

# Study of CNBC Performance and Impacts

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## Final Report

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February, 2019



### **Executive Summary**

As its operations wound down in 2018, the Canadian Neutron Beam Centre (CNBC) requested a summary analysis of its performance and impacts. This report provides highlights of the benefits that materials research using neutron beams at the CNBC has offered to this country's academic communities and industries. It also aims to serve as a valuable resource in support of discussions regarding nuclear innovation in the future. The Canadian community of neutron beam users is working to secure access to alternative facilities for the next decade. In parallel, the Government of Canada has signalled a need for national discussions with stakeholders about investments for the longer term.

To capture a record of the facility's legacy, this study set out to document the CNBC's performance and impacts within its research community, for its industry collaborators, for the students whose education included hands-on research at the CNBC, and ultimately for Canada's innovation economy. The indicators included, for example, user demographics, publication and other bibliometric statistics, industry collaborations, and career paths of the highly qualified personnel (HQP) trained at the CNBC.

The major findings of this report are:

#### *The CNBC and Its Place in Canada's Innovation Economy*

- 1) ***The CNBC Was a Specialized and Leading International Facility:*** The CNBC was a key element of Canada's research infrastructure. The CNBC's publication record and scientific impact, as measured by citation rates, are on par with comparable international facilities. The CNBC has been a valued source of collaboration with the U.S.
- 2) ***The CNBC Has Been a Key Element of Canada's Innovation Economy:*** The CNBC's contribution to innovation in Canada is framed by four fundamental observations:
  - a. Manufacturing's high level of Business Enterprise Research and Development (BERD) makes it a key element and indicator of a strongly innovative economy, because manufacturing relies on research;
  - b. Materials research underpins innovation in manufacturing, and the CNBC was an enabler of materials research in Canada;
  - c. Canada's publications in materials research are well regarded and contribute positively to Canada's overall research quality; and
  - d. The quality of research conducted at the CNBC is on par with leading global standards of excellence.
- 3) ***The CNBC Was an Essential Research Tool for Canada's Manufacturing Base:*** The CNBC enabled materials research fields that underpin advances in manufacturing, such as: enhanced steel pipe integrity for the oil and gas industry; better alloys for the automotive and aerospace sectors; and better materials for drug delivery.

### *The CNBC's Contributions to Academic Excellence*

- 4) ***The CNBC Was Canada's Most Valuable Research Asset:*** The CNBC was considered the most impactful research facility in this country by the international scientific community.
- 5) ***The CNBC Was a Nationwide Facility:*** The CNBC drew researchers from across the country, in numbers proportionate to where R&D is conducted in Canada, which made it the most broadly accessible and widely leveraged national user facility for materials research.
- 6) ***The CNBC Was Valued by Canada's Research Chairs:*** A high proportion of Canada Research Chairs made use of the CNBC, underscoring the breadth of the materials research applications of neutron beams and the importance of this facility to Canada's leading researchers.
- 7) ***The CNBC Facilitated Highly Valued Research Outcomes:*** Research outcomes from the CNBC in key areas of materials research, including research that informs energy and biomedical technologies, have had a higher scientific impact than similar research conducted without the CNBC. The CNBC was a positive contributor to Canada's overall record of research quality.

### *The CNBC's Role in University–Industry Collaborations*

- 8) ***The CNBC Attracted Industry-Focused Research and Collaboration:*** Researchers who used the CNBC attracted a high proportion of collaborative industry research dollars from a broad cross-section of Canada's research and development (R&D) investing sectors. The CNBC stood out as a highly industry-centric research institution.

### *The CNBC's Contribution to HQP Development*

- 9) ***The CNBC Was an Engine of HQP Supply:*** The CNBC supported the development of highly qualified personnel deployed in Canada's academic, industrial manufacturing, and scientific R&D sectors. Almost all students who attended the CNBC eventually achieved a Master's or Doctorate degree—a much higher progression rate than is the norm in Canada. The industry-centric approach at the CNBC offered student researchers an environment that was distinctly different from that of universities; this industry focus corresponds to a higher proportion of CNBC student alumni being deployed in industry than in academia, which differs significantly from Canadian trends. CNBC alumni have achieved influential leadership roles in Canada and internationally.
- 10) ***Students Developed Valuable Experience and Skills at the CNBC:*** Student alumni identified how the portable skills they developed at the CNBC impacted their subsequent careers. These skills included:
  - a. A disciplined approach to time pressures, as experiments used very limited resources, i.e., neutron beams;

- b. An appreciation for applied science and industry-oriented research;
- c. An awareness of the value of people who provide coaching and support to students in their development;
- d. An appreciation of the importance of safety and security when conducting research, which is applicable in many other industries, such as pharmaceuticals and oil and gas.

These findings support the overall conclusion that ***the CNBC has had a positive impact on Canadian innovation, research, and industry, as well as on the development of highly qualified personnel in Canada; thus, the CNBC will be sorely missed.*** There is currently no replacement in Canada for the research capabilities that were offered by the CNBC. The findings of this report suggest that many research activities in Canada will cease, and the skills and expertise that have found their way into the Canadian economy from the CNBC may not be available in Canada in the future.

This report presents the detailed findings that underpin these broad conclusions.

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## **1.0 Introduction**

As its operations wound down in 2018, the Canadian Neutron Beam Centre (CNBC) requested a summary analysis of its performance and impacts. This report aims to provide highlights of the benefits that the materials research using neutron beams at the CNBC has offered to this country's academic communities and industries. It also aims to serve as a valuable resource in support of discussions regarding nuclear innovation in the future. The Canadian community of neutron beam users is working to secure access to alternative facilities for the next decade. In parallel, the Government of Canada has signalled a need for national discussions with stakeholders about investments for the longer term.

To capture a record of the facility's legacy, this study set out to document the CNBC's performance and impacts within its research community, for its industry collaborators, for the students whose education included hands-on research at the CNBC, and ultimately for Canada's innovation economy. The indicators included, for example, user demographics, publication and other bibliometric statistics, industry collaborations, and career paths of the highly qualified personnel (HQP) trained at the CNBC.

Canada has invested in the neutron beam laboratory, known today as the CNBC, over the 60-year lifetime of Atomic Energy of Canada Limited's (AECL) National Research Universal (NRU) reactor in Chalk River, Ontario. This investment has produced scientific and technological impacts for an external user community through publications; it has contributed to the education and professional development of HQP; and it has promoted the development of knowledge for industry clients and collaborators. With the NRU reactor's closure in 2018, it is appropriate to not only take stock of these impacts over the CNBC's lifetime, but also to make Canada's return on this investment a matter of public record.

Canadian Nuclear Laboratories (CNL) envisions a future for Chalk River Laboratories (CRL) that, in ten years' time, could include several demonstration Small Modular Reactors (SMRs) and a new materials test reactor. Also, the Canadian nuclear industry has been developing the concept of a nuclear innovation council with representatives from the federal and provincial governments. The Government of Canada has stated that "an innovation council could enable collaboration and promote both power and non-power applications of nuclear expertise and technologies."<sup>1</sup> The Canadian Small Modular Reactor Roadmap Steering Committee, in a recent report entitled "A Canadian Roadmap for Small Modular Reactors," also recommends the creation of a nuclear innovation council.<sup>2</sup>

This report is intended to serve as a valuable reference to support discussions about non-power applications of nuclear technology, including the possibility of adding a neutron beam mission to a future materials test reactor.

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<sup>1</sup> "Government of Canada response to the House of Commons Natural Resources Committee report on the nuclear sector." Oct 5, 2017. p.19. [http://cins.ca/docs/HC\\_FINA\\_report\\_2017\\_12.pdf](http://cins.ca/docs/HC_FINA_report_2017_12.pdf)

<sup>2</sup> "A Call to Action: A Canadian Roadmap for Small Modular Reactors," 2018. The Canadian Small Modular Reactor Roadmap Steering Committee. [https://cna.ca/wp-content/uploads/2018/11/SMRroadmap\\_EN\\_nov6\\_Web.pdf](https://cna.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web.pdf)

### *Other Work Underway*

The CNBC has produced various reports on its activities and performance, typically with an annual focus, for parties such as AECL, CNL, the National Research Council (NRC), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Canadian Institute for Neutron Scattering (CINS). Indications of performance metrics regarding the CNBC's scientific reputation have appeared in assessments by the Council of Canadian Academies (CCA) in 2006 and 2012. Natural Resources Canada (NRCan) commissioned a study by KPMG in 2014 that evaluated Canadian nuclear science and technology (S&T) facilities and their contributions to innovation in Canada, with development of that report led by Strategic Policy Economics. The KPMG report covered the CNBC's performance for the period 2007–2013 in the context of other nuclear-licensed facilities for materials research, such as TRIUMF and the Canadian Light Source (CLS).<sup>3</sup> KPMG's study tracked the broad outcomes achieved by these facilities, including the academic and industry engagement of the CNBC, international experts' opinions of the CNBC, and case studies on industry partnerships with the CNBC.

To fully record its lifetime impacts, the CNBC has recently performed or commissioned other work, including:

- Gathering a record of all publications arising from the CNBC and its predecessor branches of AECL to serve as a reference for researchers and for bibliographic analyses;
- Procuring a bibliometric analysis of the CNBC's identified publications from Science-Metrix to consider a broader timeframe (1980–2018) and to benchmark against other prominent international neutron beam user facilities; and
- Conducting other historical research covering key scientific and programmatic developments.

### *Objectives of This Study*

This study considers a longer time period (1980–2018) than the 2014 KPMG study and reflects more recent information to achieve the following four objectives:

- To extract and repackage CNBC-relevant findings and material from the 2014 KPMG report.** This includes information supporting the correlation between materials research and advanced economies with the purpose of providing a specific focus on the role that the CNBC has played in Canada's innovation economy.
- To review the findings of the Science-Metrix bibliometric study recently commissioned by the CNBC.** The purpose is to summarize and frame the findings of the Science-Metrix study to supplement those in the 2014 KPMG report and to give a greater focus to the contributions of CNBC-specific research.
- To revisit and update the analysis of the funding sources for the neutron beam user community.** Updated user lists are used to identify NSERC funding sources for the period 2001–2018.

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<sup>3</sup> KPMG 2014.

- d) **To analyze the lasting impact on highly qualified personnel trained in research using neutron beams at the CNBC.** The careers of student alumni are outlined from the time of their research engagement at the CNBC through to their careers today. Selected alumni have been interviewed regarding the contributions that their experiences at the CNBC have made to their subsequent careers.

### *Structure of This Report*

The main body of this report is structured into six sections as follows:

#### Section 2.0 – Methodology

This section provides an overview of the methodologies deployed to achieve the four objectives of this report, listed above.

#### Section 3.0 – Overview of the CNBC

This section summarizes the CNBC and its history, the role that the CNBC played within Canada's nuclear S&T infrastructure, and how the CNBC's infrastructure and resources compared to similar international neutron beam user facilities.

#### Section 4.0 – Advanced Economy Innovation, Manufacturing, and Materials Research

This section summarizes the findings of the 2014 KPMG report regarding the relationship between innovative economies, manufacturing, R&D expenditures, and materials research. It opens with a discussion of the key success factors of innovative economies to set the context for the measures of the CNBC's impact. It closes with a discussion of international collaborations in materials research, the relationship between the research conducted at the CNBC and U.S. facilities, and the bibliometric outcomes of international neutron beam user facilities similar to the CNBC.

#### Section 5.0 – Contributions of the CNBC to University Research

This section presents the CNBC's contributions to Canada's academic research infrastructure and outcomes, and specifically to Canada's reputation for high quality research. It compares the CNBC's scientific reputation with other major research facilities in Canada, based on surveys of experts conducted by the Council of Canadian Academies. It examines the proportion of Canada Research Chairs making use of the CNBC as an indicator of the extent to which the facility's resources have supported the research of high-performing university faculty. It assesses how the CNBC was leveraged by academic users distributed across the country, and it uses the Average Relative Citation (ARC) benchmark for bibliometric analyses to assess how these users have achieved impacts with their research. The bibliometric outcomes are contrasted with those of academic researchers in Canada who do not use the CNBC.

#### Section 6.0 – Industry Engagement with the CNBC

This section describes how industry made use of the CNBC directly, through direct commercial engagement, as well as indirectly, by sponsoring collaborative research with

Canada's academic researchers. The outcomes underscore the extent to which industry users from all sectors of Canada's economy engaged with the CNBC.

#### **Section 7.0 – The CNBC's Contribution to HQP Development**

This section looks at student users and how their careers have progressed, from the initial time they spent at the CNBC, to their subsequent educations, to their careers in academia or industry today. Several case studies based on interviews with CNBC student alumni are provided to give additional insight into how the careers of these highly qualified personnel have been impacted by their experiences at the CNBC.

#### **Section 8.0 – Summary and Concluding Remarks**

Finally, the report concludes with a summary and concluding remarks regarding the overall performance and impact of the CNBC.

## **2.0 Methodology**

The methodology employed in this report was distinct for each of the four objectives.

a) **To extract and repackage CNBC-relevant findings and material from the 2014 KPMG report.**

The findings in the KPMG report were reviewed for their relevance to the CNBC, interpreted in light of the original research conducted for the present study, and repackaged generally using the original source data. Data was updated as necessary to complement the objectives of this report.

b) **To review the findings of the Science-Metrix bibliometric study recently commissioned by the CNBC.**

Access to the underlying data produced by Science-Metrix in 2018 was provided by the CNBC. This data reflected bibliometric results for the period 1980–2017. This underlying data was produced based on specific reports that the CNBC provided to Science-Metrix. The detailed results were assessed for implications, and new figures were created to convey additional insights.

Science-Metrix had previously conducted a bibliometric analysis of the CNBC as part of the 2014 KPMG report. The 2014 Science-Metrix bibliometric results were assessed and repackaged here to provide comparisons to the 2018 results. The 2014 Science-Metrix analysis assessed all publications from 2007 to 2013 produced by those researchers who appeared on lists of university faculty researchers associated with the specific nuclear S&T facilities and research areas being studied at that time.<sup>4</sup>

c) **To revisit and update the analysis of the funding sources for the neutron beam user community.**

The CNBC provided an updated list of recent university faculty users as of 2018 to be added to the list of researchers used in the 2014 KPMG report. The 120 researchers were included in the NSERC data analysis of industry collaborations. The NSERC data was accessed to obtain the Canada Research Chair (CRC), Industrial Research Chair (IRC), and Collaborative Research and Development (CRD) grants for these researchers, as well as a total for all researchers who received such grants from NSERC from 2001–2018. Of the 120 researchers, an average of 100 were NSERC-funded each year. (Some retired or left the country, while others were hired during this time). The NSERC database identifies the matching industry partners for collaborative grants. The matching partners were mapped to Canadian industry sectors to illustrate the degree to which various sectors in Canada have engaged in research at the CNBC. Data for the CLS, TRIUMF, and universities was extracted from the 2014 KPMG report for the 2008/09–2012/13 period.

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<sup>4</sup> The 2014 Science-Metrix analysis used the Canadian membership list of CINS as a close proxy for the users who conducted research at the CNBC. The differences between the original KPMG data set and the recently obtained CNBC data set may be material to interpreting the results.

- d) **To analyze the lasting impact on highly qualified personnel trained in research using neutron beams at the CNBC.**

The CNBC provided the names of student users who attended the CNBC as part of their university studies (known henceforth as student alumni) and the time during which they attended the CNBC. From these names, internet research captured publicly available educational and employment history. The detailed histories of student alumni, including information received from the CNBC, have been kept confidential.

The student alumni were classified by highest level of education attained and current employment sector. The educational and employment data sets were analyzed and used to inform the figures and insights in this report. Individual student alumni were selected for interviews based on the timespan of their engagement with the CNBC and the seniority of the employment positions they obtained, with an aim to capture a diverse sample of student alumni from various employment sectors. The objective was to reflect the many different possible career progressions that student alumni embarked on since their time at the CNBC. The CNBC confirmed the willingness of the selected student alumni to be interviewed for this project before these individuals were approached by the project team.

### **3.0 Overview of the CNBC**

The contribution that the CNBC has made to Canada's research capabilities and outcomes is best understood when characterized within the context in which the CNBC fulfilled its role. This section gives a summary of the CNBC, its history, and the role it played within Canada's nuclear S&T infrastructure, as well as how the CNBC's infrastructure and resources compared to those of similar international neutron beam user facilities.

#### **3.1 About the CNBC**

The CNBC enabled academic and industry users to apply uniquely powerful neutron instruments and methods to advance their programs of materials research and innovation. The specialized facilities and expertise of the CNBC supported business innovation and served as a resource for Canadians to train and work at the leading edge of science and technology.

Each year, over 200 scientists, engineers, students, and university faculty from an array of government laboratories, industry sectors, and universities participated in research that depended on access to the CNBC's six neutron beamlines. Over a five-year period, such research participants included more than 700 individuals from over 60 departments in about 30 Canadian universities, and from over 100 foreign institutions in over 20 countries. The CNBC enabled industry research in sectors such as nuclear energy, aerospace, automotive, oil and gas, defence, and primary metal production. Typically, the CNBC provided more than 85% of its neutron beam time to the user community. The CNBC was also Canada's contribution to a global network of about 15 major neutron beam laboratories, thereby leveraging collaborations and facilitating the exchange of people and knowledge.

The CNBC was located at the NRU reactor at AECL's Chalk River Laboratories (CRL). The NRU reactor was a multi-purpose research reactor that supported science and industry in three ways simultaneously:

- It was Canada's only major neutron source, supplying neutrons for the CNBC;
- It was Canada's only major materials testing reactor, supporting nuclear energy R&D; and
- It was an important production facility in the global supply of medical radioisotopes.

##### **3.1.1 History of Neutron Scattering, Materials Research, and the CNBC**

Research using neutron beams grew out of the pioneering efforts of scientists at the National Research Council's Chalk River site to build the National Research Experimental (NRX) reactor, completed in 1947, and to use neutrons from that reactor for research. In 1952, the NRC spun off AECL to promote the peaceful use of nuclear energy and operate CRL.

Don Hurst was the inspiration behind the neutron scattering program, gathering key scientists such as Trudi Goldschmidt, Andy Pressesky, Philip Tunnicliffe, Norman Alcock, and John Spiers. This ground-breaking team developed early neutron beamlines and demonstrated the

enormous potential of neutron diffraction by solving the molecular structure of gases such as carbon dioxide and oxygen, and of liquid deuterated ammonium chloride.

In 1950, Hurst hired Bertram Brockhouse, who took the lead on developing inelastic neutron scattering to study the motions of atoms in solids. The initial demonstration of inelastic neutron scattering using the first triple-axis spectrometer, which Brockhouse invented, was reported in 1955 by Brockhouse and Alec Stewart. In 1958, Brockhouse developed his ‘constant-Q’ method, which greatly simplified inelastic neutron scattering experiments. These were pioneering accomplishments that led to Brockhouse’s Nobel Prize in Physics in 1994, nearly 40 years later. Over that period, his methods had been replicated and further advanced at major neutron sources around the world, enabling many new areas of research in solid state physics. The selection of Brockhouse for the prize reflected the versatility and irreplaceability of neutron beams as scientific tools capable of providing insights about materials that other scientific techniques cannot offer.

The NRU reactor began operating in 1957. Because this reactor was ten times more powerful than the NRX reactor, most of the neutron scattering research taking place at NRX was moved there. In 1960, Neutron Physics became a separate branch of AECL and was headed by Bertram Brockhouse, reflecting the growing importance of neutron beams in physics research. Brockhouse left Chalk River in 1962 to become a professor at McMaster University, and he sent many of his graduate students back to the NRU reactor to do experiments.

The foundation laid by CRL’s early scientists made Chalk River a world leader in using neutron beams to solve research questions about materials—and the next generation of scientists continued building on this legacy. Dave Woods became the leader of the neutron scattering team after Brockhouse left. Then, between 1961 and 1965, a new generation of neutron beam researchers joined AECL. Chief among them were experimentalists Gerald Dolling, Brian Powell, Bill Buyers, Peter Martel, Eric Svensson, and Tom Holden, along with theorist Varley Sears. The scientific contributions of this cohort characterized Chalk River’s highly reputable neutron scattering program well into the 1990s, and users gained access by collaborating with these renowned scientists.

In 1983, Tom Holden worked with Brian Powell and Gerald Dolling to demonstrate stress scanning of intact nuclear power reactor components. The technique was developed into a commercial service—one that was selected over American counterparts to assist in the investigation into the 1986 Space Shuttle Challenger disaster. Neutron diffraction at the CNBC was used to study an as-manufactured section of a booster rocket casing that was identical to the one involved in the disaster. Results showed that the stress distribution in the casing’s material was acceptable, thus redirecting the investigators to look elsewhere. Subsequently, Chalk River became the go-to place for failure analyses for high-profile incidents, such as the problematic Point Lepreau Nuclear Generating Station shutdowns in 1997 and 2001; the Space Shuttle Columbia accident in 2003; and the train derailment that spilled 800,000 litres of oil into Alberta’s Lake Wabamun in 2005. This commercial service ran successfully for over 25 years, providing proprietary data to enhance safety, increase reliability, and optimize manufacturing

processes in numerous sectors (e.g., the aerospace, automotive, rail, and marine transportation industries; metal production; the oil and gas industry; and defence manufacturing).

The construction of two neutron beamlines, which comprised the DUALSPEC facility, marked a turning point for general user access to neutron beams at Chalk River. The \$4 million construction and operations of DUALSPEC were funded jointly by AECL and grants from NSERC. The initial grant in 1985 was awarded to McMaster University, which represented applicants from ten universities to ensure that DUALSPEC would be operated as a national user facility. In 1986, the Canadian Institute for Neutron Scattering was formed to represent users' collective interests in the facility. In 1992, when DUALSPEC opened, the Neutron and Solid State Physics Branch was renamed the Neutron and Condensed Matter Science Branch to better reflect the growing impact of neutron scattering in the fields of materials science, chemistry, and biology in addition to physics. Successful operation of DUALSPEC soon led to the adoption of a national user model for the other four beamlines at Chalk River.

In 1985, Bill Buyers, together with Robin Armstrong of the University of Toronto, performed a key experiment on a crystal of  $\text{CsNiCl}_3$ . Results showed that the crystal could be classified as a totally new type of material distinguished by its topology. In other words, the discovery revealed that the electrons in certain kinds of materials ('topological' materials) can organize collectively to produce properties that, like the number of holes in a donut, can only be identified by examining the object as a whole. Topological materials had been predicted by mathematical theorists, including Duncan Haldane, who hypothesized that an energy gap (i.e., the Haldane gap) would appear in certain types of topological materials if they existed. However, these theorists were not taken seriously until Buyers' experiment overturned the wisdom of the day by confirming the existence of the Haldane gap. Over the next several years, Buyers and others followed up this discovery with more observations of similar behaviours in other materials. The theorists who had initially made the predictions were awarded the Nobel Prize in Physics in 2016, when the magnitude of this discovery's importance was better known. The field of topological materials has dominated frontline research in condensed matter physics for the last 20 years, and scientists now believe that topological materials may hold keys to realizing valuable technologies, such as quantum computing, superconducting computing, and spintronic computing.

