the-decade/

[5] https://3dprint.com/86557/3d-printed-brain/

[6] Clark,S (2016) 'Flexible thinking could short-circuit old-fashioned electronics' *The Australian,* 5 Sept., page 22

[7] Wikipedia, https://en.wikipedia.org/wiki/Internet_of_things

[8] http://techemergence.com/artificial-intelligence-plus-the-internet-of-things-iot-3-examples-worth-learning-from/

In its 9 years of existence, ANFF has morphed into a collaborative capability that has gained the respect of its users and is seen as an essential component of their doing world-leading research and of providing a route to ensuring that this research has the potential for significant commercial impact. The world market for technologies and products of the type supported by the ANFF fabrication facilities is estimated as $US 3 trillion by 2020[9].

Figure 1 – ANFF's specialist technical staff provide expert fabrication and support for its 2700 researchers

ANFF is incorporated, is governed by a Board drawn predominantly from Australian industry, and is advised by an International Advisory Committee of those with experience in operating similar capabilities overseas. It draws significant funding from its 19 participating universities and CSIRO, and from State Governments.

ANFF is unique amongst NCRIS capabilities in that its facilities focus on ***processes to manufacture*** new materials, objects and devices. ANFF's nodes comprise clean rooms stocked with specialised processing tools that together make it possible to fabricate a structure down to an extremely small scale. Approximately half of the cost of establishing ANFF nodes to date has been for the clean rooms and specialised laboratories themselves. These existing clean rooms will accommodate future versions of fabrication tools that may not, as yet, have even been conceived of. Techniques such as molecular self-assembly, biomimetic processing and supramolecular and atomic chemistry are seen as potential pathways for future fabrication processes that will eventually be replicated in full-scale manufacturing plants. There is scope to develop novel fabrication processes as well as novel devices. New characterisation techniques for the study of biological materials such as single molecules strongly depend on fabrication facilities, examples being the helium atom microscope and super resolution fluorescent microscopy.

3. Responses to Questions Posed

Questions

Question 1:	Are there other capability areas that should be considered?

The capability focus areas listed in the Issues Paper are quite comprehensive and include the continuing presence of a fabrication capability to provide the research infrastructure necessary to

[9] Roco, M. (2010), *Research Directions for Societal Needs in 2020*, http://www.nano.gov/node/948

develop devices and processes at the micro- and nano-scales. Fabrication will be an important continuing national competency and will increasingly draw on converging technologies and give rise to devices that are smaller and better integrated into the external world. Significant research challenges exist in integrating nano-electronic and nano-photonic devices into the biological world, further exploring quantum effects and elucidating the physical and chemical properties of hard-soft interfaces.

What does appear to be missing in the capability focus areas is the development of Australian competency in what will be termed ***Translational Science and Engineering (TSE).*** This has at its heart the development of skills and infrastructure necessary to take promising scientific developments through to developments having a potential economic impact. It also embraces the front end of the invention process where advanced computational models are used to predict the behaviour of chemical, physical and biological systems, predisposing subsequent experimentation to areas likely to show the greatest promise. It also entails numerous aspects of **Systems Engineering**, an under-recognised and poorly-served discipline that can require years of experience across multiple engineering domains, and which is often essential to embed devices and components created in the lab into more complex products and systems that can solve real world problems.

A TSE capability focus area would provide for access to state-of-art modelling software, design software and scale-up and demonstration facilities that allow products and processes to be developed to a stage where their path to commercialisation can be efficiently evaluated. It would also encourage the cross disciplinary collaboration important for the assembly of systems and prototypes and where innovation can be realised.

Examples of the sorts of facilities provided under this focus area would be:

- State-of-art software for **computational chemistry and materials science** to guide the development of new atomic and molecular species and to provide a basis for more efficient scientific experimentation.
- Advanced engineering software packages for **component integration, simulation and prototype design**
- **Larger scale fabrication and testing facilities** (e.g. a nano-electronics/photonics fab; a pharmaceutical or biochemical mini-production facility) where Australian expertise in high technology manufacture could be developed and demonstrated.

The availability of such software would also merit the employment of specialist engineering staff who could offer expert design services that would complement the software and ensure efficient utilisation. Just as NCRIS machinery requires specialist staff to operate the hardware, so too can software require specialist "super-users" to fully recognise and exploit its functionality.

The missing capability focus area is currently embraced by the engineering profession. But, in world terms, Australian researchers are relatively poorly served by such research infrastructure except in those areas (minerals, offshore processing, water treatment) where Australia already has a significant international presence. Other countries (see answers to Questions 12-14) have research infrastructure facilities aimed at filling this gap.

For the micro/nano areas that it embraces, ANFF would see significant national benefit in developing its facilities for the front-end and back-end engineering skills described. Giving Australian researchers good access to the best available software packages, adequate high performance computing time, and professional engineering expertise on how to apply this technology, would much enhance the ability of researchers to do effective research and to follow this through with significant impact. Areas of high national significance that would benefit would include quantum computing, security, environmental monitoring and medical diagnostics.

The development of a TSE capability will require an active dialogue with engineering academics, those in industry and CSIRO. It will complement other recent activities[10] to promote the translation of public sector research into commercial application.

Question 2: Are these governance characteristics appropriate and are there other factors that should be considered for optimal governance for national research infrastructure?

The key characteristics provided for an optimal governance model are appropriate but should perhaps sit within a framework of higher-level goals set for the Australian research system and Australian industry policy, for which the support provided by quality research infrastructure is an important contributor. The balance of capability activity between servicing research that leads to high quality, citable publications and that which leads to applied outcomes could thus be more readily set, with elements of new research infrastructure chosen accordingly.

It is apparent that no one governance model will optimally fit all present and future capabilities. What is needed is a governance model where operation of the capability can be handled effectively, with risk contained, and an ability to plan strategically to meet changing circumstances. There is need for a governance (and reward) model that encourages greater collaboration between institutions, so that the whole is much greater than the sum of the parts. Governance in isolation tends to maximise individual institutional objectives rather than those demanded of a collaborative research infrastructure network.

From a governance structure viewpoint, ANFF's experience is that it has been well served by incorporation and a board predominantly drawn from senior industry figures. This has enabled it to avoid the parochialism that can be evident in representative governance models. It has also provided an outreach to Australian industry. Should the independence of the governing body be one of the desirable characteristics of an NCRIS capability?

The handling of intellectual property within a capability can be a factor inhibiting collaboration. ANFF, for example, has found it desirable not to make claims on intellectual property arising from use of its facilities unless an entirely new fabrication process is developed. What is needed in a good capability governance model is for the intellectual property and moral rights policies to be set in a way that is transparent, timely and encouraging of inter-researcher cooperation, especially across disciplinary and institutional boundaries. ANFF's experience is that when a number of institutions

[10] https://theconversation.com/researchers-may-be-motivated-by-impact-but-that-is-not-enough-to-achieve-it-63409?utm_medium=email&utm_campaign=Latest%20from%20The%20Conversation%20for%20August%2018%202016%20-%205439&utm_content=Latest%20from%20The%20Conversa

are involved in collaborative research, this can attenuate subsequent intellectual property determinations. The development of uniform intellectual property decision processes across the Australian public research sector would seem desirable.

Attention is also drawn to the increasing impact of Government regulation (e.g. ITAR and dangerous materials supply) on the pursuit of some critical research. Overly burdensome regulation is hampering the efforts of some researchers in their use of ANFF facilities for innovative research.

Question 3: Should national research infrastructure investment assist with access to international facilities?

Question 4: What are the conditions or scenarios where access to international facilities should be prioritised over developing national facilities?

Access to international facilities provides the Australian researcher with the opportunity to do cutting-edge work on facilities that are at a more advanced stage of development than those available in Australia. Some such facilities are unique because of their complexity or investment involved. In others, in the longer term, equipment development will lead to them becoming ubiquitous with the capability becoming available in Australia. In the latter case it may be desirable for Australian researchers to gain experience overseas so that they can accelerate their research once the equipment is available locally. Against this is the consideration that, in the interests of developing Australian industry in new areas, it may well be desirable to strive to develop Australian infrastructure capacity. A case in point would be the further development of Australia's research efforts in quantum computing. In one approach an offshore fabrication facility such as IMEC would be used for further development[11]. In another, every attempt would be made to develop scale-up and proving capacity within Australia, following a TSE initiative.

ANFF believes that these decisions should continue to be made on a case-by-case basis, with due consideration given to the importance of the research from a national perspective and the advantages offered by the offshore facility, balanced by the desirability of infrastructure funds being invested in Australia so that leakage of intellectual know-how does not occur. Clear national benefits should be demonstrated where access to international facilities is given priority over national facilities, particularly given the risk of IP loss offshore and the costs involved in travel. Whilst it is probably desirable for the Australian Research Council to make the decision to fund offshore use, the advice of NCRIS should be sought.