In 1997, the neutron beam facility and its scientists were transferred to the National Research Council. This change reflected the fact that the laboratory's scientific user facility mission was better suited to Canada's national science organization than to AECL, which at that time was refocusing its efforts on its CANDU power reactor commercial business. The facility operated under the name Neutron Program for Materials Research until 2005, when it was renamed the Canadian Neutron Beam Centre to better reflect its national mission. Throughout the NRC years, the user community helped attract funds from NSERC and the Canada Foundation for Innovation (CFI) to boost operations, providing excellent support for users and their experiments. The beamline capabilities were enhanced, and a new neutron beamline was built: the D3 reflectometer, completed in 2007. The CNBC reached an operational peak around 2008, with its six beamlines highly subscribed by a community of more than 700 research participants over a

five-year period. These participants included users of all types, from students and post-doctoral researchers to industry and government scientists from across Canada and around the world. Over 50 scientific publications and technical reports were produced each year, and services to industry generated a cumulative \$6 million in fee-for-service revenue from over 200 projects.

Responsibility for funding and operating the CNBC was transferred back to AECL in 2013 and then to AECL's successor, Canadian Nuclear Laboratories, which was created in 2014 to operate all of the facilities at Chalk River Laboratories. In February 2015, the final shutdown date of the NRU reactor was announced. Despite the pending closure, the CNBC team strove to extract as much value and impact from the reactor as possible in its final years of operation. The user community remained strongly engaged, and research participants grew to nearly 800 in number in the final five years. All beamlines were collecting data until the NRU reactor's final shutdown on March 31, 2018.

### **3.1.2 Research Capabilities and Facilities**

Foreign world-leading neutron beam facilities outpaced the CNBC in the late 1990s and 2000s by adding new beamlines and capabilities, which opened up many new possibilities for the application of neutron beams. Yet most of the CNBC's beamlines still performed among the best in the world for 'workhorse' applications until the NRU reactor's final shutdown in 2018. Among these high-performing beamlines were a powder diffractometer, a polarized triple-axis spectrometer, a neutron reflectometer, and a stress mapping diffractometer.

The stress mapping diffractometer enabled a multitude of industry experiments, such as the failure analyses described earlier. The neutron reflectometer (the newest beamline, completed in 2007) was used to study thin films and surfaces, providing insight into corrosion, hydrogen storage materials, and coatings for medical devices. The polarized triple-axis spectrometer was heavily used for the study of quantum materials, including topological materials. The powder diffractometer was frequently used for solving the structures of new and modified materials, many of which have potential for clean energy applications, while others were alloys being examined to determine the impact of industrial processing methods on the alloys' microstructures. These are a few examples from the wide range of materials research enabled by these versatile and irreplaceable tools.

### **3.1.3 Circumstances Leading to the CNBC's Closure**

In late 2007, there was an unplanned and high-profile shutdown of the NRU reactor that lasted for close to a month. Then, a heavy water leak led to another unplanned shutdown of NRU beginning in May 2009 and lasting for 15 months. Both shutdowns resulted in a global shortage of the medical isotope molybdenum-99, which is used in millions of medical diagnostic procedures around the world every year. The repair in 2009 was very challenging, thereby creating uncertainty over whether the reactor would be restarted at all. The repair job was completed in August 2010 at a cost of well over \$100 million. Following the repair, AECL implemented heavy maintenance and upgrades to prevent further disruptions to the supply of

medical isotopes. In February 2015, the Government of Canada announced that it would support an application for license extension only until March 31, 2018, citing heavy financial costs and changes in the medical isotope market that had reduced reliance on the NRU reactor. CNL immediately confirmed that March 31, 2018 would be the NRU reactor's final day of operation. Without the NRU reactor, the CNBC could not continue.

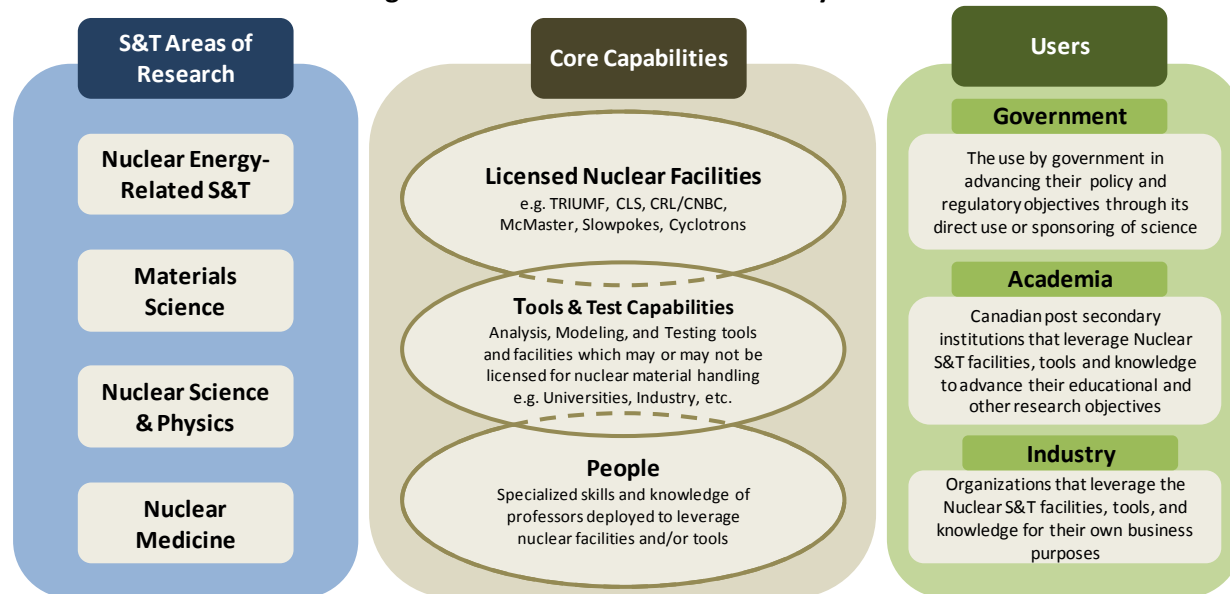
### **3.2 Defining Canada's Nuclear S&T Ecosystem and Associated Facilities**

Canada's nuclear S&T ecosystem can be characterized by its areas of research, its core capabilities, and its users, as shown in Figure 1.<sup>5</sup>

- Nuclear S&T areas of research – Specific areas of research enabled by nuclear S&T research infrastructure;
- Core capabilities – Facilities, capabilities, and expertise used in applying nuclear technologies for research; and
- Users – Those government, academic, and industry researchers who leverage nuclear S&T capabilities.

A key characteristic that sets the Canadian nuclear S&T experience apart from developments in other nations is Canada's commitment to applying nuclear technologies toward peaceful applications. This has enabled Canadian scientists to focus on applications such as energy, materials research, and medicine.

**Figure 1 – Canada's Nuclear S&T Ecosystem**



Sources: SECOR 2011, Strapolec analysis

<sup>5</sup> Definition of Canada's nuclear S&T landscape as developed by SECOR in previous studies for the Canadian Nuclear Association (CNA).

*Four Areas of Nuclear S&T Research* – Four research areas capture the breadth of nuclear S&T applications in Canada:

1. Nuclear Energy – Research used across the full spectrum of the nuclear lifecycle, from the mining of uranium to the treatment and disposal of nuclear waste;
2. Nuclear Medicine – Research used for the diagnosis and treatment of disease;
3. Materials Research – A multidisciplinary research area with broad applications across manufacturing and other industry sectors; and
4. Nuclear Science and Physics – Other research enabled by nuclear facilities, including fundamental studies of atomic nuclei and particles.

Over the last six decades, Canadian scientists have been at the forefront of developments in each of the four nuclear S&T research areas outlined above. Examples of major accomplishments include (1) the fact that Canadian reactor technology was among the first and most innovative to emerge globally, and (2) technologies used to produce molybdenum-99 for use in medical diagnosis were pioneered in Canada.

*Three Core Capabilities* – Nuclear S&T capabilities include all facilities, people, expertise, and analytical tools applied in:

- The conduct of R&D for the nuclear energy or nuclear medicine sectors or for the advancement of nuclear science; or
- The support of R&D or non-R&D activities (for either nuclear or non-nuclear applications) that occur at research facilities licensed by the Canadian Nuclear Safety Commission; or
- The conduct of R&D for non-nuclear applications where that R&D makes use of capabilities at licensed nuclear research facilities.

*Three Types of Users* – Nuclear S&T research facilities are used by government, academia, and industry. This report focuses on how academia and industry benefitted from the CNBC.

### **3.3 Canadian Nuclear S&T Facilities**

The major facilities considered to be part of Canada's nuclear S&T ecosystem are:<sup>6</sup>

1. The Canadian Neutron Beam Centre (CNBC);
2. The Canadian Light Source (CLS);
3. TRIUMF; and
4. Nuclear-related universities; and
5. The AECL-owned facilities at Chalk River Laboratories.

While the CNBC was Canada's primary facility for materials research using neutron beams, the CLS and TRIUMF are also major national user facilities offering access to versatile capabilities for materials research. More specifically, the CLS offers x-rays, and TRIUMF offers muon

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<sup>6</sup> Based on KPMG, 2014 ("Nuclear S&T Clusters"), modified for the purposes of this report. For this report, the AECL cluster based at Chalk River Laboratories was split to enable a focus on the CNBC.

beams. Nuclear-related universities are those post-secondary institutions with smaller licensed nuclear facilities or with university faculty who specifically conduct research in support of the nuclear energy sector. Because university faculty users of AECL's facilities at CRL are primarily focused on nuclear energy research, there is significant overlap between the user communities of CRL and the nuclear-related universities. Thus, for the rest of this report these research communities are treated as one community, designated "nuclear energy researchers," which is distinct from the communities of university faculty users of the CNBC, TRIUMF, and the CLS.

Each facility has unique capabilities and expertise that together represent a complementary set of research tools that Canadian academics, scientists, and industry can access. TRIUMF mainly acts as a centre for nuclear medicine and physics research. Although the applications of the CLS and the CNBC are broad, CLS users tend to focus on applied research for the agriculture and mining industries, while CNBC users focused more on the materials testing of industrial components and primary metals. Having access to all of these facilities enhances the depth and breadth of the research that can be conducted by Canada's researchers.

### **3.3.1 Canadian Academic Users of Nuclear S&T Facilities**

Canada's nuclear S&T facilities each have their own distinct ecosystem of academic users across the country.<sup>7</sup> Figure 2 identifies the mix of research focus areas for university faculty researchers conducting research at each facility based on their classification into the four areas of nuclear S&T research discussed earlier.<sup>8</sup>

The distribution of academic users by focus area across facilities shows that each facility attracts a distinctly different mix of researchers.<sup>9</sup> Users associated with TRIUMF are primarily involved in nuclear medicine-related research, followed by physics and materials research. At the CLS and the CNBC, users are mostly in the materials research-related field. The CLS has a cadre of users conducting research in nuclear medicine. The CNBC has a group of users focused on physics research, as does TRIUMF.

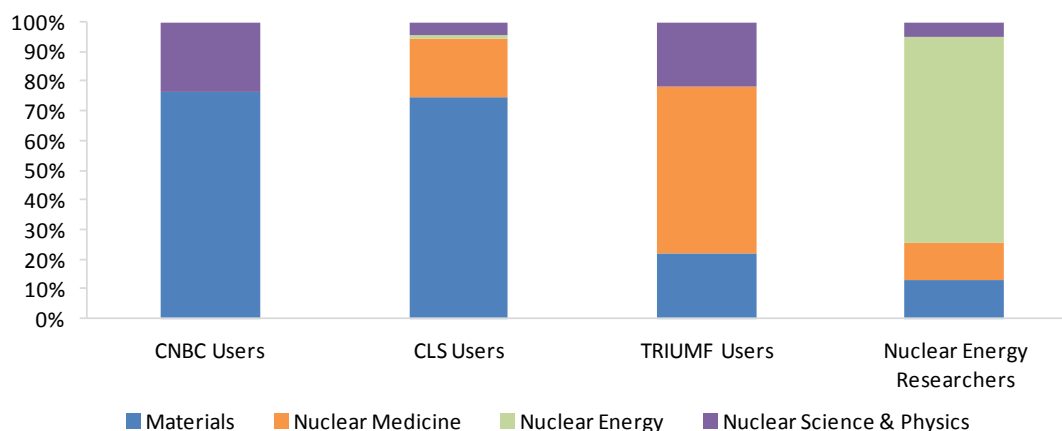
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<sup>7</sup> The 2014 KPMG report identified individual Canadian academic users whose research activities were enabled by the capabilities of nuclear S&T facilities. For this study, the CNBC provided an updated list of recent users to complement the list of CINS members used in the KPMG report, which represented users from earlier timeframes.

<sup>8</sup> Data from the 2014 KPMG report was used for the TRIUMF, CLS, and aggregated nuclear-related university statistics. New CNBC data was compiled from CNBC-provided user lists.

<sup>9</sup> For consistency, only Canadian university faculty researchers are included in this analysis. Data does not include staff researchers at TRIUMF, the CLS, the CNBC, or CRL. This aligns the bibliometric analysis conducted with the analysis of NSERC-funded research.

**Figure 2 – Distribution of Nuclear S&T Researchers by Area of S&T Research and Facility**  
(% of University Faculty Researchers)



Source: KPMG 2014, Strapolec analysis

### 3.3.2 A Closer Look at Materials Research in Canada's Nuclear S&T Facilities

Materials research is defined broadly in this report and includes research activities carried out on a wide range of materials and substances that are deployed in manufactured products across all industry sectors in Canada. While all of Canada's nuclear S&T user facilities are involved in materials research, they each have distinct research applications within that broad field. The diversity of research being carried out using these facilities ranges widely, from experiments on complex superconducting materials that have the potential to improve how energy is stored and transmitted, to research on novel ways to diagnose and treat diseases. Each facility's materials research capabilities are described below, along with sample projects funded by NSERC.

**The CNBC** – Materials research at the CNBC was largely focused on the analysis and testing of industrial materials (e.g., materials that have applications in oil and gas, manufacturing, aerospace, power generation, etc.), in addition to quantum materials. Examples of research topics with industrial application that were carried out by users of the CNBC included:

- Induction hardening of bevel gears for aerospace applications;
- The integrity of steel pipes with dents or surface defects for oil and gas transportation and for nuclear power plants;
- New materials for improving the energy-efficiency of wind turbines and electric car engines;
- The development of automotive and aerospace alloys based on lightweight metals; and
- Materials for improving drug delivery and medical diagnostic devices.

**TRIUMF** – The facilities at TRIUMF enable materials research on complex materials and condensed matter. Materials research projects carried out at TRIUMF include the design and study of novel quantum materials, as well as applications for nuclear probe techniques in materials research.

**The CLS** – A large portion of the materials research carried out at the CLS focuses on agriculture, veterinary science, mining, and geology. Examples of materials research carried out by researchers at the CLS include: studies on the molecular structure and bioavailability of soil; experiments regarding the eradication of plum pox virus from Canadian orchards using molecular approaches; seismic imaging of deep-seated structures; and the development of an autonomous robotic manipulator for mining applications.

These facilities each cater to different areas of scientific research. An interview with Canada Research Chair in Complex Materials, Professor Young-June Kim, sheds additional light on this distinction, as shown in Box 1.<sup>10</sup>

#### **Box 1 – Canada’s Toolbox of Materials Research Capabilities**

“The x-rays at CLS are complementary to CNBC. X-rays cannot say much about magnetism. The muon facility at TRIUMF is very much a magnetic probe but doesn’t tell much about structure. The three facilities [TRIUMF, the CLS, and the CNBC] in combination are highly complementary and have the potential to reveal information about collective properties and behaviour of complex materials.”

– Interview with Professor Young-June Kim, Canada Research Chair in Complex Materials

The CNBC’s distinctive role among Canada’s nuclear S&T facilities was the advancement of materials research to support manufacturing technologies across a broad spectrum of industry sectors in Canada.

### **3.3.3 Research Specializations of Canada’s Nuclear S&T Facilities**

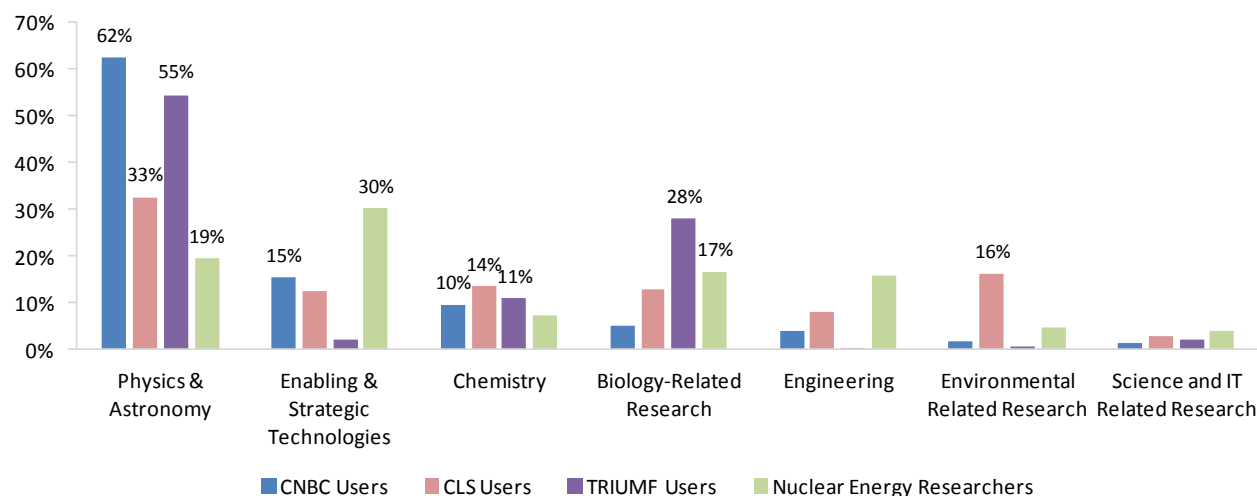
Users of the CNBC, the CLS, or TRIUMF, and nuclear energy researchers each address distinct research areas.<sup>11</sup> Figure 3 shows, by research field, the percentage of total published papers associated with the various nuclear S&T facilities. The percentage of papers that each facility contributes to the various fields indicates how the facilities differ in their specializations. The results depict complementary research efforts at these facilities, which, in aggregate, reflects a mosaic of research capabilities within Canada’s nuclear S&T research community.

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<sup>10</sup> From the 2014 KPMG report.

<sup>11</sup> CNBC data is for all papers arising from the CNBC during the period of 1980–2017. The remaining data is for all papers associated with a list of 428 users during the period of 2007–2013, as defined in the KPMG report.

**Figure 3 – Distribution of Publications Associated with Canadian Nuclear S&T Facilities**  
(% of Papers Published in Various Fields)<sup>12</sup>



Source: KPMG 2014, Science-Metrix 2018, Strapolec Analysis

Most (87%) publications arising from the CNBC are in the fields of Physics and Astronomy, Enabling and Strategic Technologies, and Chemistry. The largest research area for publications from the CNBC is Physics and Astronomy, with 62% of all publications. Enabling and Strategic Technologies and Chemistry account for 15% and 10% of publications, respectively.

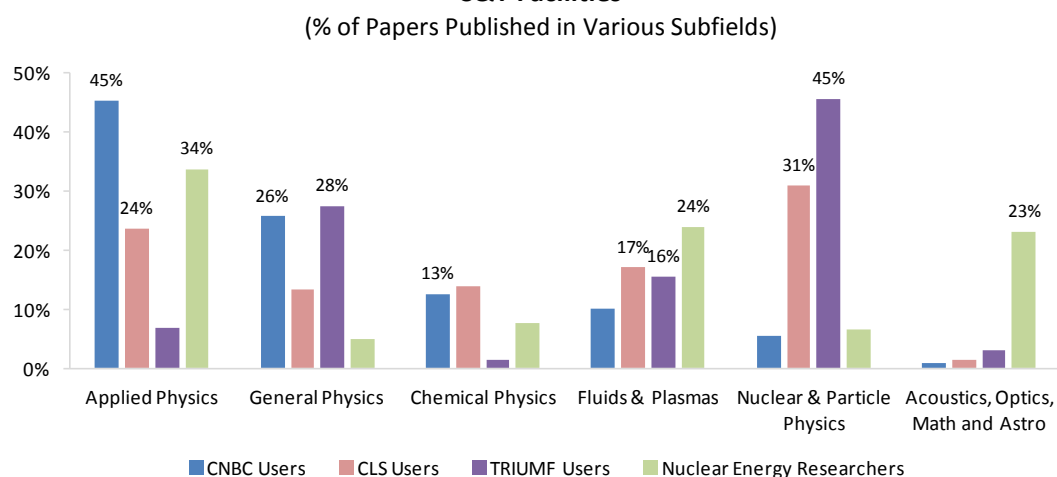
Publications in Physics and Astronomy also make up the largest proportion of papers arising from TRIUMF and the CLS. TRIUMF has the largest proportion of Biology-related research publications (mostly related to nuclear medicine) of all the facilities. The CLS is the only facility that has a sizeable proportion of papers in Environmental-related research. Nuclear energy researchers mostly focus on Enabling and Strategic Technologies, but also contribute to Physics and Astronomy and Biology-related research (mostly related to nuclear medicine).

The data for the top three research fields in publications arising from the CNBC suggests some commonality between the CNBC and the other nuclear S&T facilities. For example, Physics and Astronomy is an important field for all facilities. However, each of these research fields is made up of a number of subfields that provide insight into additional areas of specialization. Figures 4 to 6 show the distribution of papers arising from each facility for subfields associated with the top three CNBC research fields.

<sup>12</sup> Several research fields were grouped into related categories and consist of the following fields:

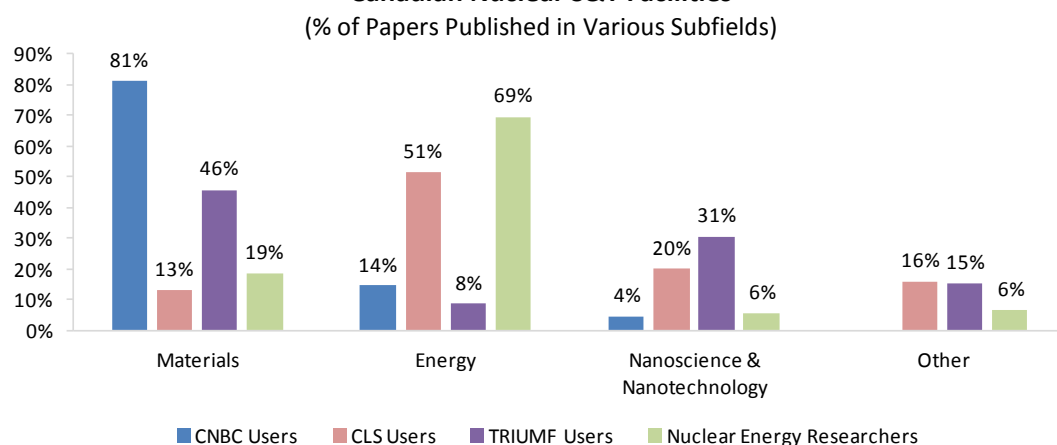
- Environmental-related research: Agriculture, Fisheries and Forestry, Earth and Environmental Sciences;
- Biology-related research: Biology, Biomedical research, Clinical Medicine;
- Science and IT-related research: Built Environment and Design, general Science and Technology, Information and Communication Technologies, Mathematics and Statistics; and
- Other: Economics and Business, Historical Studies, Philosophy and Theology, Psychology and Cognitive Sciences, Public Health and Health Services, Social Sciences. (The 'Other' category makes up only ~1% of all papers arising from all facilities; as such, it is therefore excluded from the analysis.)

**Figure 4 – Distribution of Publications in Physics and Astronomy by Subfield Across Canadian Nuclear S&T Facilities**



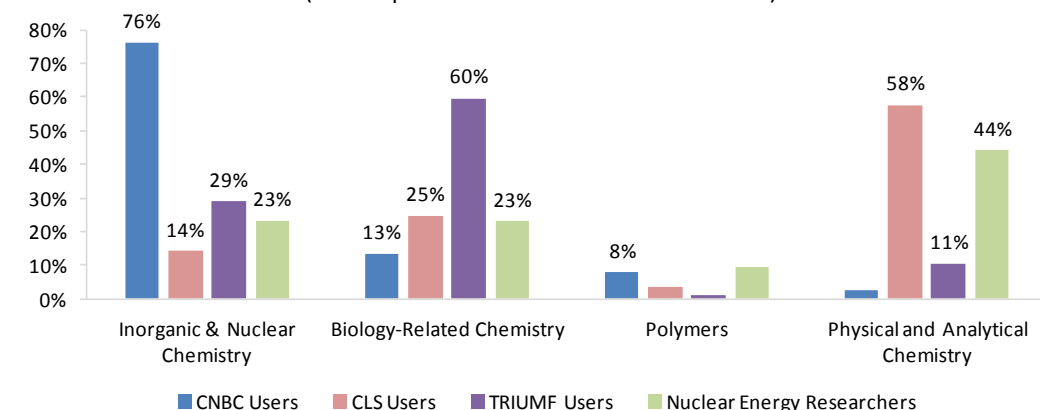
Source: KPMG 2014, Science-Metrix 2018, Strapolec Analysis

**Figure 5 – Distribution of Publications in Enabling and Strategic Technologies by Subfield Across Canadian Nuclear S&T Facilities**



Source: KPMG 2014, Science-Metrix 2018, Strapolec Analysis

**Figure 6 – Distribution of Publications in Chemistry by Subfield Across Canadian Nuclear S&T Facilities**



Source: KPMG 2014, Science-Metrix 2018, Strapolec Analysis

In the Physics and Astronomy field, the greatest proportion of publications arising from the CNBC is in the Applied Physics subfield, as Figure 4 shows; in fact, no other facility has such a focus on Applied Physics research. Papers associated with TRIUMF are primarily in the subfield of Nuclear and Particle Physics, and TRIUMF has the greatest proportion of publications in this subfield as compared to the other facilities. The second largest subfield for papers arising from the CNBC is General Physics, which is also TRIUMF's second largest subfield. Papers stemming from research at the CLS are across all subfields more broadly. Applied Physics is also the top subfield for papers arising from nuclear energy researchers, but a substantial number of papers from these universities are also in the subfields of Fluids and Plasma as well as Acoustics, Optics, Mathematical Physics, and Astronomy and Astrophysics.<sup>13</sup>

As shown in Figure 5, within the Enabling and Strategic Technologies field, most papers arising from the CNBC and TRIUMF are in the Materials subfield. Most publications arising from the CLS and nuclear energy researchers focus on the Energy subfield. The second largest subfield of papers arising from nuclear energy researchers is Materials. Both the CLS and TRIUMF are associated with a moderate number of publications in the Other<sup>14</sup> category of subfields, with 16% and 15% of publications, respectively.

The fact that most publications arising from the CNBC in the Enabling and Strategic Technologies field are focused on the Materials subfield reflects the CNBC's capabilities as a materials testing facility. TRIUMF can also be considered a materials testing facility, though to a lesser extent than the CNBC. In contrast, a relatively large proportion of papers arising from TRIUMF are in the Nanoscience and Nanotechnology subfield, as Figure 5 shows.

Figure 6 presents the publication distributions within the field of Chemistry. Most of the publications arising from research at the CNBC are in Inorganic and Nuclear Chemistry. In contrast, the majority of publications arising from research at TRIUMF are in Biology-related Chemistry.<sup>15</sup> Papers stemming from research at the CLS and nuclear energy researchers are most frequently in Physical and Analytical Chemistry.

The data from publications across all of these subfields shows that each nuclear S&T facility in Canada specializes in distinct areas of research.

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<sup>13</sup> "Acoustics, Optics, Math, and Astro" in Figure 4 corresponds to multiple areas of research that were combined into a single category: Acoustics, Optics, Mathematical Physics, and Astronomy and Astrophysics.

<sup>14</sup> The 'Other' research subfield category includes the following subfields: Strategic, Defence and Security Studies, Biotechnology, Optoelectronics and Photonics, and Bioinformatics.

<sup>15</sup> Research subfield categories consist of the following research areas:

- Physical and Analytical Chemistry: Physical Chemistry, Analytical Chemistry.
- Biological-related Chemistry: General Chemistry, Organic Chemistry, Medicinal and Biomolecular Chemistry.

### 3.4 Canada's Materials Research Facilities in a Global Context

Many advanced economies have access to materials research facilities, some of which provide services similar to those offered by the CNBC. This section identifies comparable international neutron beam user facilities and summarizes how the CNBC's research productivity compared to that of its international peer facilities.

#### 3.4.1 International Research Reactors

Most advanced nations have a major neutron source, as summarized in Figure 7.<sup>16</sup> Neutron sources can be used for multiple purposes. While in operation, Canada's NRU reactor was one of the most powerful neutron sources in the world, supporting medical isotope production, materials research using neutron beams (identified as "neutron scattering" in the figure), and nuclear R&D. The majority of the world's neutron sources do not support all three of these functions.

**Figure 7 – Comparison of Major Neutron Sources Around the World**

			Used For:		
Facility Name	Country	Start Date	Isotope Production	Neutron Scattering	Nuclear R&D
Research Reactors					
NRU	Canada	1957	x	x	x
NBSR	USA	1967		x	
ATR	USA	1967	x		x
SAFARI-1	South Africa	1965	x	x	
OPAL	Australia	2006	x	x	
ILL	France	1971		x	
HFR	Netherlands	1961	x		x
FRM-II	Germany	2004	x	x	
JRR-3M	Japan	1990	x	x	
HBWR	Norway	1959			x
HANARO	Korea	1995	x	x	x
Spallation Sources					
ISIS	UK	2007		x	
SNS	USA	2007		x	

Source: KPMG 2014, Strapolec analysis

<sup>16</sup> Other neutron sources comparable to the NRU reactor include: the National Bureau of Standards Reactor (NBSR), U.S.; the Advanced Test Reactor (ATR), U.S.; the South African Fundamental Atomic Research Installation 1 (SAFARI-1), South Africa; the Open Pool Australian Lightwater (OPAL) reactor, Australia; Institut Laue-Langevin (ILL), France; the High Flux Reactor (HFR), Netherlands; Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM-II), Germany; Japan Research Reactor No. 3 Modified (JRR-3M), Japan; the Halden Boiling Water Reactor (HBWR), Norway; the High-Flux Advanced Neutron Application Reactor (HANARO), South Korea; the ISIS Neutron and Muon Source at Science and Technology Facilities Council (ISIS), UK; and the Spallation Neutron Source (SNS), U.S.

### **3.4.2 Assessing International Comparators for Neutron Beam User Facilities**

The CNBC commissioned Science-Metrix to compare the bibliometric performance of the following five international neutron beam user facilities with that of the CNBC:

- Institut Laue-Langevin (ILL), France;
- Laboratoire Léon Brillouin (LLB), France;
- Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR), U.S.;
- Los Alamos Neutron Science Center (LANSCE), U.S.; and
- The National Institute for Standards and Technology (NIST) Center for Neutron Research (NCNR), U.S.

The facilities, instruments, and experimental practices of these neutron beam user facilities are similar to those of the CNBC.

Publication outputs and portfolios vary considerably between the international user facilities examined.<sup>17</sup> The CNBC is a smaller facility than the international ones listed above. In 2016, it had 6 neutron beam instruments and 121 users. Of the comparators, the next smallest in size is LANSCE, with 7 neutron beam instruments and 249 users in that same year. In terms of publication output, 743 papers arose from the CNBC and 1,516 arose from LANSCE from 2000–2017.<sup>18</sup> In contrast, the ILL was the most active of the facilities, with its 55 neutron beam instruments and 831 users in 2016, and 7,802 papers from 2000–2017.

To account for differences in size, and for the large variation in performance that could occur because of this, each user facility's publication output was analyzed and compared on a per-user and per-instrument basis. Figure 8 shows the number of users per instrument at each facility, and the number of papers produced per user over the 2009–2013 timeframe.<sup>19</sup> It can be seen that fewer users per instrument generally correlates with a higher number of papers per user, with the facility with the lowest number of users per instrument—ILL—showing the highest number of papers per user. The two facilities with the highest number of users per instrument, HFIR and NCNR, show the fewest papers per user. The CNBC had the second lowest number of users per instrument and the third highest number of papers per user.

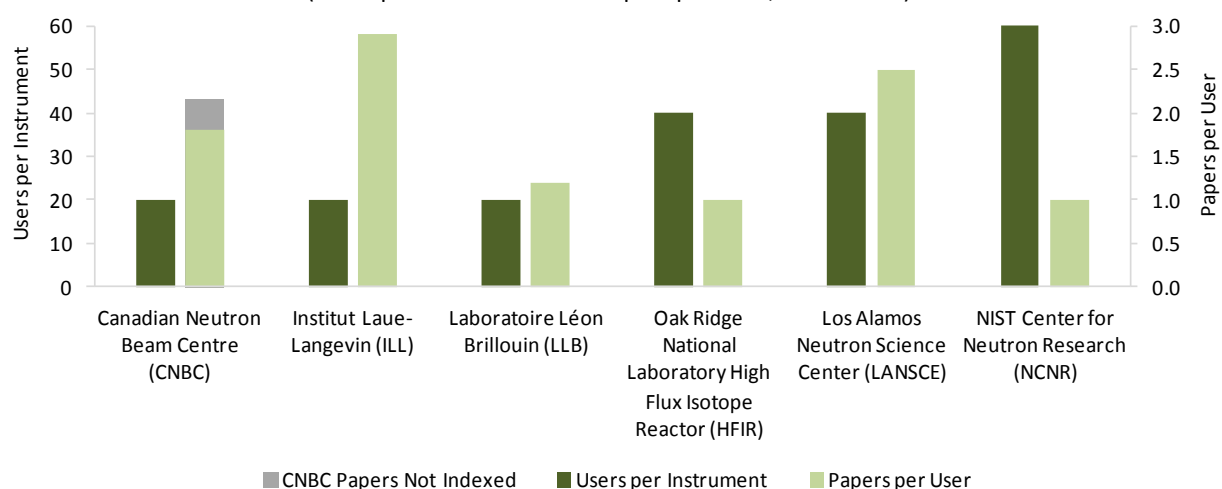
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<sup>17</sup> Science-Metrix 2018.

<sup>18</sup> The CNBC publication list contained approximately 1,600 papers for the period 1980–2017, 292 of which were not indexed by the Web of Science (WoS) database (produced by Clarivate Analytics). Many of these were published in Engineering conference proceedings, but the list also included journal articles and book chapters. The CNBC itself considers that it has had a stronger focus on Engineering than its comparators, and that a greater proportion of its publication output would be made up of Engineering conference papers as compared to the other user facilities included in this comparison.

<sup>19</sup> The period 2009–2013 was used by Science-Metrix as a period of relative stability in the instrument portfolios of the selected neutron beam user facilities in order to compare publication output on a per-instrument basis.

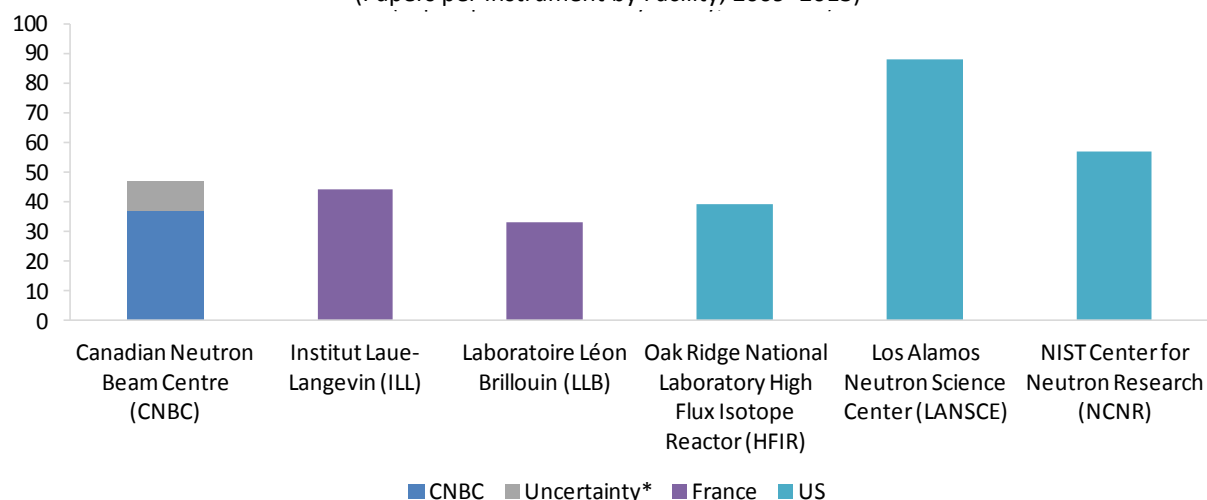
**Figure 8 – Instrument Use and Publication Output of the CNBC vs. International User Facilities**  
(Users per Instrument and Papers per User, 2009–2013)



Source: Science-Metrix 2018, Strapolec Analysis

Figure 9 shows the number of papers per instrument arising from each facility during the period 2009–2013. Looking at publication output through this lens lowers the variations caused by facility size. Provided that beam time is fully utilized at each facility, papers per instrument is a more useful metric for comparing productivity. Even despite the unindexed papers and the effect of the NRU reactor’s shutdown in 2009–2010, the CNBC’s output is similar to that of the much larger French facilities (ILL and LLB) and HFIR in the U.S.

**Figure 9 – Publication Output per Instrument at the CNBC vs. International User Facilities**  
(Papers per Instrument by Facility, 2009–2013)



\*Uncertainty reflects the unindexed CNBC papers and the reduced beam time available at the CNBC due to the NRU reactor’s shutdown in 2009–2010.

Source: Science-Metrix 2018, Strapolec analysis

**3.5 Summary Implications of the CNBC's Role in Canada's Nuclear S&T Ecosystem**

The CNBC provided a unique research capability that complemented and fulfilled the mosaic of capabilities in Canada's nuclear S&T ecosystem. The CNBC's publication record shows that its use by researchers was comparable to usage at larger international neutron beam user facilities.

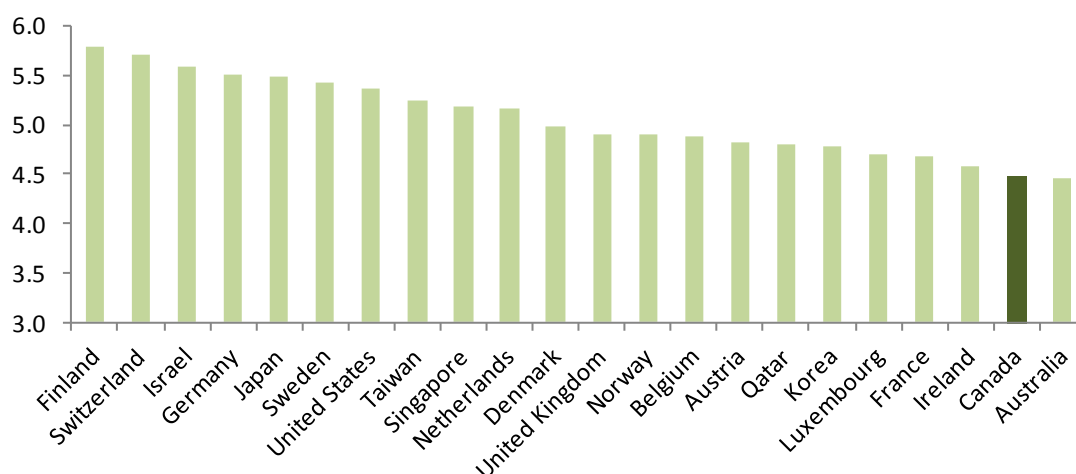
#### **4.0 Advanced Economy Innovation, Manufacturing, and Materials Research**

As part of its Global Competitiveness Index, the World Economic Forum (WEF) developed the Innovation Index to capture the main contributors to an internationally competitive economy. This section first summarizes the findings of the 2014 KPMG report regarding the relationships between innovative economies, R&D expenditures, the manufacturing sector, and materials research. It then explains how it is through these relationships that the materials research enabled by the CNBC supported a foundation for Canada’s success as an innovative economy on the global stage.

##### *Canada as an Innovative Economy*

Canada ranked 21<sup>st</sup> on the WEF Innovation Index in 2013 as shown in Figure 10.<sup>20</sup> In its 2013–2014 “Global Competitiveness Report,” the WEF classifies Canada as an innovation-driven economy on the basis that Canada “benefits from highly efficient markets, well-functioning and transparent institutions, and excellent infrastructure” while “successfully nurturing its human resources.”

**Figure 10 – WEF Innovation Index Score by Country, 2013**



Source: WEF 2013, KPMG 2014

##### *Measures of Contribution to Innovation*

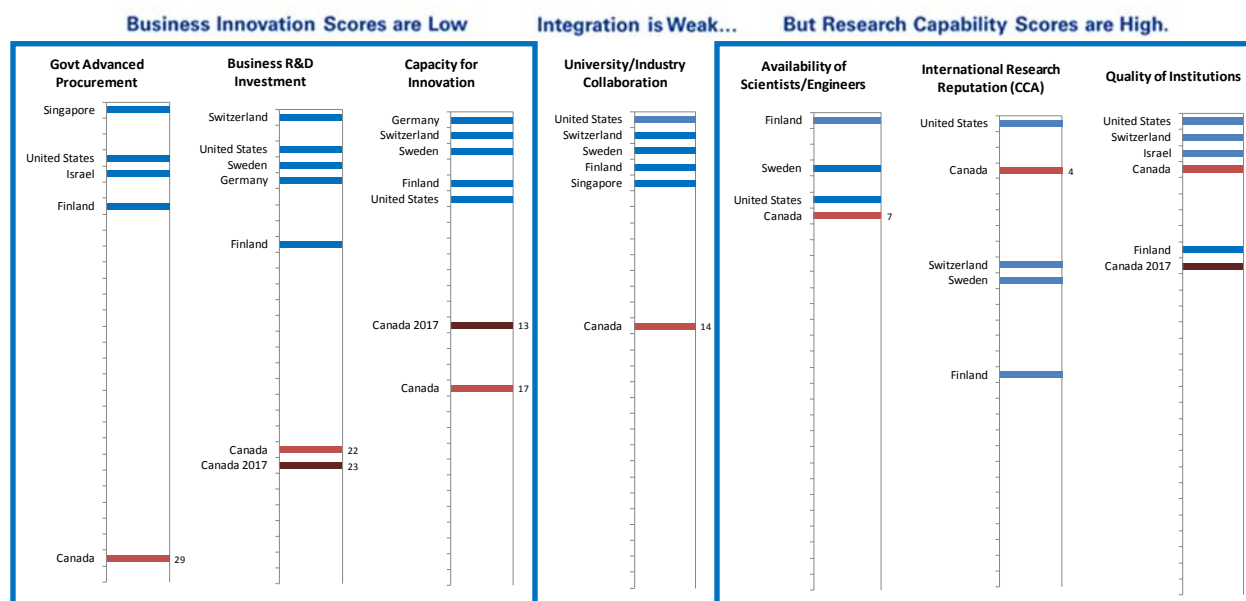
There are three main aspects of an economy that contribute to its innovation capacity: (i) business propensity for innovation; (ii) scientific research capability; and (iii) the extent to which the first two aspects are integrated.<sup>21</sup> Figure 11 depicts how a number of countries rank in regards to these three parameters according to surveys conducted by the WEF and the Council of Canadian Academies (CCA). These surveys found that, while Canada’s business innovation scores are low and integration with Canada’s research capability is weak, Canada’s research

<sup>20</sup> WEF “The Global Competitiveness Report” 2013–2014.

<sup>21</sup> CCA 2012, WEF 2013.

capability scores are high. According to the CCA, Canada has “much to celebrate in terms of our knowledge and talent base.”<sup>22</sup>

**Figure 11 – Research Capability, Integration, and Business Innovation Scores from the CCA and WEF**



Source: KPMG 2014, WEF 2017, Strapolec Analysis

Since the KPMG report was published in 2014, Canada’s innovation ranking has moved up to thirteenth place, according to the WEF’s 2017 “Global Competitiveness Report.” However, Canada’s ranking decreased in terms of quality of institutions, business R&D expenditures, and multi-stakeholder collaboration (not shown). However, Canada improved on its capacity for innovation and benefitted from new comparators recently added, including a diversity index.

### *Quantifying the CNBC’s Contribution to Canada’s Innovation Capacity*

To flesh out the parameters in Figure 11, Section 5.0 of this report examines how the CNBC has contributed to the quality of Canada’s research institutions; Section 6.0 explores the extent to which the CNBC has contributed to university–industry collaboration; and Section 7.0 looks at the contributions the CNBC has made to the availability of scientists and engineers.