[11] http://www2.imec.be

Question 5: Should research workforce skills be considered a research infrastructure issue?

Question 6: How can national research infrastructure assist in training and skills development?

Question 7: What responsibility should research institutions have in supporting the development of infrastructure ready researchers and technical specialists?

There are two aspects to these issues. One is the continued provision of highly trained professional staff to operate the equipment in capabilities and to provide expert advice to the research users of the capability. For a capability like ANFF the strengthening of its competencies and linkages in the medical field would be desirable. The other is to use the capability as a training ground for senior students who will then go out to populate new facilities and high technology industries as well as industry personnel themselves. It depends very much on the nature of the capability.

ANFF has wrestled with the problem and initially focussed on attracting experienced staff from overseas. As it has matured, local staff have been trained to take increasingly important roles. There remains the problem of providing these staff with continuity of employment and a career path, though the Government's decision in 2015 to provide continuing funding for the NCRIS program has helped here. ANFF's structure is such that its senior technical staff are on University payrolls. This approach is considered worthwhile for NCRIS-funded capabilities. A problem faced here, however, is that staff attracted to these roles are coming from the same talent pool as Australia's most promising academics. Within the university environment little emphasis is placed on non-academic career pathways. If NCRIS facilities are to attract and retain staff within the university sector this needs to be addressed.

Figure 2 – Customised training programs are available within ANFF facilities to meet individual researcher needs.

As a way of strengthening the research-support capacity of facilities, the Melbourne Centre for Nanofabrication also appoints Technology Ambassador Fellows[12] from the public and private research sectors who spend part-time periods for up to two years with this ANFF node bringing expertise and fostering developments in nanofabrication capability.

The training of senior undergraduates and postgraduates using NCRIS capabilities is seen as a key opportunity for capabilities such as ANFF that are focused on developing new technologies and materials. A study of overseas capabilities (e.g. the Marvel Facility at the University of California,

[12] http://nanomelbourne.com/newsletter/2016-anff-vic-technology-ambassador-fellowships

Berkeley[13]) has shown that it is graduates who have been trained in major infrastructure facilities are, on graduation, most likely to induce their companies to use the facilities, or, themselves set up start-up companies reliant on the services provided by the facilities. Within ANFF, for example, both the University of South Australia and the University of Newcastle offer winter schools to familiarise undergraduates with nanofabrication technology. Some limited internships with ANFF facilities are available to doctoral students. For those international students exposed to facilities like ANFF in their postgraduate research studies, experience shows that they retain links with Australian researchers on returning to their countries of origin, producing collaborative international research and innovation and international marketing opportunities for new technologies.

Using appropriate NCRIS capabilities as training grounds for graduates and those from industry populating Advanced Manufacturing developments in Australia would seem a very effective way of capturing further benefits from the NCRIS program. ANFF, for example, is exploring this, with the concept of offering a formal competency qualification for trained users of its facilities. In addition, ANFF specialist staff can be available to offer specialist units in undergraduate programs to ensure that Australian students are fully conversant with new technologies.

Question 8: What principles should be applied for access to national research infrastructure, and are there situations when these should not apply?

The principles espoused under Section 3.5 are appropriate and are applied in ANFF facilities, with prioritisation of use determined by node access committees. It is noted that international facilities similar to ANFF do not generally charge the full cost (i.e. that including amortisation of capital equipment) to industrial users, this being seen by respective governments as a way of encouraging their industries to develop and adopt new technologies. However, collaboration with public sector researchers is generally encouraged.

By way of example, ANFF requires that its access processes be transparent and encourage non-host use. Whilst no claim is made on intellectual property brought in by users, arrangements can be made for secure use of facilities by industry, provided this does not significantly hamper use by public sector researchers. Hourly user rates for industry-related projects are lowest when these involve collaboration with a public sector collaborator, as in an ARC Linkage grant.

There is an opportunity to make use of cross-facility or cross-capability software to enhance collaboration – examples are booking systems that allow a researcher to access a network of facilities. Universities in the USA are beginning to use such systems to manage their core facilities. Some Australian universities (e.g. UNSW) are currently exploring this possibility.

Question 9: What should the criteria and funding arrangements for defunding or decommissioning look like?