But first, Section 4.1 examines the Canadian context for business R&D investment and how such investment relates to manufacturing in the world’s advanced economies. Section 4.2 looks at Canada’s international research reputation, especially in terms of how the materials research conducted at the CNBC has contributed to this reputation and how those materials research areas relate to leading manufacturing economies. Section 4.3 looks at the CNBC’s international collaborations, the relationship between the Canadian and U.S. materials research agendas, and the bibliometric performance of the CNBC as compared to its international peer facilities.

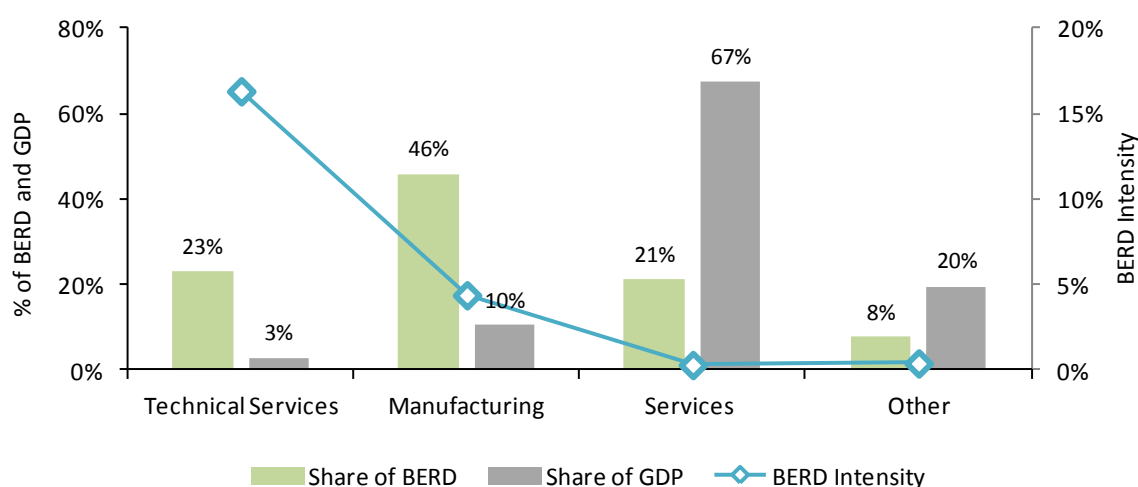
<sup>22</sup> CCA 2012.

#### 4.1 Business R&D and Manufacturing in Innovative Economies

The WEF Innovation Index described above identifies that business R&D investment is a key contributor to an innovative economy. Business Enterprise Research and Development (BERD) spending is the measure of business sector R&D activities that is used to inform the Innovation Index. BERD also provides funding for industry–university collaborations, a subject explored in Section 6.0.

The rest of this section shows that R&D investment occurs primarily in manufacturing in Canada. It then describes how Canada’s BERD and manufacturing sector compare on an international stage. Figure 12 shows the BERD-related statistics for Canada divided into four economic sectors.

**Figure 12 – Share of BERD, Share of GDP, and BERD Intensity in the Canadian Economy, 2013**



Source: Statistics Canada Table 27-10-0002-01 and Table 27-10-0273-01, Strapolec analysis

Though only 13% of Canada’s Gross Domestic Product (GDP) is in manufacturing and Technical Services,<sup>23</sup> almost 70% of BERD occurs in these two sectors. Canada’s BERD intensity<sup>24</sup> shows that these two sectors attract most of Canada’s BERD, and their contribution to GDP is heavily dependent on R&D spending.

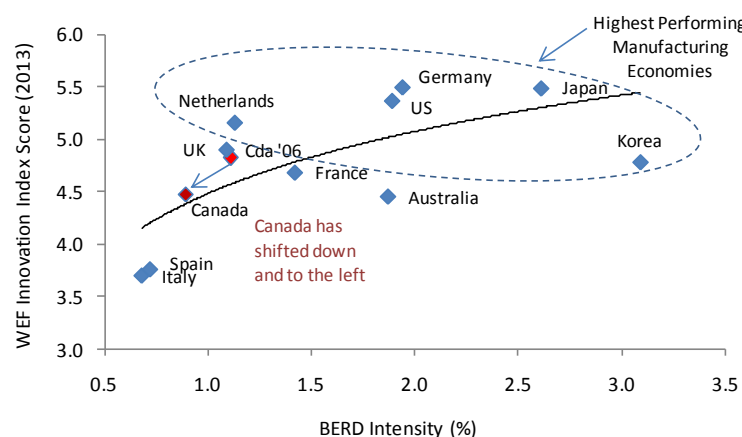
The 2014 KPMG report identified a peer group of nations and compared Canada’s innovation measures to those of the countries in this group. Figure 13 shows the correlation between the BERD and Innovation Index scores for the peer comparator nations. Generally, higher BERD leads to higher Innovation Index scores. Canada’s BERD and innovation scores are both much lower than the scores for most nations in its peer group. Furthermore, Canada’s placement in

<sup>23</sup> Technical Services is defined for the purposes of this report as a grouping of three industries in the North American Industry Classification System: Architectural, engineering and related services (NAICS 5413), Management, scientific and technical consulting services (NAICS 5416), and Scientific research and development services (NAICS 5417).

<sup>24</sup> BERD intensity for a sector is calculated by dividing that sector’s BERD by that sector’s GDP. This measure indicates the degree to which R&D constitutes part of that sector’s GDP.

2011 is noticeably lower than it was in 2006, highlighting the 8% degradation in Canada's innovation score as its BERD declined over this five-year period.

**Figure 13 – Innovation and BERD Intensity Among Canada's Peer Nations**  
(2013 WEF Innovation Index Score vs. 2011 BERD Intensity as per the OECD's 2013 Scoreboard)

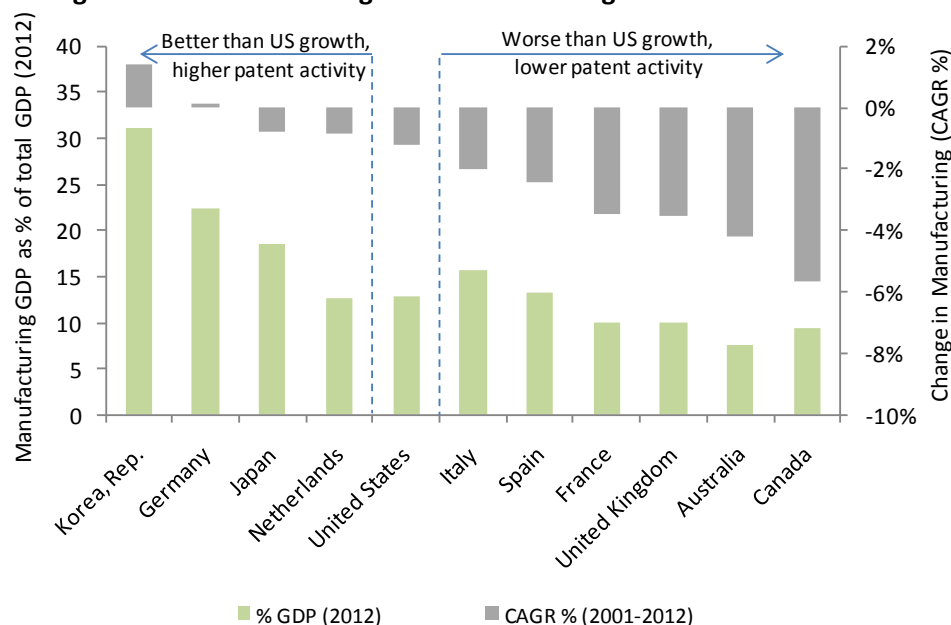


Source: WEF 2013, KPMG 2014, Strapolec analysis

Figure 13 also highlights that high WEF Innovation Index scores correlate strongly with economies that have strong manufacturing sectors (i.e., the Netherlands, the U.S., Germany, Japan, and the Republic of Korea – also known as South Korea).

Figure 14 ranks each of Canada's peer nations according to its manufacturing sector's Compound Annual Growth Rate (CAGR) between 2001 and 2012. South Korea, Germany, and Japan enjoyed both the highest growth and the highest proportion of manufacturing in their economies. These three countries also had the highest BERD intensity in 2011, which correlates with the top performance of their manufacturing sectors. In contrast, the Netherlands—a country that also has a significant manufacturing sector—had achieved a higher Innovation Index score than France and Australia, despite having lower BERD intensity than France and Australia.

Figure 14 – Manufacturing GDP Trends Among Canada's Peer Nations



Source: OECD 2013, KPMG 2014, Strapolec analysis

France, the U.K., Australia, and Canada saw significant degradation in their manufacturing sectors from 2001 to 2012. The erosion of Canada's manufacturing sector since 2001 cut Canada's manufacturing in half, from almost 18% of GDP in 2001 to 9% in 2012; this accompanied declines in both Canada's BERD intensity and its Innovation Index Score, as shown in Figure 13. South Korea is distinguished as the only economy in the peer group that has seen its manufacturing sector grow significantly.

Two contributing factors of manufacturing success that relate to BERD are (i) the quality of the research performed, and (ii) the commercialization of that research. Section 4.2 examines Canada's research record in manufacturing-related materials research fields. Commercialization effectiveness is measured by patents.

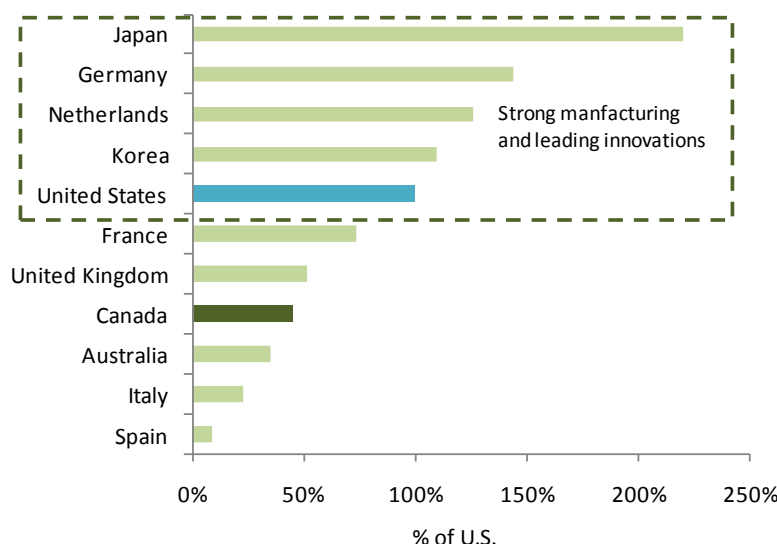
### Patents

Patenting is discussed in this report primarily to acknowledge the important role that it plays in advancing innovation in an economy. BERD is not the only driver of success. Figure 15 shows the ranking of triadic patents<sup>25</sup> per capita for Canada and its peer nations, normalized as a percentage of the U.S.'s triadic patent activity. The CCA has identified a relationship between BERD and patent activity:<sup>26</sup> countries with low BERD, like Canada, have low patent activity.

<sup>25</sup> Triadic Patent Families are defined as a set of patents registered to protect the same invention at the following three patent offices: the European Patent Office (EPO), the Japan Patent Office, and the U.S. Patent and Trademark Office. Patent counts are based on the earliest priority date, the inventor's country of residence, and use fractional counts. Data mainly derive from the EPO Worldwide Statistical Patent Database (October 2007). Figures from 1999 onwards are estimates.

<sup>26</sup> CCA 2012.

**Figure 15 – Patent Activity Among Canada’s Peer Nations**  
(Per Capita Triadic Patents as Normalized to U.S., 2005)



Source: OECD 2008, Strapolec analysis

Further, BERD and patent activity are correlated strongly with manufacturing. Comparing Figure 15 to Figure 14 shows that countries with higher patent activity typically have large manufacturing sectors and have seen less degradation in their manufacturing sectors as a share of their economies. In strong patent environments, intellectual property (IP) is kept out of the public domain to protect the IP until it can be commercialized, typically by the manufacturing sector. Weaker patenting environments are less effective at retaining IP for the purposes of sustaining competitive advantage.

The weak patenting environment in Canada (i.e., only about half as many triadic patents per capita as the U.S.) may contribute to Canada’s low score on industry–university research collaboration, shown in Figure 11. The contribution that the CNBC made to industry–university collaborations is described in Section 6.0.

### Summary

The analysis in this section identified the following insights:

- Canada’s BERD is primarily in the manufacturing sector;
- Canada’s decline in BERD has coincided with its decline in manufacturing and its weakening Innovation Index score;
- Canada ranks low on BERD and patenting activity when compared to high-performing manufacturing nations such as South Korea, Germany, and Japan; and
- Manufacturing is an important component of an innovative economy, and it relies on research.

## **4.2 Canada's Research Capability and Materials Research at the CNBC**

International research reputation is an important indicator of research capability and is a factor in the WEF Innovation Index, as shown in Figure 11. This section looks at Canada's international research reputation and how the fields of materials research that were pursued at the CNBC impact Canada's overall reputation. It also examines how materials research capability correlates with manufacturing activity in Canada and its peer nations.

The CCA has reported that Canada's research contributions have been well regarded within the international community.<sup>27</sup> The CCA's assessment was based on two methods:

- (1) A survey of national and international experts, wherein each expert was asked to identify the top five leading countries in his or her field of expertise; and
- (2) A bibliometric analysis conducted by Science-Metrix. While the scholarly impacts of scientific research are complex processes, the bibliometric practice of measuring citations made to scientific publications by other scholarly papers is the best approach currently available to capture these phenomena. This measure is referred to as the Average Relative Citation (ARC) factor.

The KPMG report reviewed both the reputational and bibliometric results of the CCA's findings and developed perspectives that relate specifically to the natural sciences, as shown in Figure 16 and Figure 17, respectively.<sup>28</sup> Among its peer nations, Canada ranked sixth overall for both its reputation for research capability in the natural sciences and for its ARC score.<sup>29</sup> ARC scores for the natural sciences are relatively similar among most G7 nations.<sup>30</sup>

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<sup>27</sup> CCA 2012.

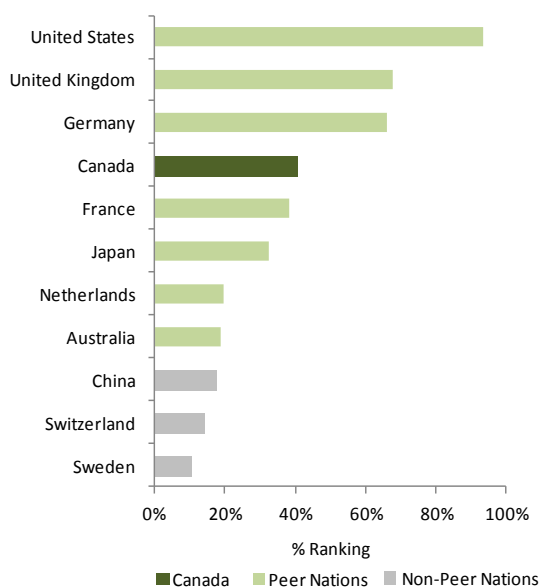
<sup>28</sup> KPMG 2014.

<sup>29</sup> International ARC score is the ARC score for papers that result from international collaborations.

<sup>30</sup> Figure 17 highlights a well-recognized deficiency in the bibliometric approach. Non-English-speaking nations tend to have lower International ARC scores. This is evidenced in Figure 17, where South Korea, Japan, India, Brazil, and China are shown with the lowest ARC scores.

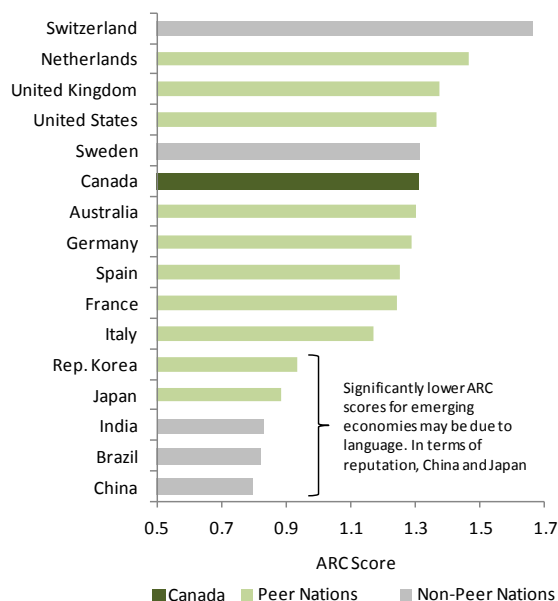
**Figure 16 – International Ranking for Natural Sciences Reputation**

(% of Experts Who Ranked Each Nation as a Top Five Nation in their Field)



Source: CCA 2012, KPMG 2014, Strapolec Analysis

**Figure 17 – International Comparison of ARCs for Natural Sciences (2010)**



Source: CCA 2012, KPMG 2014, Strapolec Analysis

### Materials Research at the CNBC

The contribution that the CNBC has made to Canada's international ARC score can be assessed from the outcomes of the research activities in which the CNBC was engaged.

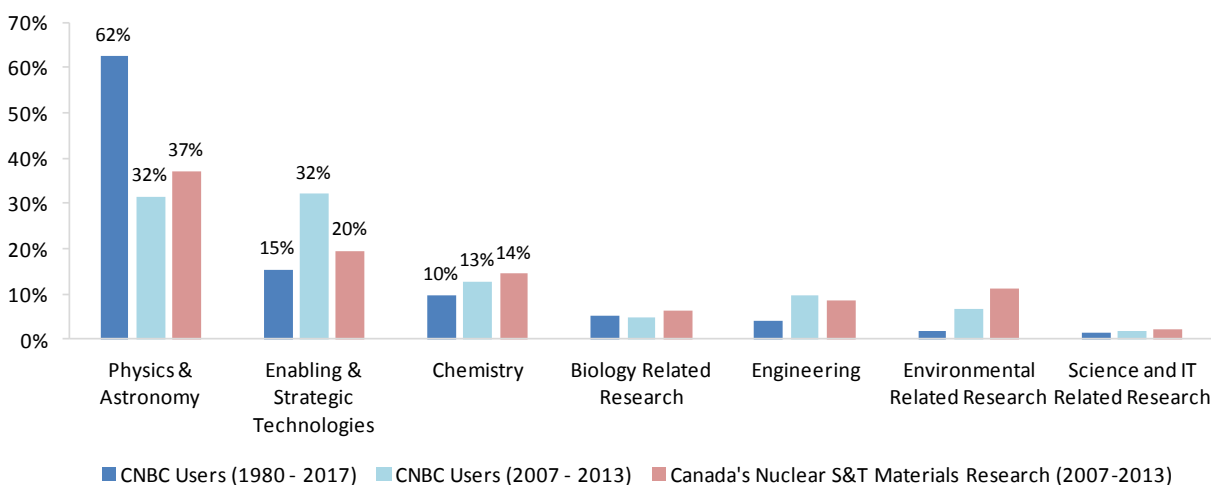
Figure 18 shows the percentage of research papers arising from the CNBC from 1980–2017 for each of the fields of research defined for global bibliometric analyses. The results are contrasted against those for publications from 2007–2013 arising from the CNBC as well as from Canada's nuclear S&T materials researchers overall, as examined in the KPMG report.<sup>31</sup>

<sup>31</sup> Several research fields were grouped into related categories and consist of the following fields:

- Environmental-related research: Agriculture, Fisheries and Forestry, Earth and Environmental Sciences.
- Biology-related research: Biology, Biomedical research, Clinical Medicine.
- Science and IT-related research: Built Environment and Design, General Science and Technology, Information and Communication Technologies, Mathematics and Statistics.

The Other category makes up only ~1% of all papers across all facilities, and so is not relevant to this analysis and has thus been excluded.

**Figure 18 – Distribution of Materials Research Publications by Field of Research**  
(% of Papers Published)



Source: Science-Metrix 2018, KPMG 2014, Strapolec Analysis

The top five materials research fields that materials researchers publish in are: Physics and Astronomy, Enabling and Strategic Technologies, Chemistry, Biology-related research, and Engineering. Physics publications include specializations in materials research, as characterized by Science-Metrix.<sup>32</sup> Similarly, Enabling and Strategic Technologies includes materials science, which refers to a specific subset of materials research, as a subfield.<sup>33</sup> It is thus not surprising that over 75% of CNBC publications are in these two fields. Regardless of the timespan examined, Figure 18 shows that about 80% of the publications arising from the CNBC are in the leading three fields (i.e., Physics and Astronomy, Enabling and Strategic Technologies, and Chemistry), with the remaining 20% being in the other four fields (i.e., Biology-related research, Engineering, Environmental-related research, and Science and IT-related research). These seven fields are collectively defined for the purposes of this analysis as materials research fields.

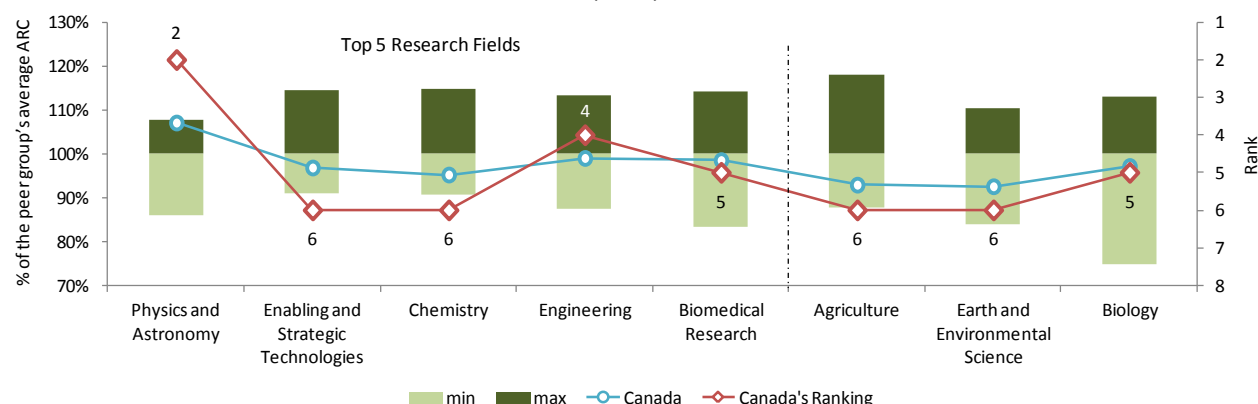
Figure 19 depicts Canada's ARC scores for the leading materials research fields in relation to the average, minimum, and maximum ARC scores for the peer group of nations in those same fields. The top five fields are those most relevant to CNBC publications. To give context to how Canada's ARC scores compare, Canada's ranking within the top nine<sup>34</sup> peer nations is also indicated.

<sup>32</sup> KPMG 2014.

<sup>33</sup> Science-Metrix website.

<sup>34</sup> Excluding Japan and South Korea due to bibliometric biases.

**Figure 19 – International Peer Comparison of Canada’s ARC Scores by Field of Research (2010)**



Source: CCA 2012, Strapolec analysis

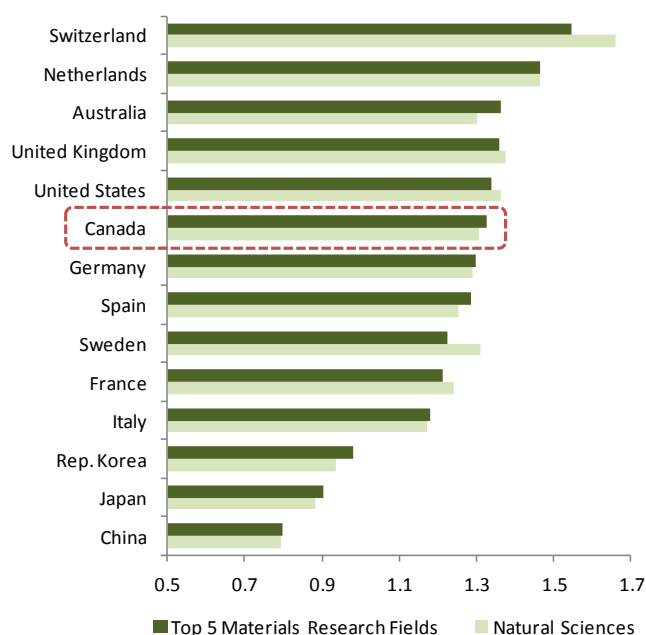
Of the nine-country field, Canada has an above-average ARC in Physics and Astronomy—the CNBC’s predominant field of publication. Canada also ranks above average in Engineering citations and average in Biomedical research and Biology citations. Canada ranks sixth in all remaining fields, including Chemistry and Enabling and Strategic Technologies, as well as Agriculture (which includes Forestry and Fisheries) and Earth and Environmental Sciences, two important sectors in Canada’s economy.

#### *International ARC in Materials Research*

Figure 20 compares Canada’s ARC for the top five materials research fields<sup>35</sup> against the overall natural sciences ARC of nations previously shown in Figure 17. Canada ranks the same among its peer nations for both the top five materials research fields and natural sciences. However, the gap between Canada’s ARC value and those of the top 5 has significantly narrowed. The narrowed gap is most noticeable for the US and the UK, due to Canada’s ARC for materials research being higher than natural sciences, whereas for those nations with whom the gap with Canada has narrowed, it is lower.

<sup>35</sup> The role of materials research in Canada’s bibliometric ranking among peer nations is best illustrated by its weighted average publications, at the national level, for the top five fields where materials researchers publish.

**Figure 20 – International Materials Research ARC Comparison  
(2010)**



Source: CCA 2012, Strapolec Analysis

### *The Relationship Between Materials Research and Manufacturing*

The Specialization Index (SI) is a bibliometric measure of how concentrated a country's overall research is in particular areas of interest. Figure 21 presents the SI for the top five materials research fields for Canada and its peer nations. The strong manufacturing economies illustrated in Figure 14 all have high SI scores in materials research fields.

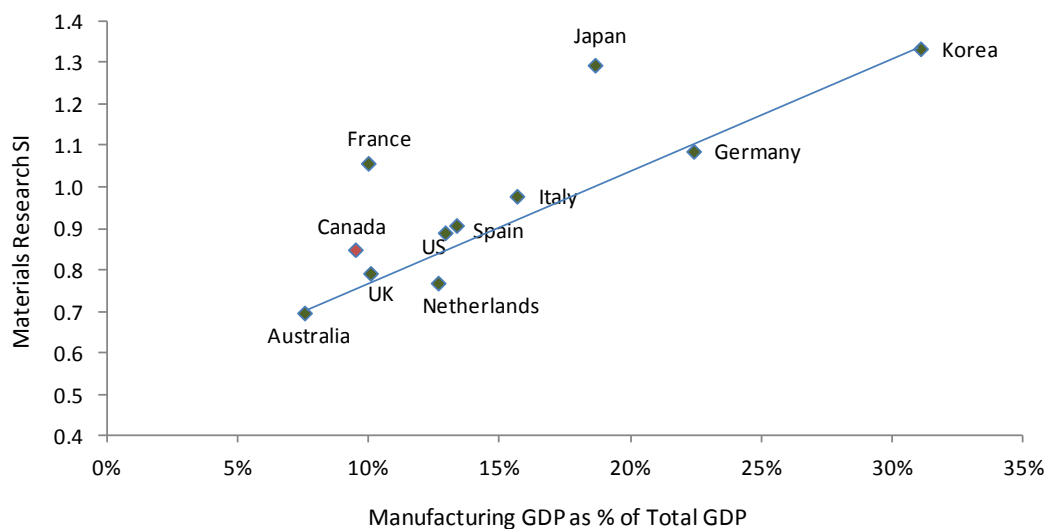
**Figure 21 – Materials Research Specialization Index (SI) for Peer Nations**  
(Average of the Top Five Materials Research Fields,<sup>36</sup> 2010)



Source: CCA 2012, Strapolec analysis

Figure 22 plots the SI for materials research against the size of the manufacturing sector in each peer nation. There is an evident correlation between successful manufacturing economies and their specialization in materials research.

**Figure 22 – Materials Research SI vs. Manufacturing GDP**  
(Canada and Its Peer Nations)



Source: CCA 2012, OECD 2012, Strapolec analysis

France and Japan have a stronger research focus on materials research than the size of their manufacturing sectors would suggest. The remaining countries are more tightly coupled to a trend line relating materials research activity to the size of that country's manufacturing sector.

<sup>36</sup> The top five materials research fields are Chemistry, Engineering, Physics and Astronomy, Enabling and Strategic Technologies, and Biology-related research.

Canada would appear to have a higher than expected materials research SI given the size of its manufacturing economy. This may be due to the identified rapid reduction in its manufacturing GDP, which may precede impacts to BERD priorities. However, the fact that Canada's materials research SI is somewhat lower than that of other nations while its ARC scores are higher supports the conclusion that Canada is strong in the critical materials research areas that the CNBC specialized in.

### *Summary*

The analysis in this section provides several insights:

1. The research areas that the CNBC specialized in encompassed a broad range of materials research;
2. Canada's capabilities in materials research provide a positive contribution to how its overall ARC scores compare internationally;
3. The level of materials research activity in a given country correlates with that country's manufacturing activity; and
4. The research capabilities provided by the CNBC are important to a manufacturing-based economy.

### **4.3 International Nuclear S&T Materials Research Collaborations**

The degree to which researchers collaborate internationally can indicate the strength of a country's research capability. Competitive capabilities attract foreign researchers, creating interactions that enable the sharing of ideas and the proliferation of knowledge across the world. Thus, collaborations are important to an innovative economy.

This section looks at the collaborative record of the CNBC and its peers and then examines the specific collaborations that the CNBC engaged in. With the CNBC's reliance on U.S. collaborations, commonalities between the materials research agendas of Canada and the U.S. are discussed. The section closes with a discussion of the bibliometric records of the CNBC and its international peers, with particular focus on the U.S. peers that the CNBC collaborated with the most.

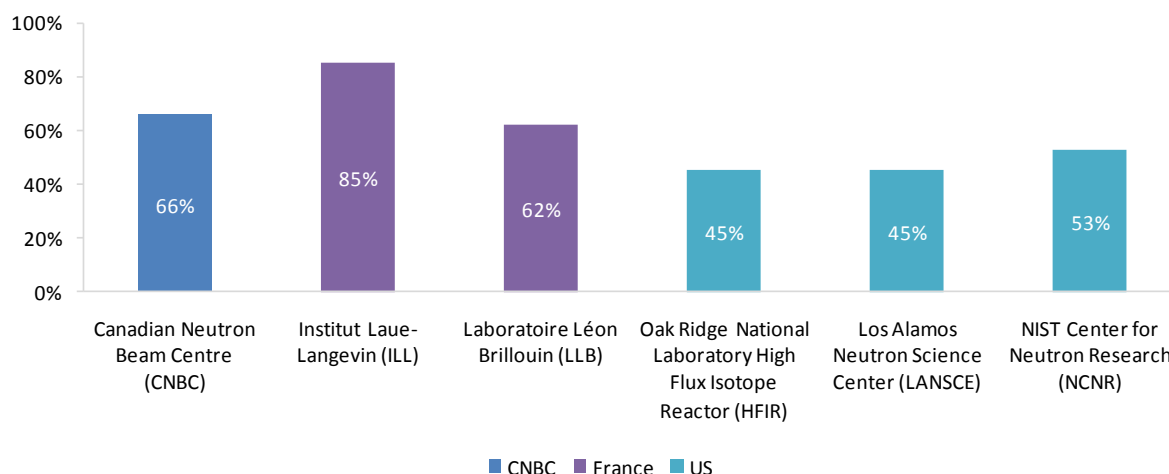
#### **4.3.1 The CNBC and International Collaboration**

Figure 23 shows the International Collaboration Rate<sup>37</sup> (ICR) of the CNBC and other leading neutron beam user facilities, discussed in Section 3.4.2.

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<sup>37</sup> The ICR for a given facility is a measure of how many papers arising from that facility are co-published with international partners as a proportion of that facility's total publication output.

**Figure 23 – International Collaboration of the CNBC vs. Comparable International User Facilities**  
(% ICR by Facility)

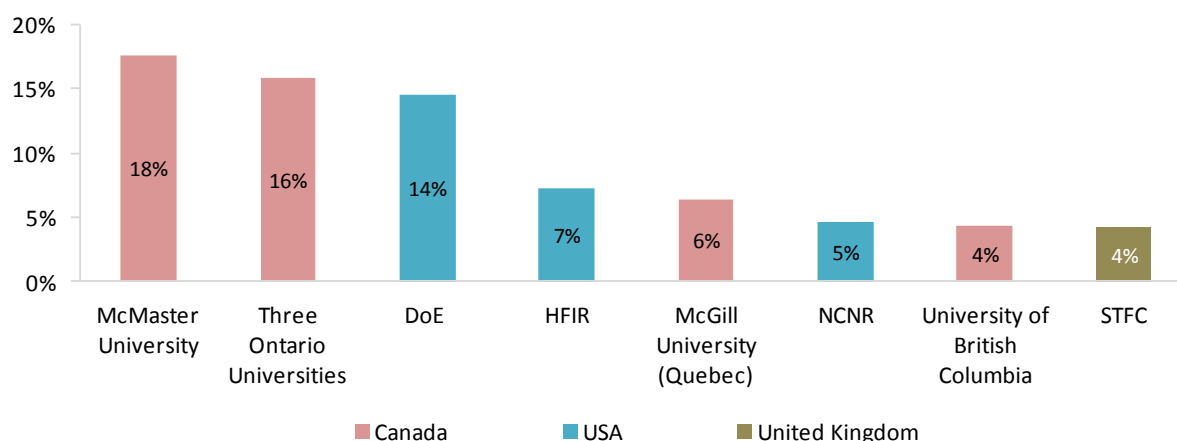


Source: Science-Metrix 2018, Strapolec Analysis

The CNBC has the second highest ICR compared to other comparable neutron beam user facilities, with 66% of papers arising from the CNBC being co-published with international partners. The only other facility in this peer group with a higher ICR than the CNBC is France's ILL with 85%. ILL collaborations may be positively influenced by its close proximity to various European countries that have a high propensity for collaboration. Comparable U.S. facilities have a generally lower ICR score, reflective of the propensity for the U.S. to collaborate less as a nation as a result of its sizable and diverse domestic research capability.<sup>38</sup>

Figure 24 looks at the most frequent collaborators of the CNBC for the period 1980–2017.<sup>39</sup>

**Figure 24 – The CNBC's Most Frequent Collaborators**  
(% of Total Papers Arising from the CNBC, 1980–2017)



Sources: Science-Metrix 2018, Strapolec Analysis

<sup>38</sup> KPMG 2014

<sup>39</sup> Science-Metrix 2018, "Collaborator" includes users and the co-authors of their papers that arose from the CNBC.

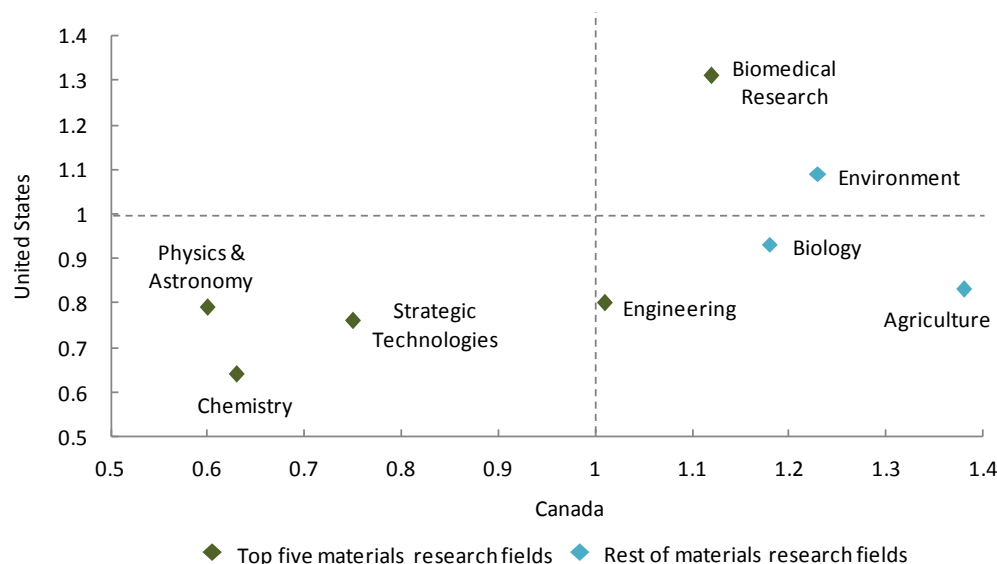
McMaster University is the CNBC's most frequent collaborator, with its faculty researchers named as authors on 18% of publications arising from the CNBC. Faculty researchers from three other major Ontario universities<sup>40</sup> authored 16% of the publications arising from the CNBC. This demonstrates a strong relationship between the CNBC and Ontario's academic community. Altogether, researchers from Ontario universities represent over one-third of the CNBC's collaborators.

Institutions in the U.S. are the CNBC's dominant international collaborative partners. Together, the U.S. Department of Energy (DoE), HFIR, and the NCNR account for 26% of the CNBC's total collaborators. The CNBC's eighth largest collaborator is the Science and Technology Facilities Council (STFC). All of these facilities operate their own neutron sources, demonstrating that there is a lot of collaboration within the global neutron beam community, and also that neutron beam users often do experiments at more than one facility.<sup>41</sup>

#### 4.3.2 The Canada–U.S. Relationship Regarding Materials Research Priorities

Figure 25 shows the correlation between U.S. and Canadian research priorities as measured by the SI of various fields of materials research. Overall, the correlation of the SI for most fields shows that the U.S. and Canada have similar specializations when it comes to research in fields supported by materials research. Seeing as Canada and the U.S. invest in similar materials research-related areas, it is not surprising that the U.S. is the CNBC's leading international research collaborator.

**Figure 25 – Alignment of U.S. and Canadian Research Specializations**  
(Specialization Index of Eight Natural Sciences Fields in WoS, 2011)



Source: CCA 2012, Strapolec analysis

<sup>40</sup> The other Ontario universities among the CNBC's top collaborators consist of (in descending order of collaborations): the University of Guelph, the University of Toronto, and the University of Waterloo.

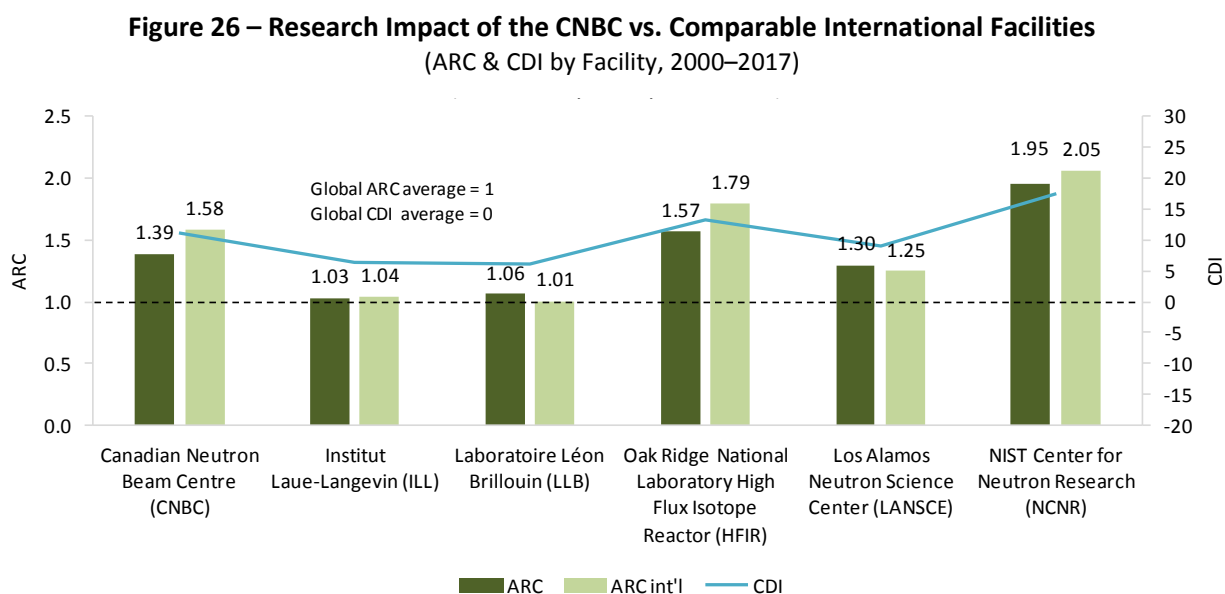
<sup>41</sup> CNBC interviews.

In the top five materials research-related fields, the U.S. places a higher priority on Physics and Astronomy and on Biomedical research than Canada does, while Canada places a higher priority on Engineering. The two countries prioritize Chemistry and Enabling and Strategic Technologies similarly.

In the fields with less direct use of materials research, Canada places a much higher priority on materials research related to Biology, Environment, and Agriculture than the U.S. does.

### 4.3.3 Comparing the CNBC's Performance to Equivalent International Institutions

With the alignment of research priorities between Canada and the U.S., performance comparisons between the countries' respective neutron beam user facilities can be made based on ARCs. Figure 26 shows the ARCs, the international ARCs<sup>42</sup>, and the Citation Distribution Index<sup>43</sup> (CDI) scores for the CNBC and comparable U.S. and French facilities for the period 2000–2017.<sup>44</sup>



Source: Science-Metrix 2018, Strapolec Analysis

The CNBC ranks highly among comparable international neutron beam facilities; with an ARC of 1.39, it comes in third behind the NCNR and HFIR. When considering only internationally collaborated publications, papers arising from the CNBC are significantly more cited than those of arising from the French facilities (ILL and LLB) or LANSCE.<sup>45</sup>

<sup>42</sup> International ARC is the ARC score for papers that result from international collaborations.

<sup>43</sup> The CDI is a measure of the degree to which published papers consistently achieve high citation scores, and is an alternative metric to the ARC score.

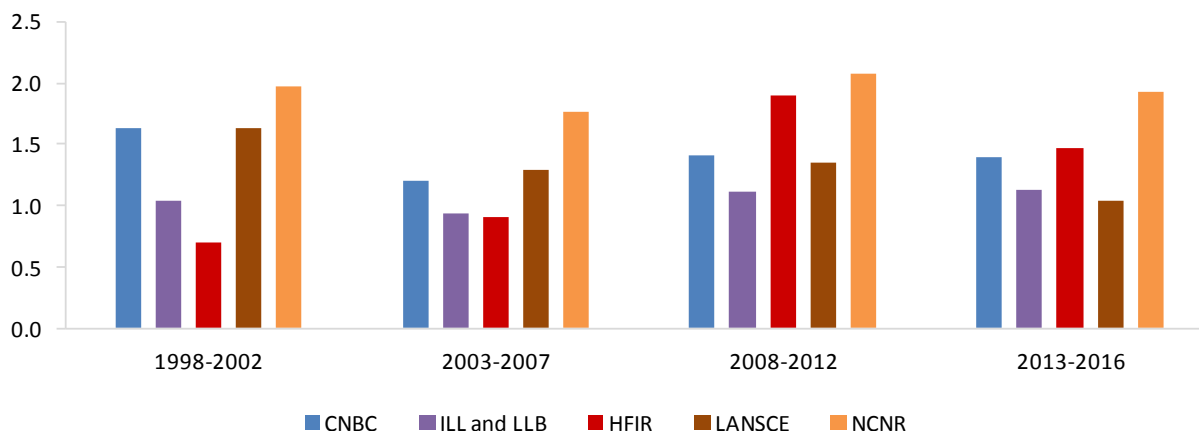
<sup>44</sup> The period 2000–2017 was chosen because citation data sets are incomplete for many facilities before 2000.

<sup>45</sup> The French facilities' impact scores may be influenced by an English language bias that exists in the bibliometric process, which could be part of the reason why those facilities have much lower ARCs and CDI scores.

The CDI scores of these facilities produce similar rankings to those based on ARCs, with the CNBC again having the third highest score.

While these average ARCs may be indicative of overall long-term performance, the time horizon captured in Figure 26 is long, and the outcomes for each facility have varied over that period. Figure 27 shows how the ARC scores of the CNBC and comparable international facilities have varied in five-year increments from 1998–2016.