Defunding and decommissioning should, as indicated, be part of the life cycle of national research infrastructure. The Commonwealth already has experience with defunding similar aggregations of

[13] Report on Endeavour Fellowship experience, Dr W McKenzie, ANFF, 2015

research effort such as ARC Centres of Excellence and Cooperative Research Centres. Criteria such as the research supported no longer being on the Significant Research Challenges list or no longer attracting significant ARC or NHMRC project funding would be pointers to the need for review. Also, if the equipment underpinning the capability has become low cost and widely distributed, the case for a central NCRIS facility may have lessened. The defunding and/or decommissioning approach should be one where useful equipment is relocated to individual institutions or CSIRO or industry consortia. To enable this to happen, relocation expenses and a tapering period for operational funding should be available.

ANFF, for example, has organised its agreements with partners such that, should ANFF be wound up, established facilities will revert to host institutions. A significant negative however is that expertise, inter-university collaboration and open access will be lost under the projected arrangements.

It should be noted that de-facto decommissioning can occur in the absence of certainty around future funding arrangements, since experienced staff can become fearful of job security if future funding becomes unstable. This can lead to an unfortunate feedback loop where the fear of losing funding itself causes a facility to become unviable.

Question 10: What financing models should the Government consider to support investment in national research infrastructure?

Capabilities like ANFF have been very successful in gaining financial support for capital equipment from State Governments, institutions and CSIRO. Because the base infrastructure (functioning cleanrooms) is already established, adding new capital equipment is possible. Already universities have been encouraged to place major items secured under LIEF funding in ANFF nodes, where they operate under the NCRIS wide-access umbrella. The possibility of extending this approach to industry and having industry-sourced equipment located in ANFF nodes is being explored, as is the possibility of encouraging industry consortia to part-support the purchase of new capital equipment. For capabilities like ANFF that are focused on fabrication of prototypes, ultimately to assist the development of new manufacturing industries, the challenge of attracting industry support becomes one of convincing management of the benefits of shared facilities that can lower their capital costs in exploring new technologies. Linking NCRIS activities to the various government initiatives to foster industry development (where appropriate) would seem attractive and could offer alternative sources of capital funding.

Question 11: When should capabilities be expected to address standard and accreditation requirements?

For the purposes of authentication of output, it is highly desirable that facilities address standards and accreditation requirements. For example, in those facilities that handle measurement it is essential that internationally accepted standard methods are adhered to. From the viewpoint of the Fabrication capability, the use of ISO 9000 protocols for manufacture, six sigma standards and the concept of lean production have been applied at the Melbourne Centre for Nanofabrication and are being increasingly applied at other nodes. The availability of calibrated equipment to test for regulatory compliance of fabricated materials or components is important in its own right, and could also be considered as a useful service for industry partners as well. A scheme could also be expanded to encourage facilities owned by industry to be made more widely available to researchers. For example, equipment to test for shock and vibration, temperature, or EMI/EMC is available in industry that could be contributed to benefit of the research sector. This approach is a helpful one as fabrication is taken from the prototype development stage to the proving stage prior to full-scale commercialisation. Similarly, medical devices to be used in clinical studies must adhere to acceptable international standards. An example would be the application of Good Manufacturing Practice (GMP)[14] to pharmaceutical manufacture. But ANFF's experience is that these initiatives do cost appreciable amounts to implement and this must be built into future estimates of operating costs.

Question 12: Are there international or global models that represent best practice for national research infrastructure that could be considered?

Question 13: In considering whole of life investment including decommissioning or defunding for national research infrastructure are there examples domestic or international that should be examined?

Question 14: Are there alternative financing options, including international models that the Government could consider to support investment in national research infrastructure?

This response from ANFF applies to offshore facilities providing similar fabrication capabilities to ANFF. ANFF has closely monitored the functioning of these facilities and, in the case of the American and European facilities has joined with them in collaborative programs to explore scientific developments in nanotechnology and related fields.

Within the USA, the NNCI (National Nanotechnology Coordinated Infrastructure) program, announced by the National Science Foundation in September, 2015[15] is an extension of the previous (10-year) NNIN (National Nanotechnology Infrastructure Network) started in 2004. NNCI involves 16 sites, 8 of which were previously NNIN sites. It is to be funded over 10 years, with the first 5 years of funding totalling $US81 million. 27 universities are involved. The US Department of Energy (DOE) also sponsors a network of 5 nanofabrication facilities allowing open access[16].