**Figure 27 – ARC for the CNBC and Comparable International Facilities in Five-Year Increments**  
(ARC by Period, 1998–2016)



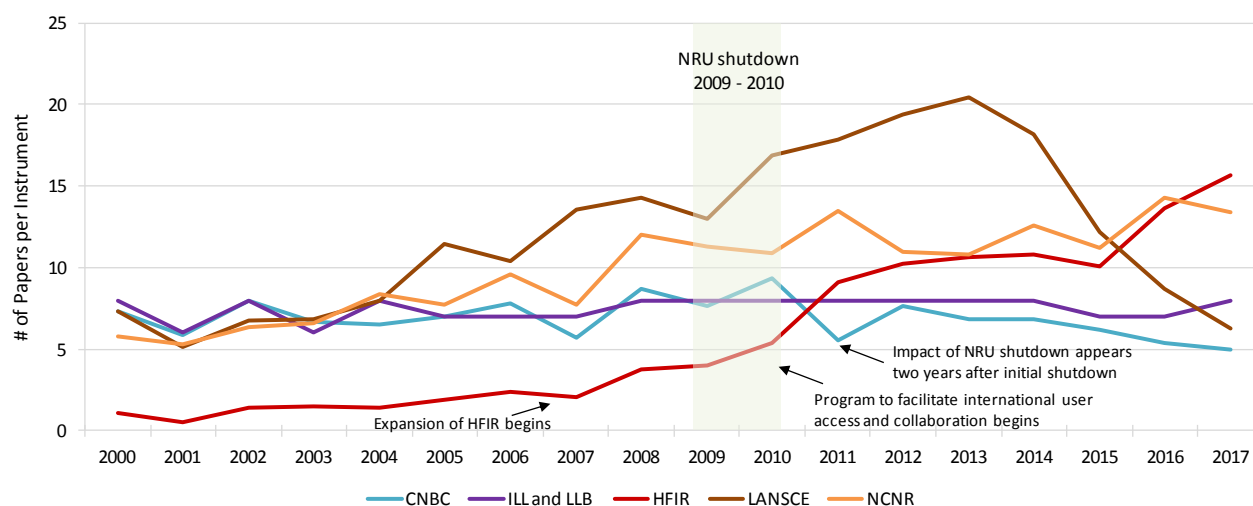
Source: Science-Metrix 2018, Strapolec Analysis

The ARCs for each of the facilities have evolved in somewhat common patterns, generally decreasing during the period 2003–2007, increasing during the period 2008–2012, and decreasing again during the period 2013–2016. HFIR is an exception, experiencing an increase in ARC from 2003–2007, followed by a much larger increase from 2008–2012, putting it almost on par with the NCNR for that time period before decreasing again from 2013–2016. The French facilities, ILL and LLB, do not follow this trend during the 2013–2016 period either, increasing slightly instead. The CNBC shows similar behaviour to the French facilities, sustaining its ARC score over the 2013–2016 period.

The earlier observation that the HFIR-related publications achieved a nearly 15% higher ARC score than the CNBC’s publications (see Figure 26) is almost entirely attributable to activity during the period from 2008–2012. The ARCs of the CNBC and HFIR are similar during the 2013–2016 period. The only facility that sustained a higher ARC than the CNBC during the whole 1998–2016 timespan is the NCNR.

As ARCs are a result of a weighted average over the number of papers arising from a facility in a given year, the volume of papers should also be considered when interpreting the implications of the facilities’ ARC scores. Figure 28 shows the publication output per instrument per year for the CNBC and comparable international facilities.

**Figure 28 – Publication Output Trend for the CNBC vs. Comparable International Facilities**  
(Number of Papers per Instrument)



Source: Science-Metrix 2018, Strapolec Analysis

Figure 28 shows that until 2010, CNBC users were publishing about as many papers per instrument as users of the NCNR and the French facilities were, and significantly more than HFIR users. In 2011, the number of papers arising from the CNBC dropped sharply—a delayed consequence of the NRU reactor’s unplanned shutdown in 2009–2010<sup>46</sup>—which, following a slight recovery in 2012, proceeded to slowly decline until its closure.

The increase in publications arising from HFIR during this same period is a product of investments made in the early 2000s; specifically, a new program to facilitate international user access and collaboration at Oak Ridge National Laboratory (ORNL) was completed in 2009.<sup>47</sup> The publication rate of papers arising from HFIR continued to increase through to 2018 and now exceeds the publication rate for the NCNR. The publication rate of LANSCE-related papers has declined rapidly since 2014 due to the U.S. government’s decision to discontinue that facility’s user access and focus instead on military research. Output from the new Spallation Neutron Source (SNS) at ORNL has been ramping up since it came online in 2007, and now ORNL is the source of a majority of neutron beam users’ publications in the U.S.<sup>48</sup>

Figure 29 illustrates the relationship between the output of publications arising from the CNBC and the ARC scores it has achieved over the 2000–2017 period.

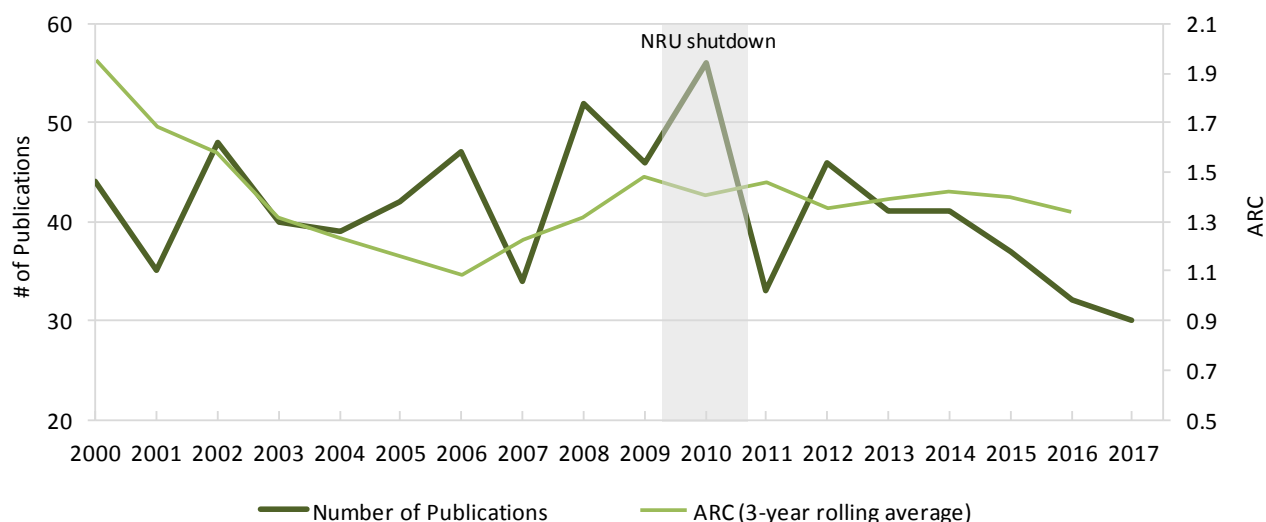
<sup>46</sup> The unplanned shutdown of the NRU reactor referred to here occurred from May 2009–August 2010, but the impact on publications did not materialize until two years after the shutdown began because it generally takes some time after an experiment is conducted to develop and publish a research paper.

<sup>47</sup> Based on interviews with CNBC staff and former HFIR staff. Publicly available records shown for the HFIR prior to 2010 may be understated according to CNBC.

<sup>48</sup> The SNS was not one of the comparator facilities in the Science-Metrix study. Nonetheless, this observation was drawn by the CNBC using further data from ORNL’s PuSH database, which provides lists of all papers arising from both of its neutron sources. The database is available at: <https://neutrons.ornl.gov/publications>

**Figure 29 – Publication Output and ARC Trend for the CNBC, 2000–2017**

(# of Publications and ARC Score by Year)



Source: Science-Metrix 2018, Strapolec Analysis

For the last decade of its operation, the CNBC consistently maintained an ARC score above 1.3, even during and immediately following the 15-month unplanned shutdown of the NRU reactor in 2009–2010, which speaks to the quality of the research enabled by that user facility. These ARC scores were sustained even as the number of publications began to decline in the run-up to the cessation of the CNBC’s operations. This may be due to the CNBC’s focus on maintaining a strong interaction with its user community and postponing any “wind-down of activities” in order to maximize the value extracted from the NRU reactor during its final years of operation.

#### 4.3.4 Summary

The analysis in this section provides several insights:

- CNBC users collaborated significantly with international peer organizations that have their own neutron beam facilities; This may be supported by the similar research agendas of Canada and the U.S.; and
- The quality of CNBC research outcomes sustained a high benchmark as compared to its international peer facilities despite challenges posed by the NRU reactor’s shutdown and ongoing investments in foreign neutron beam user facilities.

#### **4.4 Conclusion**

This section's analysis of the factors contributing to an innovative economy identifies five fundamental observations that build a narrative to support the CNBC's contribution to innovation in Canada:

- Manufacturing's high BERD makes it a key element and indicator of a strongly innovative economy, and manufacturing relies on research;
- Materials research underpins innovation in manufacturing;
- Canada's publications in materials research are well regarded and contribute positively to Canada's overall research quality;
- The CNBC was a unique enabler of materials research in Canada; and
- The quality of research conducted at the CNBC is on par with research conducted at similar international facilities.

The CNBC has been a key element of Canada's innovation economy. The quality of its research outcomes and the specialized areas in which research using the CNBC was performed show that the CNBC has contributed to Canada's status as an innovative economy. The CNBC was a valued source of collaboration with the U.S. in several relevant, unique, and specific research fields. The CNBC's research outcomes sustained comparable relevance to those of its international peers, as determined by ARC scores, even during the final years of the facility's operation.

## **5.0 Contributions of the CNBC to Academic Research**

The WEF Innovation Index described in Section 4.0 identifies that the quality of a nation's research institutions is a key parameter in the development of an innovative economy. The CNBC has contributed to Canada's academic research infrastructure and outcomes. This section examines Canada's most valuable infrastructure elements for supporting academic research and looks at the relationship those elements had with the CNBC. The use of the CNBC by Canada's Research Chairs is examined, followed by a discussion of how academic users across Canada leveraged the CNBC. Finally, the impact of the research conducted at the CNBC on the ARC scores for Canada's overall materials research is presented. These bibliometric outcomes are contrasted with those for academic users in Canada who do not have access to the CNBC.

### **5.1 The Value of Canada's Research Infrastructure**

The CCA has described the value of Canada's research infrastructure in two reports.<sup>49</sup> In 2006 and 2012, the CCA published survey results of approximately 1,500 of Canada's most highly cited research experts. Respondents were asked to rate the value of various elements of Canada's research infrastructure. The surveys were designed to determine the degree to which certain elements (e.g., specific facilities, institutions, collaboration networks, and government funding agencies) led to advantages in scientific research in Canada.

The results of the CCA surveys are presented here, with particular focus on two components that highlight the role the CNBC played in providing advantages to Canadian researchers:

1. Knowledge production and support infrastructure; and
2. Federal and Big Science research facilities.

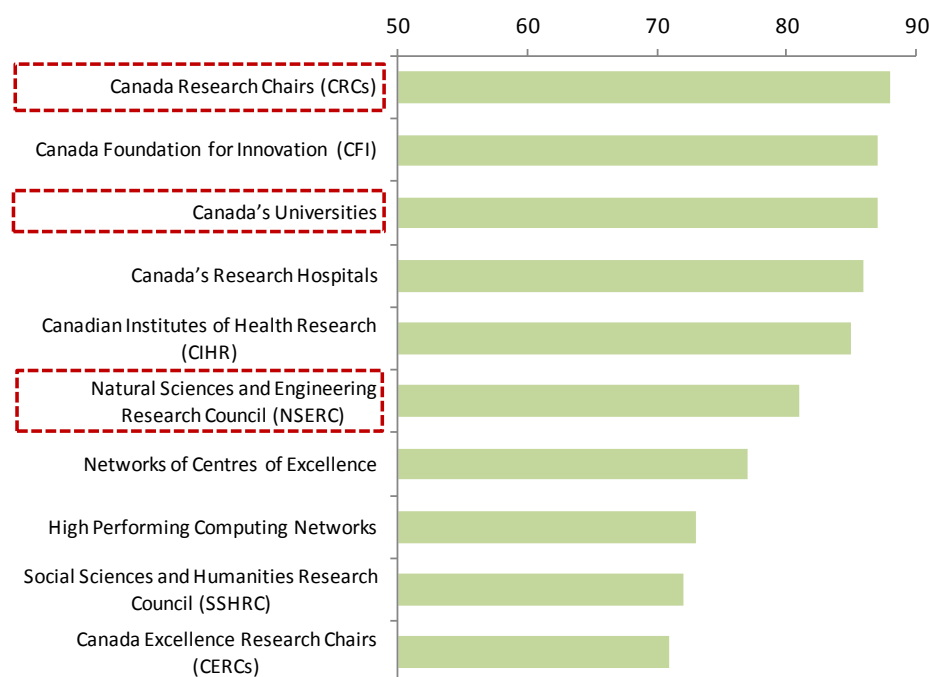
#### **5.1.1 Knowledge Production and Support Infrastructure**

Figure 30 presents the results of the 2012 CCA survey regarding the enabling elements of Canada's infrastructure for developing research knowledge.

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<sup>49</sup> CCA 2006, CCA 2012.

**Figure 30 – Opinions of Canada’s S&T Experts Regarding Canada’s Research Infrastructure, 2012**  
(% of Survey Respondents Stating that Element Is Advantageous  
Relative to Similar Elements in Other Advanced Nations)



Source: CCA 2012, Strapolec analysis

In the 2012 survey, the Canada Research Chair program, the Canada Foundation for Innovation (CFI), and Canada’s universities were identified as the three most advantageous elements of knowledge production and support infrastructure for Canadian researchers.<sup>50</sup>

Canada Research Chairs are a key component of Canada’s national strategy for R&D. Created in 2000, the CRC program established research professorships in eligible degree-granting institutions across the country. The relationship between the CNBC and the CRC program is discussed in Section 5.2.

Universities are the foundational institutions that support academic researchers in Canada. In all, 98% of Canadian universities conduct some research using nuclear-licensed facilities, including the CNBC. University faculty researchers who use the Chalk River Laboratories or small nuclear-licensed facilities at universities, or otherwise participate in nuclear energy research are referred to here as ‘nuclear energy researchers,’ as defined in Section 3.3. The geographic distribution of nuclear energy researchers and academic users of the CNBC, TRIUMF, and the CLS is discussed in Section 5.3.

NSERC was identified as advantageous by over 80% of survey respondents. NSERC is the government funding mechanism that supports university research activities in natural sciences

<sup>50</sup> CRCs and the CFI are innovations introduced in the late 1990s and are critical funding mechanisms for all university research in Canada.

and engineering; it also provides matching funds for collaborative university–industry research. Section 5.2 examines the relationship between the CNBC, CRCs, and NSERC funding for pure academic research. The relationship between the CNBC and NSERC-funded industry collaborative research is discussed in Section 6.

### **5.1.2 Canada’s Federal and Large-Scale Science Research Facilities**

Canada’s federal and Big Science research facilities include four major nuclear S&T facilities: the CNBC, TRIUMF, the CLS, and the AECL-owned facilities at Chalk River Laboratories. Also included on the list of Canada’s major research facilities are the Sudbury Neutrino Observatory (SNO), the Amundsen icebreaker, the infectious disease laboratories, astronomical observatories, CANARIE, the National Research Council institutes, and other federal laboratories. Both the 2006 and 2012 CCA surveys assessed the advantages that these facilities provide as perceived by Canada’s research experts, while the perspective of international researchers was surveyed only in the 2006 report.<sup>51</sup>

Figure 31 presents the international perspectives captured in the CCA’s 2006 survey alongside the average of the domestic perspectives captured in the 2006 and 2012 surveys regarding the perceived value of Canada’s various federal and Big Science research facilities.<sup>52</sup>

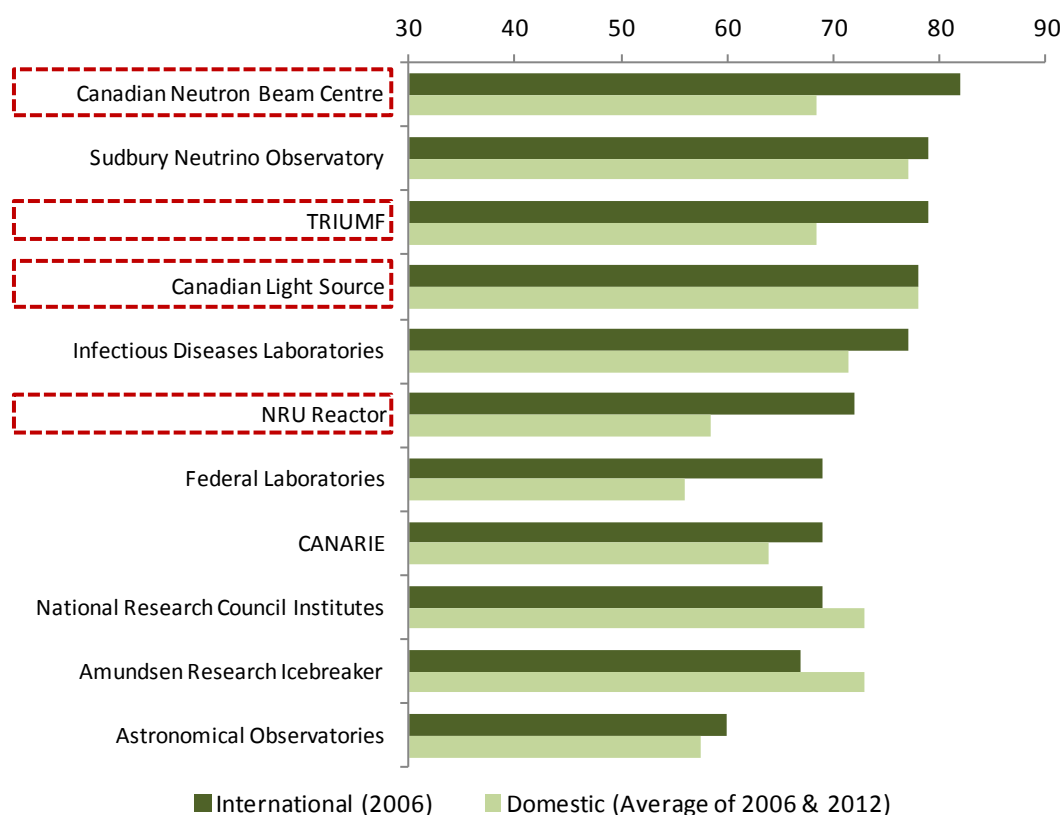
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<sup>51</sup> The CCA engaged contacts in the Department of Foreign Affairs and International Trade Canada to approach Science Counsellors and Trade Commissioners stationed in Canadian Embassies around the world to obtain reports and other data to complement the domestic survey and provide an indication of the international perspective on Canadian research advantages.

<sup>52</sup> Compiled from averaging the CCA 2006 survey Figures 6.3 and 6.8 with the findings of the 2012 CCA survey.

**Figure 31 – International and Domestic Views on Canada’s Research Facilities<sup>53</sup>**

(% of Survey Respondents Stating that the Element is Advantageous  
Relative to Similar Elements in Other Advanced Nations)



Source: CCA 2006, CCA 2012, Strapolec analysis

Figure 31 shows that Canada’s research community places nuclear S&T facilities in the top seven rated facilities in the country. Domestically, the most highly rated are the CLS and SNO, followed by the Amundsen icebreaker and the NRC institutes. The CNBC and TRIUMF are approximately tied in sixth place, with over 70% of Canadian researchers considering them to be highly advantageous to Canada’s research ecosystem. Other federal laboratories are ranked last.

The international perspective placed Canada’s nuclear S&T facilities in the top six most advantageous assets available in the country, with the CNBC rated as the number one most advantageous facility to scientific research above all other facilities in the group. The high degree to which international researchers have rated the CNBC as being advantageous correlates with the high international ARC achieved by publications arising from the CNBC, as discussed in Section 4.4.3.

<sup>53</sup> The genome facility and NEPTUNE Canada were not included in the 2006 survey and hence not mentioned here. The CNBC was not included in the 2012 survey, but the CNBC and TRIUMF had equivalent rankings in the 2006 survey, so it has been assumed for this illustration that they would have remained equivalent in the 2012 survey had the CNBC been included. The value for the CNBC in 2012 has thus been set equal to TRIUMF in Figure 31.

## 5.2 The CNBC and CRCs

Canada Research Chairs are awarded to the top Canadian academics within their areas of research, and overall the program supports a broad diversity of research areas. The proportion of CRCs making use of the CNBC is an indicator of the extent to which the facility's resources have supported the research of high-performing university faculty over a broad array of research areas.

Table 1 looks at the university faculty researchers who hold CRCs. The proportion of CRC holders among university faculty users of the CNBC and among nuclear energy university faculty are contrasted with the overall population of NSERC-funded faculty researchers.<sup>54</sup>

**Table 1 – Average Annual Number of CRCs**

	Number of Professors with NSERC Grant				% of Professors with Grants in Canada	
	CNBC Users	Nuclear Energy Researchers	Rest of NSERC	Total	CNBC Users	Nuclear Energy Researchers
Any NSERC Grant	100	99	9801	10000	1.0%	1.0%
CRC NSERC Grant	17	8	748	774	2.3%	1.1%
% of NSERC Professors with CRC Grants	17%	8%	8%	8%	226%	109%

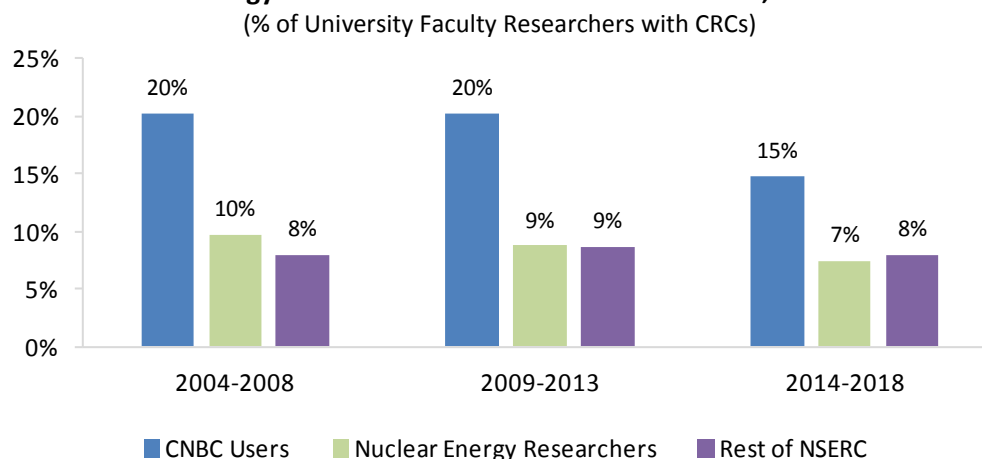
*Source: Strapolec analysis of NSERC funding database, values may not add due to rounding*

The concentration of CRCs among CNBC users is double that which would be expected based on NSERC averages. In the average year, there were 100 university faculty researchers in the CNBC user community who were funded through NSERC, representing 1% of the total number of university faculty researchers receiving NSERC funds. On average, 17 of those 100 CNBC users were CRCs, representing over 2% of Canada's overall number of CRCs. The share of CNBC users who are CRCs (17%) is double the CRC share (8%) among the entire population of NSERC-funded researchers.

Figure 32 shows the change over time in the proportion of CNBC users and nuclear energy researchers who have CRC grants in contrast to the population of NSERC-funded researchers overall. Among nuclear energy researchers during the 2004–2008 period, 10% held CRCs, compared to the rest of NSERC at 8%. The CNBC had its highest proportion of CRCs from 2009–2013, while the proportion of nuclear energy researchers CRCs declined slightly during that period to be on par with NSERC averages. The proportion of CRCs in both groups declined from 2014–2018, with nuclear energy researchers CRCs falling below NSERC averages. For the CNBC, this decline may have been related to the facility's imminent closure, but it still retained almost double the proportion of CRCs than NSERC averages.

<sup>54</sup> Based on an analysis of academic researchers who received NSERC grants during the period 2001–2018.

**Figure 32 – Proportion of University Faculty Researchers with CRCs at the CNBC vs. Nuclear Energy and NSERC-Funded Researchers Overall, 2004–2018**

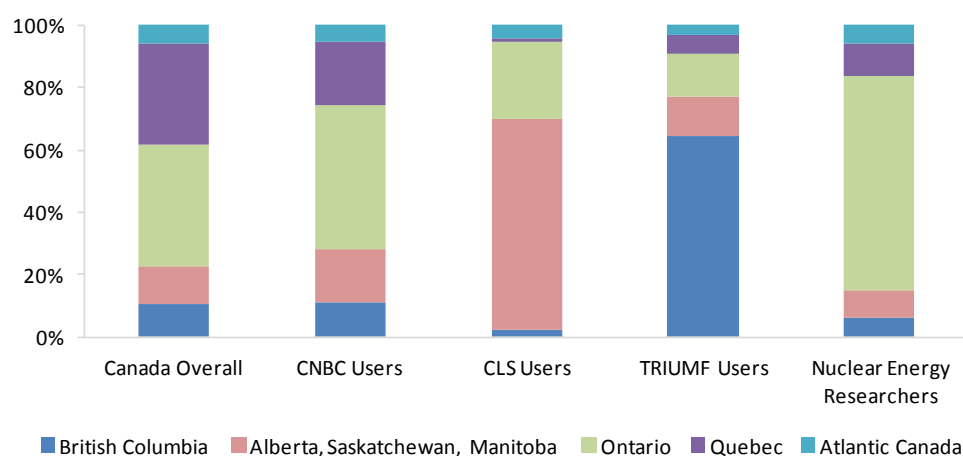


Source: Strapolec analysis of NSERC funding database

### 5.3 Geographic Distribution of University Faculty Researchers Who Use Nuclear S&T Facilities

The geographic distribution of the four communities of university faculty researchers associated with Canada's nuclear S&T facilities (as defined in Section 3.3) is provided in Figure 33. With the exception of CNBC users, each community is heavily based in the region where the facility is located. For instance, TRIUMF and the CLS are highly associated with researchers from BC and the prairies, respectively; nuclear energy researchers are primarily from Ontario, which hosts the Chalk River Laboratories. For the CNBC, this pattern is much less pronounced; the distribution of CNBC users is more dispersed across the country and more closely matches the distribution of university faculty conducting research with graduate students in Canada overall.

**Figure 33 – Geographic Distribution of University Faculty Researchers by Facility**  
(% of Researchers)



Sources: CNBC, KPMG 2014, Statistics Canada Table 37-10-0030-01, Strapolec analysis.

Canada Overall stats are the average geographic distribution of Master's and PhD graduates over 2000, 2005, and 2010 from Statistics Canada.

The large geographic dispersion of university faculty researchers at the CNBC shows that the CNBC was truly a national research asset. The broad geographic user base of the CNBC could be interpreted as being the result of: (1) the versatility of neutron beams as research tools; and (2) the NRU reactor being a much more powerful neutron source than those available elsewhere in Canada. The CNBC was capable of examining metals, alloys, ceramics, composites, polymers, nanostructures, biomaterials, pharmaceuticals, foods, liquids, colloids, and gels.<sup>55</sup> Thus, researchers from a variety of disciplines, industries, and backgrounds accessed the CNBC for their research.

#### **5.4 The Bibliometrics of Materials Research**

The CNBC's distinct specialization among Canadian research facilities was demonstrated in Section 3.3.3. This section builds on those findings by showing the impact of publications arising from the CNBC. The results of the Science-Metrix bibliometric report commissioned by the CNBC are compared here against two reference benchmarks:

- The bibliometric results for papers arising from Canada's nuclear energy researchers;<sup>56</sup> and
- The average Canadian bibliometric results for the fields being compared.

The results support two findings:

- The CNBC's research capabilities have had a significant positive impact on Canada's bibliometric outcomes; and
- Access to large-scale facilities, in general, enhances the value of research investigations.

Figure 34 shows the ARCs for papers arising from the CNBC, from nuclear energy researchers, and from all of Canada in regards to the CNBC's five most published fields. To provide the relative significance of the CNBC's contributions, the proportion of the CNBC's overall publications related to the fields is also indicated.<sup>57</sup>

In all cases, the ARCs for papers arising from the CNBC are higher than those for nuclear energy researchers. However, Canada as a whole has a higher ARC in Physics than the CNBC does, even though most publications arising from the CNBC are in Physics. Canada as a whole also has higher ARCs in Chemistry and Engineering, areas where the CNBC's publication contributions are less pronounced.

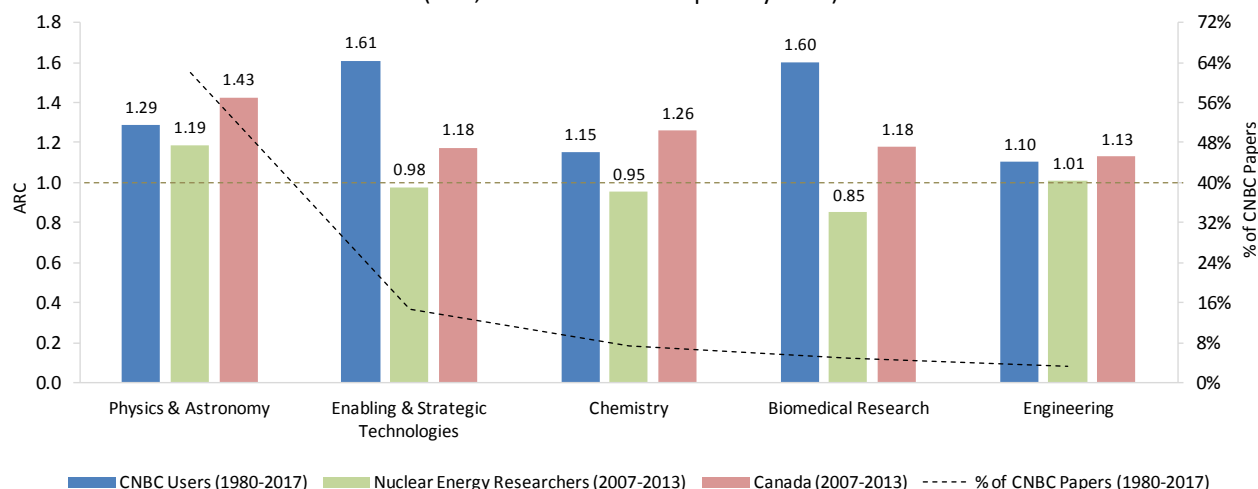
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<sup>55</sup> NRC – Canadian Neutron Beam Centre, "Neutrons: Revealing Particles," 2011.

<sup>56</sup> Estimated from the 2014 KPMG report by combining the AECL and nuclear-related university results reported therein.

<sup>57</sup> CNBC Facility 1980–2017 and % of CNBC papers data from 2018 Science-Metrix; Universities, Canada data from 2014 KPMG.

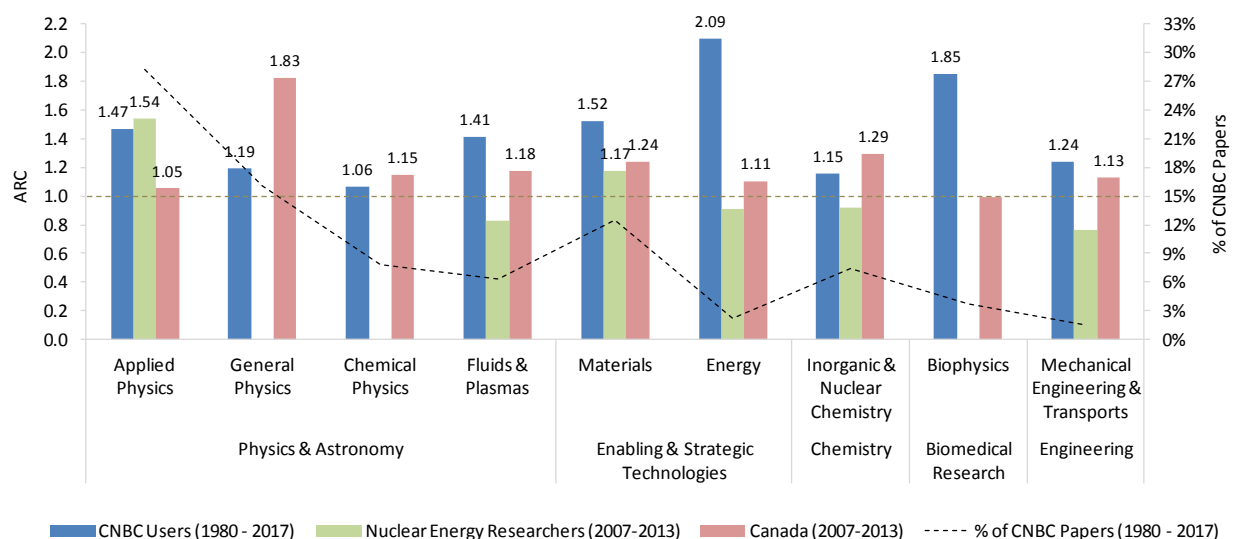
**Figure 34 – ARC Scores for the CNBC’s Most Published Research Fields vs. Nuclear Energy Researchers and All Researchers in Canada<sup>58</sup>**  
(ARC, % of CNBC Total Papers by Field)



Source: Science-Metrix 2018, KPMG 2014, Strapolec Analysis

A deeper look into the subfields of the papers arising from the CNBC shows how the aggregated ARC results in Figure 34 skew the interpretation of the CNBC’s contribution to research in the physics field. Figure 35 shows the ARC comparators for the subfields of the papers arising from research at the CNBC.

**Figure 35 – ARC Scores for the CNBC’s Most Published Subfields vs. Nuclear Energy Researchers and All Researchers in Canada**  
(ARC, % of CNBC Total Papers by Subfield)



Source: Science-Metrix 2018, KPMG 2014, Strapolec Analysis

<sup>58</sup> Canada refers to all papers published in Canada by all researchers, while nuclear energy researchers refers to all papers published by researchers using other nuclear S&T facilities at Canada’s nuclear-licensed universities.

About 70% of the papers arising from the CNBC are in the subfields in which CNBC's ARC is higher than for Canada overall (the remaining 30% are in three of the nine subfields: General Physics, Chemical Physics, and Inorganic and Nuclear Chemistry). Thus, the materials research at the CNBC has had a positive impact on Canada's research, especially in the subfields of Materials, Applied Physics, Fluids and Plasmas, Biophysics, and Mechanical Engineering and Transport. In particular, the CNBC-related ARCs for the Materials and Energy subfields are significantly higher than for those of Canada overall, with its ARC in Energy almost double that of the rest of Canada.

In the Physics and Astronomy subfields, the CNBC-related ARCs in Applied Physics and Fluids and Plasmas are also higher than for Canada overall. However, in the General Physics and Chemical Physics subfields, papers arising from the CNBC have lower ARCs than for Canada overall.

Papers arising from nuclear energy researchers have a slightly higher ARC in Applied Physics as compared to papers arising from the CNBC; interestingly, nuclear energy researchers have a much lower ARC than the CNBC in Fluids and Plasmas, a subfield in which many nuclear energy researchers publish, as was shown in Figure 4.

Except in the subfield of Applied Physics, the ARCs for publications arising from the CNBC exceed the ARCs for publications from nuclear energy researchers. This suggests that access to the large-scale, specialized, national-level infrastructure of the CNBC enhances the research outcomes of academic researchers in Canada.

### **5.5 Conclusion**

Examination of the role the CNBC has played within Canada's national research infrastructure indicates that the CNBC has provided four major benefits to Canadian research:

- The CNBC was considered the most important research facility in Canada by the international community;
- The CNBC drew users from across the country, roughly in proportion to where university faculty researchers are geographically distributed in Canada. The CNBC was a truly national research asset representing the most broadly accessible and widely leveraged capabilities available to Canadian academic researchers;
- The number of Canada Research Chairs who made use of the CNBC was significantly higher than for NSERC-funded science and engineering researchers overall, underscoring the breadth of materials research where neutron beams are applied and highlighting the importance of the CNBC to Canada's leading researchers; and
- The CNBC was a positive contributor to Canada's overall record of research quality. Research by CNBC users in the subfields of materials research most enabled by the CNBC resulted in greater scientific impact than research by non-users in the same subfields.

## 6.0 Industry Engagement with the CNBC

The WEF Innovation Index described in Section 4.0 identifies that the integration of industry and university research contributes to the development of a strong and innovative economy. This section explores the relationship that the CNBC developed with industry and the role the CNBC played in enabling university–industry research collaborations. Industry engaged with the CNBC through two mechanisms:

- Industry-sponsored academic research; and
- Direct industry commercial research.

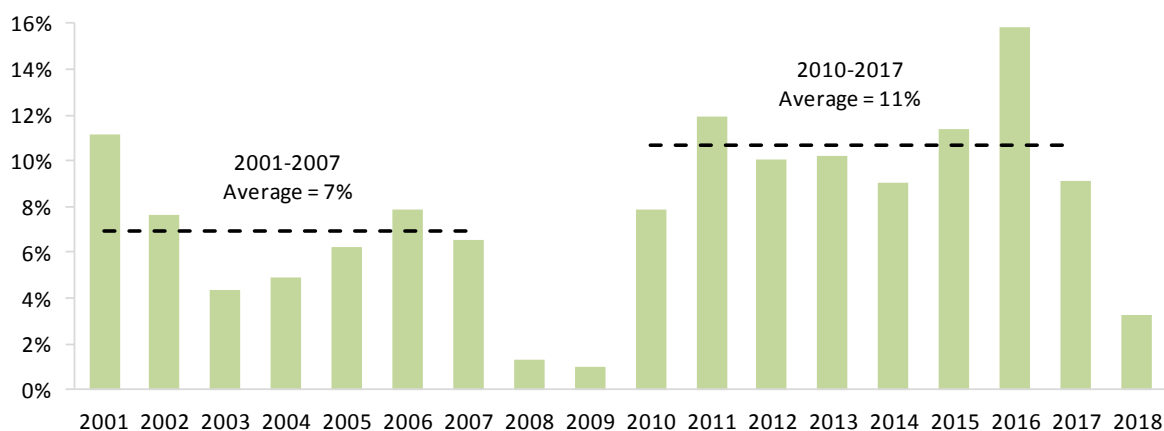
This section starts by examining the net usage of the CNBC’s instrument beam time for industry-related research, regardless of the funding mechanism. It then explores industry-sponsored academic research and direct industry commercial research, provides case studies that illustrate the importance of that research.

### 6.1 Allocation of CNBC Instrument Beam Time to Industry Applications

Beam time at the CNBC was a resource in high demand, with utilization typically exceeding 90%.<sup>59</sup>

Figure 36 summarizes the percentage of beam time the CNBC allocated to industry-related experiments from 2001–2018. The drop in utilized beam time in 2008 and 2009 was due in part to the unplanned shutdowns of the NRU reactor: one in late 2007, and a second from May 2009–August 2010, which created uncertainty surrounding the NRU reactor’s operations at that time.

**Figure 36 – Industry Beam Time at the CNBC, 2001–2018<sup>60</sup>**  
(% of Beam Time Dedicated to Industry Users)



Source: CNBC, Strapolec analysis

<sup>59</sup> Instrument down time was primarily driven by operating technician shift constraints that affected the process for changing experiment equipment setups.

<sup>60</sup> 2009, 2010, and 2018 are only partial years; statistics will be less reliable.

From 2001–2018, beam time devoted to industry-related research grew from approximately 7% from 2001–2007 (prior to the NRU reactor’s 2007 shutdown) to approximately 11% from 2010–2017 (after the NRU resumed operations in August 2010). Part of the reason for the increase could be that the CNBC placed an added emphasis on outreach to industry after the NRU shutdown.

### **6.2 Industry-Sponsored Academic Research**

The degree to which private companies co-fund academic research is a useful indicator of potential innovation impact, driven by the assumption that industry-sponsored research is more greatly motivated by shorter-term commercialization. One primary mechanism that enables industry to collaborate with academia is NSERC-sponsored industry research grant programs. As discussed above, there are various types of NSERC funding available to academic researchers in science and engineering Canada. Section 5.2 looked at NSERC funding for university research overall. This section looks at NSERC matching funding for industry-sponsored academic research. Specifically, it focuses on two kinds of matched grants:

- Industrial Research Chair (IRC) Grants, which “[provide] funding for the salary of the Chairholder, infrastructure, research tools and instruments, and general expenses related to the Chair’s program of research;”<sup>61</sup> and
- Collaborative Research and Development (CRD) Grants, which “support well-defined projects undertaken by university researchers and their partners. Direct project costs are shared by the partner(s) and NSERC.”<sup>62</sup>

These programs benefit industry as well as academic researchers. The grants provide industry with additional support for exploring research questions. They also allow university faculty researchers to be certain that their research objectives align with industry needs and enable them to oversee larger teams of graduate students.

Table 2 summarizes the degree to which CNBC users are engaged in industry collaborations through IRCs or CRDs supported by NSERC.<sup>63</sup> CNBC statistics are benchmarked against the entire NSERC database. They are also contrasted against nuclear energy university faculty researchers (as described in Section 3.3).

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<sup>61</sup> Quoted from [http://www.nserc-crsng.gc.ca/Professors-Professeurs/CFS-PCP/IRC-PCI\\_eng.asp](http://www.nserc-crsng.gc.ca/Professors-Professeurs/CFS-PCP/IRC-PCI_eng.asp)

<sup>62</sup> Quoted from [http://www.nserc-crsng.gc.ca/Professors-Professeurs/RPP-PP/CRD-RDC\\_eng.asp](http://www.nserc-crsng.gc.ca/Professors-Professeurs/RPP-PP/CRD-RDC_eng.asp)

<sup>63</sup> Data represents the period from 2001–2018.

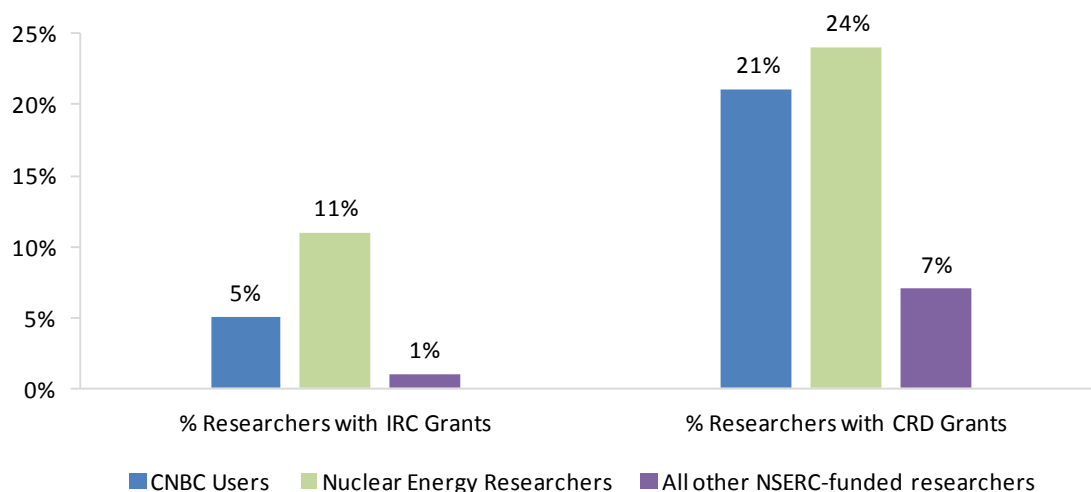
**Table 2 – Average Annual Number of IRCs and CRDs**

	Number of Professors with NSERC Grant				% of Professors with Grants in Canada	
	CNBC Users	Nuclear Energy Researchers	Rest of NSERC	Total	CNBC Users	Nuclear Energy Researchers
Any NSERC Grant	100	99	9801	10000	1.0%	1.0%
IRC Grant	5	11	119	134	3.6%	7.9%
CRD Grant	21	24	694	739	2.9%	3.2%
% IRCs	4.8%	11%	1.2%	1.3%		
% CRDs	21%	24%	7.1%	7.4%		

*Source: Strapolec analysis of NSERC funding database, values may not add due to rounding*

The results are summarized in Figure 37. CNBC users are more highly integrated with industry research than the average NSERC-funded researcher in Canada. Furthermore, only 1.2% of all NSERC-funded researchers are IRCs, whereas 4.8% of CNBC users are IRCs—a concentration that is four times greater.

**Figure 37 – Average Annual Proportion of Academic Researchers with IRC and CRD Grants as Compared to All Other NSERC-Funded Researchers in Canada**  
(% of Researchers)



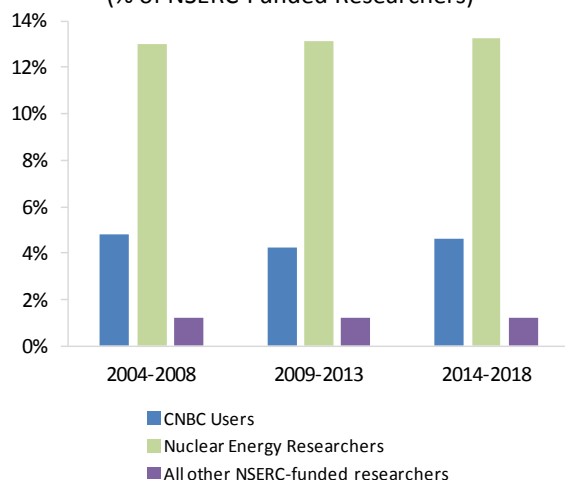
*Source: Strapolec analysis of NSERC funding database*

Figure 37 also shows that industry sponsorship of CNBC users is much higher than what is seen for other NSERC-funded researchers in Canada. In all, 21% of users conducting research at the CNBC were awarded CRD grants, which is three times greater than the 7% of all NSERC-funded researchers who received CRD grants. The nuclear energy researchers have a greater share of IRCs and CRDs, primarily due to this group being explicitly defined to include academic researchers with nuclear sector-sponsored IRCs and CRDs.