The European program was centred on the Eumina capability funded from 2009 to 2013, that provided access to €200 million worth of equipment spread over 36 installations with no fee charged to public sector users. Eumina has since been replaced by Nanoscience Foundries and Fine Analysis for Europe (NFFA-Europe)[17]. NFFA-Europe provides free access to public sector researchers and SMEs for multidisciplinary research at the nano-scale extending from synthesis and nanolithography to nano-characterisation, theoretical modelling and numerical simulation and is supported by the European Union Horizon 2020 program. It offers 9 different and complementary laboratories that

[14] http://www.ispe.org/gmp-resources
[15] http://www.nsf.gov/news/news_summ.jsp?cntn_id=136211
[16] http://science.energy.gov/bes/suf/user-facilities/nanoscale-science-research-centers/
[17] http://www.nffa.eu

offer nanostructure growth and synthesis and has 20 partner institutions. ANFF's CEO, Ms Rosie Hicks is on the Advisory Board of NFFA-Europe.

In Belgium the Interuniversity Micro Electronics Center (IMEC)[11,18] established in 1984 by the Belgium Government and now employing 2,400 staff with an annual turnover of € 415 million offers nano-electronics R&D capabilities to universities and industry. This facility took over an Intel commercial fabrication laboratory and can handle larger scale fabrication. In 2015 it received € 52 million in support from the regional and Dutch Governments and generated € 342 million in contract research income. It has offices in 7 countries worldwide.

In both the USA[19] and Europe[20] there are additional government-supported programs to foster use of facilities by emerging industries and to encourage research collaboration between the public and private sector by developing research networks as well as supporting the capturing of the commercial benefits from public sector nanotechnology research.

Canada has been particularly successful in developing a National Design Network that provides **engineering infrastructure** to accelerate research and commercialisation outcomes[21] in areas (amongst others) related to micro- and nano-fabrication.

Within Japan, focused research centres have been created under the World Premier International Research Institutes (WPI) program[22]. This program, launched in 2007, provides funding for research infrastructure as well as research activity, sourced from the Japanese Government. This program provided $AUD 3.8 billion in 2015.

The funding model that has been adopted by NCRIS and ANFF appears consonant with international best practice. As regards decommissioning and defunding the approach adopted in the transition from NNIN to NNCI is one where fabrication equipment in unsuccessful institutions is re-adsorbed into that institution's infrastructure stock, or, in rare cases is relocated elsewhere.

Regarding the provision of engineering services and larger scale facilities (e.g. a FlexiFab), the Canadian experience suggests that this can be handled by funding flow from the Commonwealth, State Governments and industry, with the last possibly entering on a take or pay user commitment. With respect to the process by which plans for provision of research infrastructure should be set, helpful comments are provided in a Swedish article[23] that examines the European approach.

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18 http://www2.imec.be/content/user/File/anual2015/imec%20annual%20report%202015.pdf
19 https://www.whitehouse.gov/sites/default/files/microsites/ostp/nni_fy17_budget_supplement.pdf
20 http://cordis.europa.eu/project/rcn/194961_en.html
21 http://www.cmc.ca/en/AboutCMC/NationalDesignNetwork.aspx
22 http://www.jsps.go.jp/english/e-toplevel/
23 http://www.kva.se/globalassets/vetenskap_samhallet/forskningspolitik/forskningsstrukturkommitten/rapport_ffsk_2012_en.pdf

Health and Medical Sciences

Question 15: Are the identified emerging directions and research infrastructure capabilities for Health and Medical Sciences right? Are there any missing or additional needed?

Question 16: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 17: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Health and Medical Sciences capability area?

The analysis presented has given little attention in the Issues paper to areas of research in biomedical engineering that are anticipated to have a profound effect on health and medical sciences in the next decade. Nano-medicine is anticipated to command annual world market of $200 billion by 2020[24]. Australia has had considerable success in developing medical products (for example, ResMed and Cochlear) and these companies and many others need a continual flow of successful R&D to maintain their world dominance. A recent analysis suggests that there will be much promise in Australia in the medical devices area[25]. In addition the success of several small Australian biotechnology companies focused on the discovery and development of pharmaceuticals over the past 2 years points to continued excellence innovation in this important endeavour (for example - Acquisition of Fibrotech by Novartis; Bionomics – Merck strategic partnerships in 2 areas pain and cognition; Starpharma – AstraZeneca deal in drug delivery; CRC-Ctx – Merck (MSD) partnership in cancer).

Areas of medical and health research that will need ongoing infrastructure support include:

- Development of diagnostic and monitoring sensors suitable for *in vivo* use and remote interrogation
- Medical processes supported by microfluidics and lab-on-a-chip
- Extra-corporeal processes for tumour sorting and removal
- Nanomedicine– including drug discovery and drug delivery
- Prothesis manufacture by 3D printing
- Nano-scaffolds for surgical procedures
- *In vitro* alternatives to animal testing and clinical studies
- Printed organs
- Biocompatible materials
- Bionic vision

These research areas will be supported by studies on self-assembly of biocompatible materials, interactions between materials and biological systems and implantable electrodes, for example.

[24] Roco, M. (2010), *Research Directions for Societal Needs in 2020*, http://www.nano.gov/node/948
[25] T. Boreham, 'Cure your financial ills: There are many promising medical devices makers', page 26, *The Australian*, 29 August, 2016

Figure 3 – Current capabilities within ANFF include applications in the areas of microfluidics, drug delivery and bionics.

Some of these research challenges are already supported by ANFF and have led to commercial products (e.g. the Vaxxas nanopatch). But what is needed is an infrastructure component that handles integration and pre-commercial production and testing to take a prototype manufactured under laboratory conditions through to a test product suitable for clinical trials. Such a facility would contain medical specialists as well as engineers to overcome the "valley of death". These areas hold great potential for Australia to develop future export markets and, accordingly, it would be desirable to be a partner in international research infrastructure collaborations so that Australia's competence becomes widely known and respected.

Environment and Natural Resource Management

Question 18: Are the identified emerging directions and research infrastructure capabilities for Environment and Natural Resource Management right? Are there any missing or additional needed?

Question 19: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 20: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Environment and Natural Resource Management capability area?

The development of the proposed nationally integrated automated database system depends critically on the availability of appropriate and robust sensors, networked and distributed lab-on-a-chip sensors and access to sufficiently powerful data storage and computing power to handle the information gathered. These are R&D areas presently supported by ANFF. Australia is a big country and water networks, for example, will require remote operation, little maintenance and wireless communication of data. In a large proportion of cases, samples will be collected in solution or put into solution for analysis, so the availability of lab-on-a-chip devices assumes significant importance. Likewise, monitoring and treatment of mining run-off and production water, aquifer monitoring, and in-situ underground processing will continue to be major issues for the resources sector, especially including the recovery of unconventional gas. Through its Materials and South Australian Nodes and the Melbourne Centre for Nanofabrication, ANFF is already providing infrastructure support for R&D in these areas, but a significant increase in demand for new technologies is anticipated.

In meeting future developmental needs for these sectors, Australia can either purchase systems from offshore (if they exist) or develop new systems suitable for international implementation, as has been so successfully done in the mining equipment industry. To be successful in the quest to be an international technology supplier, Australia needs access to an engineering-based facility to scale up from prototype and demonstrate practicality. It also needs to involve itself in international standard-setting protocols so that its technologies can have universal application.

As an example of the opportunities offered, the low-cost measurement of PFASs (poly-fluoro-alkyl substances) in water is a problem that has very recently emerged worldwide as a consequence of the heritage use of fire-fighting foams at airports. The chemicals involved are bio-accumulative and carcinogenic. Developing the technology to inexpensively monitor and treat an environmental pollutant such as this could be immensely rewarding.

Advanced Physics, Chemistry, Mathematics and Materials

Question 21: Are the identified emerging directions and research infrastructure capabilities for Advanced Physics, Chemistry, Mathematics and Materials right? Are there any missing or additional needed?

Question 22: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 23: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Advanced Physics, Chemistry, Mathematics and Materials capability area?

Research in these disciplines underpins the equipment and systems that will make possible a functioning **Internet of Things6**. It underlies advances in advanced manufacturing with research in materials science and engineering having been greatly accelerated by the Materials Genome infrastructure initiative in the USA[26]. Many of the developments in communications have resulted from investigation of the solid state by physicists. Moore's law, for example, hypothesises that the continual impressive increase in the number of transistors on a chip will come to a hiatus as transistor spacing approaches atomic dimensions. Quantum computing is seen as a possible way forward, with Australian scientists having world leadership in silicon q-bit technology. Likewise, Australia's photonics research offers the possibility of greatly enhanced communication. But it is also in the application of chemistry and biochemistry that many future exciting advances are seen.

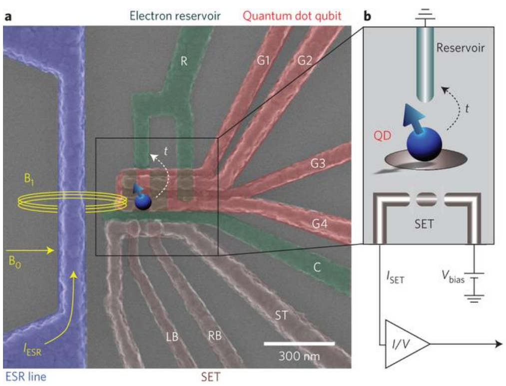

Figure 4 - False-coloured SEM image (a) and schematic diagram (b) of a Si quantum-computing device

[26] Anon (2014), *Materials Genome Initiative*, https://www.whitehouse.gov/mgi

ANFF's aim is to take world-leading science to a stage where it leads to successful start-ups. As an example, research at the Materials node, in particular the ARC Centre for Excellence in Electromaterials Research at the University of Wollongong, has, in conjunction with clinical partners, developed materials and processes to use with 3D printers to allow prototype human organs to be produced and has been the first group to print functioning neural cells on a substrate as a significant step to producing a bench-top human brain[27].

Recent additions to the national facilities available for fabrication include the $130 million Sydney Nanoscience Hub at the University of Sydney[28]. This university now has a $15 million research partnership with Microsoft in quantum computing. A recent article discusses Australia's ability to continue its international leadership in the race to build a functioning quantum computer[29]. These developments illustrate what is possible with quality national research infrastructure.

Computational chemistry is becoming increasingly powerful as a tool for predicting inter-atomic and inter-molecular behaviour and for designing molecules themselves. ANFF sees it as important that Australia strengthens its infrastructure in computational chemistry. This will involve making expensive predictive packages and associated computing power more widely available and ensuring that skilled personnel are available to advise potential users on their use. Such a capability would underpin ANFF's ability to provide efficiency in the development of new materials including supramolecular species and to anticipate interactions across interfaces in nano-catalysis , nano-medicine and sensing.

ANFF agrees with the suggestion in the Issues paper that there be an enhanced fabrication focus on packaging and integration capabilities. It would go further and suggest (as proposed in another section of the Issues paper) that a facility be developed for the at-scale and throughput pre-commercial proving of prototypes developed in ANFF laboratories. This step would involve the inclusion of engineers in the technology development process and, from a research infrastructure viewpoint would necessitate much wider access to the simulation and design packages that are used by the engineering profession. It may prove possible to make this a joint activity with Australian industry, similar to the model used in Canada[21].

ANFF notes the increasing ubiquity of certain metrology and characterisation tools that now enables them to be co-located with fabrication kit allowing for efficient monitoring of production processes.

ANFF does see merit in greater infrastructure support for precision measurement but would see opportunities for developing tools in Australia, as has been done by Australia's Science Industry. It supports the concept of a national chemistry capability but notes that some aspects of such a facility are already covered by the Materials node of ANFF.

ANFF notes that the nano-electronics industry in Australia is already involved in the space industry and is a user of ANFF facilities. At UNSW (for example) the Australian Centre for Space Engineering Research has just been involved in launching two CubeSats from the international space station[30].

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[27] http://www.electromaterials.edu.au/news/bench-top-brain-work-wins-cover-prize/

[28] http://sydney.edu.au/nano/hub/index.shtml

[29] Lawrence, S, "Race to build a quantum computer" *Create,* Engineers Australia, Vol 2, No. 8, September 2016

[30] http://www.acser.unsw.edu.au/news/aussie-satellites-to-launch-from-international-space-station

There are also a number of Australian start-ups in this area[31]. A fabrication capability having the capacity to develop technology through to the commercial testing stage could facilitate the development of a space manufacturing industry in Australia. R&D challenges include development of quantum sensor and communication technologies, highly efficient energy harvesting devices and miniaturised propulsion technologies. Included in the space science capability one might imagine international facilitation of satellite launch from the international space station. The data from sensors on a range of satellites would feedback on climate science, environmental monitoring, geological monitoring[32] and resources sectors (mining on earth or in space).

The emergence of the Internet of Things, the growing use of big data, and the prevalence of wireless devices as part of our everyday lives suggests that some research focus on areas such as electromagnetics, radio propagation, and high speed semiconductor devices is also warranted. The translation of quantum science into quantum engineering and useful devices at a higher readiness level could also be of benefit for Australian industry.

National Security

Question 27: Are the identified emerging directions and research infrastructure capabilities for National Security right? Are there any missing or additional needed?

Question 28: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 29: Is there anything else that needs to be included or considered in the 2016 Roadmap for the National Security capability area?

Timeliness and accuracy of information are important elements in enhancing national security. Current laboratory procedures for determining levels of threat (chemical and biological) are frequently cumbersome and do not provide output in a form that is readily uploaded to a national network. Low-cost, communicating sensors will increasingly dominate this field, with the e-nose, viral sensors and lab-on-a-chip technologies playing an important role. Whilst ANFF is already providing infrastructure for significant Australian R&D in these areas, integration of the elements into functioning devices suitable for long-term deployment remains a challenge. Having available a translational engineering facility with appropriate engineering R&D infrastructure would be highly desirable.

Greater involvement of DSTG and representation of the various Defence Capability Groups in the university research sector would, of course, be beneficial to these considerations.

The US Air Force Office of Scientific Research has already indicated a wish to collaborate with Australian researchers on the development of sensors for hostile environments and this offers the possibility of linking Australian efforts with those in the USA, brokered through the respective research infrastructure facilities.

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[31] http://www.deltavspacehub.com/#space20
[32] http://www.jcu.edu.au/news/releases/2016/august/hiding-in-plain-sight

Underpinning Research Infrastructure

Question 30: Are the identified emerging directions and research infrastructure capabilities for Underpinning Research Infrastructure right? Are there any missing or additional needed?

Question 31: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 32: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Underpinning Research Infrastructure capability area?

ANFF sees a future where *in silico* modelling and simulation at the elemental scale (computational chemistry, quantum modelling) will be increasingly important in predicting novel phenomena before they are confirmed or otherwise in experimental studies. Similarly, the engineering design process in going from a proof-of-concept prototype to a workable device on route to commercialisation, will be based on design and simulation packages. Both steps will require access to best-of-breed software packages and significant computing power. Making provision for these future demands will be a challenge for the capability charged with Underpinning Research Infrastructure, especially so as Australian industry joins public sector researchers in fostering new technology developments.

Data for Research and Discoverability

Question 33: Are the identified emerging directions and research infrastructure capabilities for Data for Research and Discoverability right? Are there any missing or additional needed?

Question 34: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 35: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Data for Research and Discoverability capability area?

It is moot whether the increasing capacity of data storage devices and their decreasing cost will keep pace with the quantity of data that requires storing. The challenge in providing data to researchers is one of ensuring sufficient connectability for the data to be transmitted. Are predictions available of future web traffic within Australia and the possibility of distributed storage of data using new technologies, some of which ANFF-supported researchers are exploring? A significant problem with the storage of large quantities of data and its transmission is the energy requirements of the systems used and the question of adequate heat dissipation from critical infrastructure. Miniaturisation, new materials and the possibility of photonic technology may offer solutions. Developing and testing of these will require ANFF-like R&D infrastructure backed by strong TSE support.

It is noted that a significant driving force for additive engineering is extensive data files that regulate the manufacturing process. Engineering R&D will increasingly call for the shifting of such files through the web. Do estimates of future use make provision for this?

Other comments

If you believe that there are issues not addressed in this Issues Paper or the associated questions, please provide your comments under this heading noting the overall 20 page limit of submissions.

Many future innovative research developments will take place on the cusp between customary disciplines and require interdisciplinary teams for their successful prosecution. Getting and keeping such teams together will be a challenge for Australia's research management. In turn, research infrastructure capabilities will have to be increasingly responsive to unusual challenges. It will not be enough for capabilities to continue to offer a well- established service to researchers. They must be prepared to adapt and explore new ways of doing things and link across capabilities as appropriate to support a truly inventive Australia. Their equipment needs to be maintained at the cutting edge internationally. Continuing funding for ***both*** operating ***and*** capital expenses of NCRIS capabilities needs to be provided. Incentives to encourage collaboration between research groups themselves are important to foster increased innovation, which most often occurs at the seams between disciplines.

4. Conclusion

The present NCRIS Roadmapping activity is a worthwhile exercise that will set the agenda for the provision and support of research infrastructure over the next decade. The capability focus areas given in the Issues Paper do cover the principal areas of Australian research priority. However, given the Commonwealth Government's innovation agenda, it is not clear whether offering infrastructure that provides paths to innovation is part of the Roadmapping exercise. It is suggested that ***Translational Science and Engineering*** be considered an important part of those capabilities that, like Fabrication, build devices or develop processes. The step of taking science and further developing it on its path towards making a significant impact embraces input from engineers and technologists in particular and these disciplines have their own infrastructure requirements for successful R&D.

Ideally TSE infrastructure should result from a dialogue that includes industry and can provide a venue where collaborative public sector/private sector R&D is fostered. There are good examples offshore where such infrastructure has been developed in a partnership between government and industry or industry associations.

As the provider of Fabrication competencies for Australian researchers, ANFF would see its future as including access to facilities that will allow promising scientific and technological research to maximise its impact.

7 September 2016