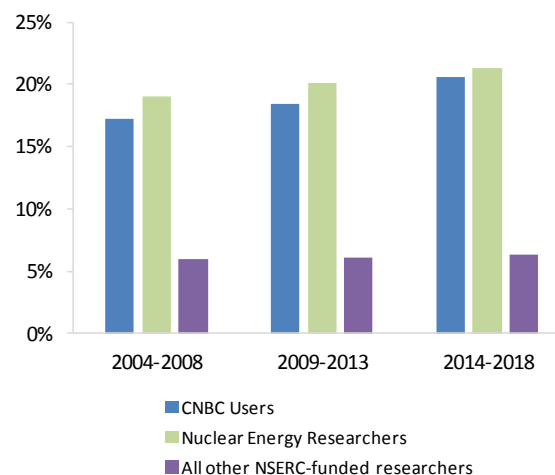
The results suggest that private companies sponsor more academic research carried out using CNBC-enabled capabilities as compared to other Science and Engineering research. This suggests that Canadian industry may be more likely to innovate or commercialize the findings from CNBC-related research.

Figures 38 and 39 show how the CNBC’s share of industry research collaborations changed over time. The CNBC user community’s engagement with industry remained at a consistently high level from 2004–2018. Over that same period, there was a steady increase in the percentage of CNBC users being sponsored by CRDs.

**Figure 38 – Change in Proportion of Researchers with IRCs, 2004–2018**  
(% of NSERC-Funded Researchers)



**Figure 39 – Change in Proportion of Researchers with CRDs, 2004–2018**  
(% of NSERC-Funded Researchers)



Source: Strapolec analysis

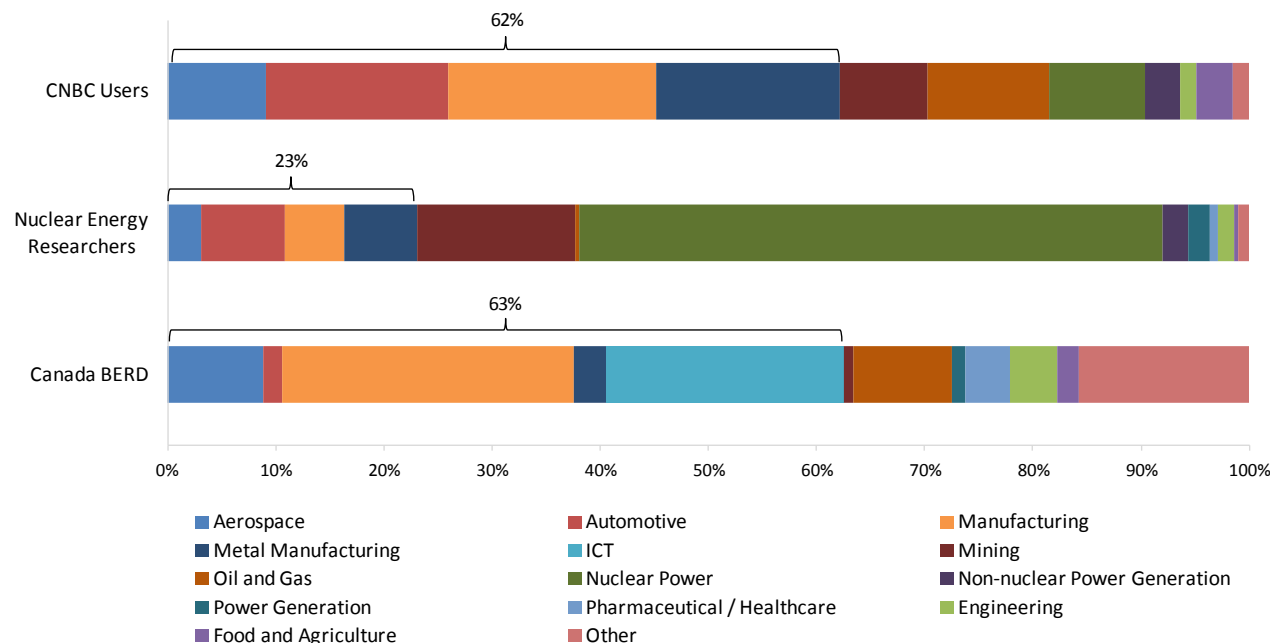
### 6.2.1 A Broad Cross-Section of Industry Applications

Figure 40 shows the mix of industry sectors that engaged in collaborative research with CNBC users from 2001–2018. This is compared to those sectors that engaged with nuclear energy researchers and to the overall dispersion of BERD expenditures by Canadian companies.

Industry sponsors of CNBC users’ research predominantly come from seven different industry sectors. The three largest sponsor sectors are the Automotive, Metal Manufacturing, and general Manufacturing sectors, which each provide almost 20% of industry funding for CNBC users. The Aerospace sector is another important sponsor, and taken together these four Manufacturing sectors represent 62% of industry collaborations at the CNBC. Other sponsor sectors of note include Mining, Oil and Gas, and Nuclear Power, which each provide 5%–10% of collaborative funding for CNBC users.

Industry funding for Nuclear Energy researchers is less concentrated in Manufacturing and more aligned with sponsors from the mining and nuclear power sectors. The large Nuclear Power share here is primarily a result of the type of researchers included in this group (i.e., predominantly university faculty who conduct research for the nuclear energy sector specifically).

**Figure 40 – Distribution of Industry Sponsors by Sector for the CNBC Compared to Nuclear Energy Researchers and Canada BERD Funding, 2001–2018**  
(% of Total Funding)



Source: Strapolec analysis of the NSERC funding database FY2001/02 to FY2017/18. Canada BERD data is the proportion of business R&D funding Canada-wide in 2011 with NAICS codes mapped to this industrial classification.

Canada's overall business R&D spending is concentrated in Manufacturing, reflecting 63% of all BERD expenditures, but its mix shows relatively high expenditures in Information and Communications Technology (ICT), general Manufacturing, and other categories. In contrast, the diversity of sectors within the CNBC's portfolio of collaborative research reflects a more balanced profile than R&D spending in Canada overall.

For sectors where industry sponsors fund more collaborative research at the CNBC than would be expected based on Canada's overall BERD spending trends, the CNBC-enabled research forms a greater portion of the overall R&D spending in those sectors. This is particularly noticeable for the Automotive and Mining sectors, which have relatively little business expenditure in R&D, but which spend a significant amount on collaborative research at the CNBC. This may be indicative of the nature of Canadian research, which tends to leverage academia, or the diverse capabilities of materials research, and specifically neutron beams, in advancing materials-based innovations in all sectors.

## 6.2.2 Importance of the CNBC to Industry-Sponsored Academic Research in Canada

The 2014 KPMG study conducted interviews with several CNBC users and provided a summary. Figure 41, extracted from the KPMG report, summarizes the views shared by a selection of academic researchers whose research spanned different sectors of the economy. They all emphasized the importance of the CNBC's materials research capabilities to their research,

which has led, or is expected to lead, to industrial applications, and they all expected a direct loss of research activity in Canada resulting from the CNBC's closure.

**Figure 41 – Case Studies: Academic Users of the CNBC**



Source: KPMG 2014

Even though the CNBC has ceased its operations, Canadian industry still has a need to conduct materials research using neutron beams. Without the CNBC, industry-sponsored researchers may have to seek access to facilities outside of Canada to support their activities.

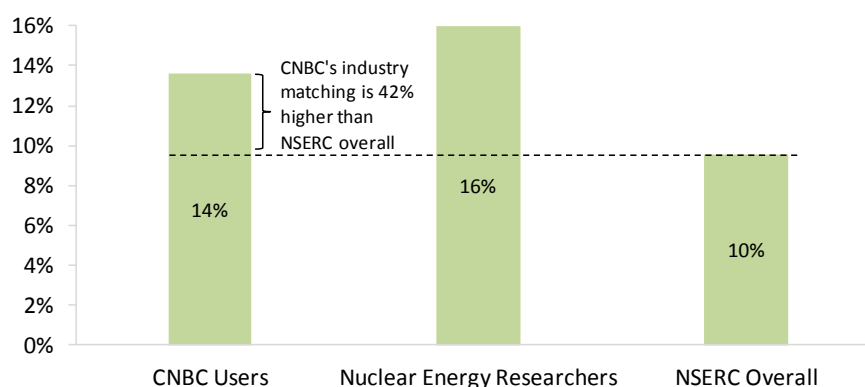
### 6.2.3 The Impact of Industry Collaboration on Funding Levels for Academic Research

Industry collaborative research funding enhances the research budgets available for university faculty researchers to pursue their research and to sustain a team of graduate students.

IRC and CRD grants have their NSERC research funding matched by industry sponsors.<sup>64</sup> The ratio of industry matching to total research funding for academic researchers who have received NSERC funding over a five-year period is shown in Figure 42.

Academic researchers conducting research at the CNBC have 42% more industry collaborative funding than NSERC-funded researchers overall, as Figure 42 shows.

**Figure 42 – Proportion of Industry Matching Funding to Total Research Funding (2008–2012)**  
(% of Total Research Funding)



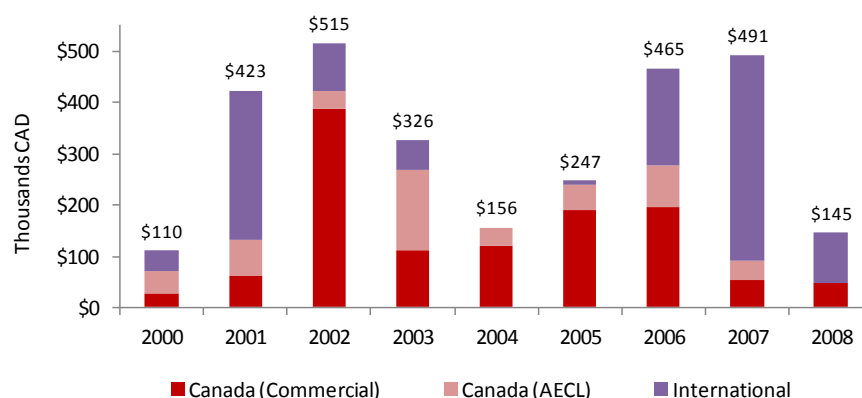
Source: Strapolec analysis of NSERC funding database FY2008/2009 to FY2012/2013

### 6.3 Direct Industry Commercial Use of the CNBC

Private companies engaged directly with the CNBC on a commercial basis to use its facilities to carry out their own research objectives. These proprietary research projects were carried out for companies in a variety of industries to improve products, determine the fitness-for-service of components, meet regulations, and enhance public safety. The distribution of the CNBC's commercial revenues from 2000–2008 is shown in Figure 43.

<sup>64</sup> This study assumes that industry and NSERC funding are matched 1:1 for IRC and CRD grants, while all other NSERC grants are not matched by industry funding. The proportion of industry-matched funding is the sum of the estimated industry funding for IRC and CRD grants divided by the sum of that industry funding and of all NSERC Discovery and Research Partnership grants for the relevant researchers.

**Figure 43 – Commercially Funded Research at the CNBC, 2000–2008**  
(Fees for Service in Thousands CAD)



Source: Strapolec analysis

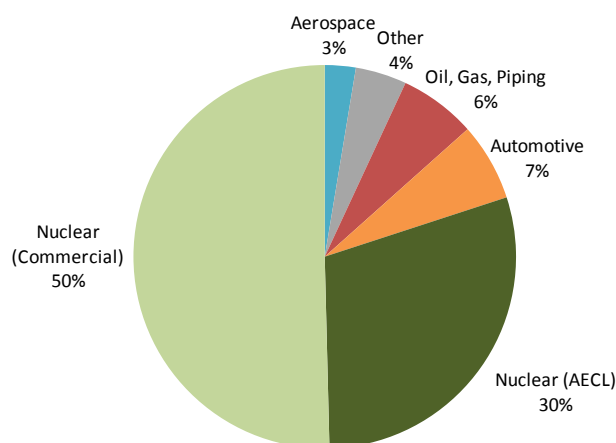
Direct commercial use of the CNBC occurred primarily before the NRU reactor’s unplanned shutdown in late 2007. This high-profile month-long shutdown was followed by a 15-month unplanned shutdown in 2009–2010. Commercial customers lost interest in partnering with the CNBC during those periods due to concerns for the NRU’s reliability, and later due to the knowledge of its impending closure after that was announced.<sup>65</sup> The CNBC had little direct commercial revenue after that time.

Approximately 60% of the CNBC’s commercial revenues were from Canadian customers. Figure 44 summarizes the nature of these domestic industry users. Most of the CNBC’s domestic fee-for-service revenue was derived from the nuclear energy industry, likely leveraging the capabilities available at CRL. The rest was primarily from the aerospace, automotive, and oil and gas sectors.

International industry users accounted for the remaining 40% of the CNBC’s commercial revenues. As Figure 45 shows, international commercial revenue was derived mostly from industry users in the U.S. (43%), but significant revenues were also received from industry users in Japan (32%) and Sweden (13%). The remainder of international commercial revenues were from industry users in Italy (5%), Australia (6%), and France (1%).

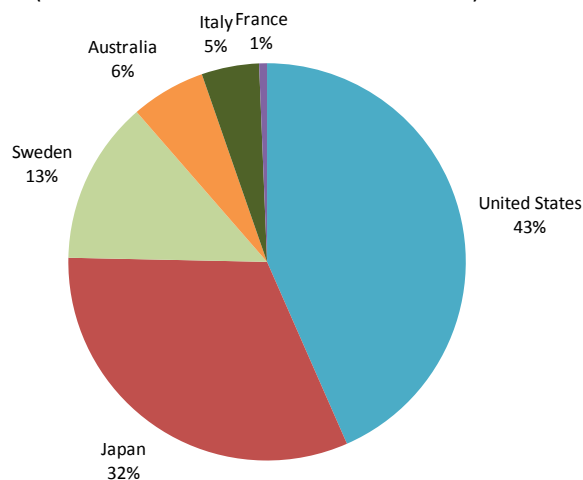
<sup>65</sup> CNBC interviews.

**Figure 44 – Domestic Commercial Revenue by Economic Sector, 2000–2008**  
(% of Domestic Commercial Revenue)<sup>66</sup>



Source: Strapolec analysis

**Figure 45 – International Commercial Revenue by Country, 2000–2008**  
(% of International Commercial Revenue)



Source: Strapolec analysis

<sup>66</sup> AECL revenue represents government-sponsored activities at AECL that made use of the CNBC. These have been estimated for illustrative purposes as 60% of all AECL-funded CNBC activities. The remaining 40% have been assumed to be on behalf of AECL's commercial clients.

### 6.3.1 Case Studies of the CNBC's Industry Users

Users who have accessed the CNBC for industry research purposes include Schlumberger, Ivaco Rolling Mills, AUTO-21, and Defence Research and Development Canada. Selected case studies of some of the industrial research projects carried out for industry at the CNBC were compiled in the 2014 KPMG report and are replicated in Figure 46.<sup>67</sup>

These case studies depict the benefits that companies have derived from their research engagements with the CNBC. Some of these industry users commented that the CNBC was the only facility capable of supporting their research.

**Figure 46 – Case Studies: Industry Users of the CNBC**



Source: KPMG summary of case studies provided by the CNBC (2014)

<sup>67</sup> More stories about the impacts arising from Canadian university and industry research using neutron beams have been published at <http://cins.ca/discover/>.

## **6.4 Conclusion**

A significant portion of the research conducted at the CNBC involved industry collaboration, which had a positive impact on Canada's ranking and status as an innovative economy. Academic users who performed research at the CNBC attracted a high proportion of collaborative industry research dollars from a broad cross-section of Canada's R&D investing sectors. Thus, the CNBC stood out as a highly industry-centric research facility.

Findings that emphasize the CNBC's industry-oriented nature include:

- CNBC-enabled research capabilities were crucial to industrial R&D in Canada;
  - Academic users of the CNBC were four times more likely to hold an Industrial Research Chair as compared to other NSERC-funded researchers in Canada;
  - Academic users of the CNBC attracted three times as many Collaborative Research and Development grants as compared to the average NSERC-funded researcher in Canada;
- Manufacturing, one of the key industry sectors critical to Canada's innovation scorecard, represented over 60% of the industry matching funds for university–industry collaborative grants awarded to CNBC users;
- The mix of industry sectors that made use of the CNBC was broadly distributed, with high sponsorship levels among the top four manufacturing sectors. This underscores the flexible nature of the CNBC's ability to support materials research that is relevant to multiple key industries; and
- 40% of directly funded commercial research at the CNBC was from international industry users, highlighting the CNBC's value as an international neutron beam user facility.

The CNBC's closure will likely hinder Canadian researchers' ability to conduct experiments in collaboration with industry. This will result in a loss of industry-sponsored research, which provides significant funding to Canada's research community and bolsters Canada's position as an innovative economy.

## **7.0 The CNBC's Contribution to HQP Development**

Section 4.0 introduced the WEF Innovation Index and identified that the availability of scientists and engineers is an important contribution to an innovative economy. The measure used to quantify that contribution is the deployment of Human Resources in Science and Technology (HRST). The highest level of HRST is Highly Qualified Personnel, which includes personnel with Master's or Doctorate degrees in science and technology. One of the important contributions that the CNBC has made over its lifetime is supporting the development of HQP.

This section looks at the student researchers<sup>68</sup> who attended the CNBC as part of their post-secondary education programs and assesses how their educations and careers developed since their time at the CNBC. It begins by characterizing these student researchers' sponsoring universities and programs of study. It then outlines the education levels they subsequently attained and their career outcomes in terms of their current sectors of employment, while also relating these trajectories to the point in their studies when they first attended the CNBC. This section closes with several case studies capturing the results of interviews with former student researchers (i.e., student alumni) to give additional insight into how their education and career trajectories were impacted by their experiences at the CNBC.

### **7.1 Characterizing the CNBC's Student Researcher Population**

The population of student researchers who attended the CNBC as part of their post-secondary education programs has been characterized in terms of several criteria:

- The location of the student researchers' sponsoring universities;
- The fields of study and degree levels they pursued; and
- The period of time they engaged with the CNBC.

#### *CNBC's Student Researchers by Province/Country of Origin*

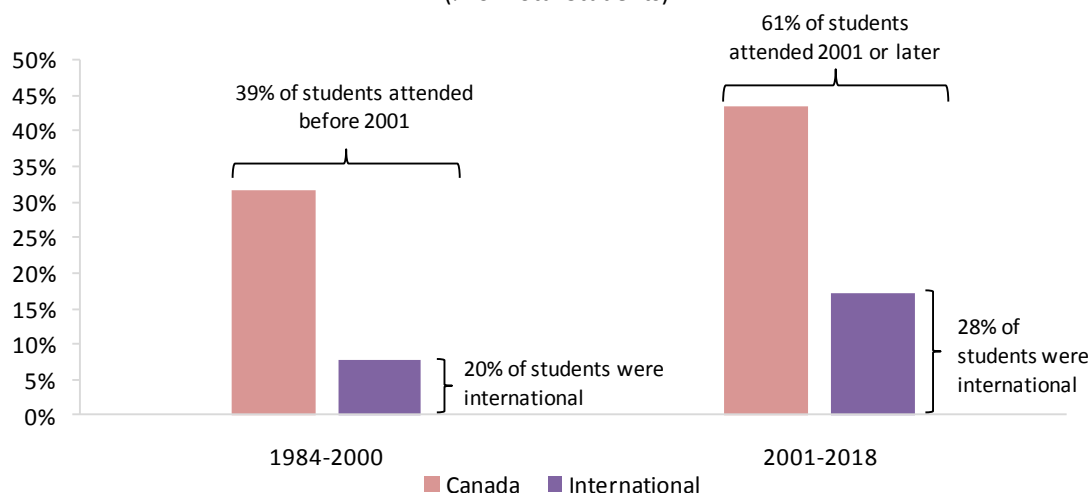
Student researchers came to the CNBC from many universities across Canada and around the world. CNBC records show that over 600 student researchers attended the facility from 1984–2018.<sup>69</sup> Figure 47 compares Canadian and international student researchers at the CNBC based on attendance before and after January 1, 2001.

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<sup>68</sup> Student researchers for the purposes of this report refers to all students who attended the CNBC while enrolled as post-secondary students. A portion of these students, particularly undergraduates, were co-op students or summer students conducting science camps who may not have conducted a specific research project at the CNBC but nonetheless gained valuable experience or training through their time at the CNBC.

<sup>69</sup> As not all such student visits were recorded, the CNBC estimates that about 1000 such students were trained at the CNBC over this period.

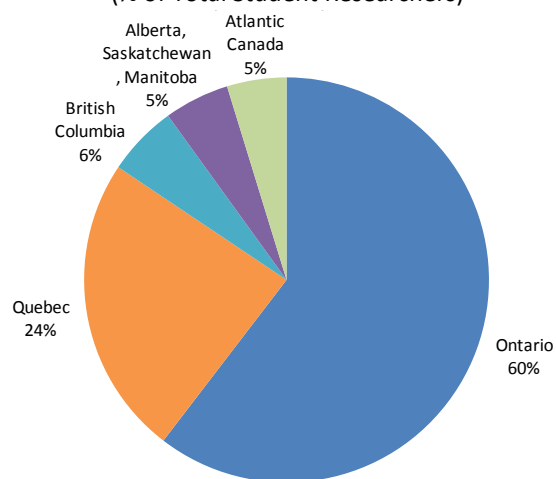
**Figure 47 – CNBC Student Researchers by Location of University and Time of Attendance**  
(% of Total Students)



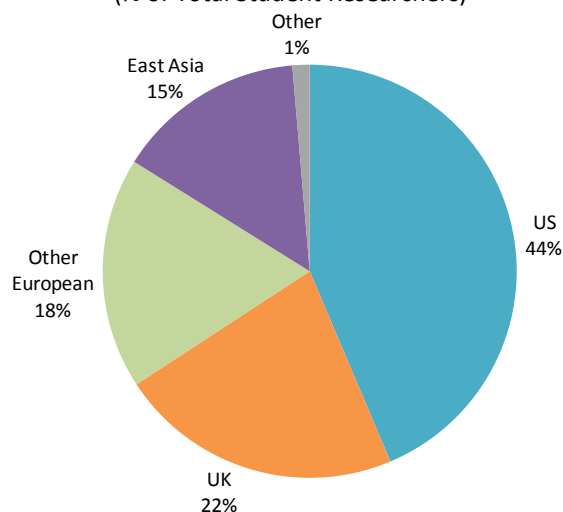
CNBC records indicate that as time progressed, the number of student researchers attending the CNBC increased. Of all student researchers at the CNBC from 1984–2018, 61% attended during the 2001–2018 timeframe—50% more student researchers as compared to the 1984–2000 period. This trend also applied to international student researchers, but at an even greater rate. Twenty percent of all student researchers at the CNBC from 1984–2000 were from other countries. This share grew to 28% for the period 2001–2018, corresponding to almost two and a half times as many international students total as compared to 1984–2000. This data shows that the CNBC’s contribution to HQP development grew over its lifetime.

Figures 48 and 49 summarize the location of the student researchers’ universities.

**Figure 48 – Distribution of Canadian Student Researchers at the CNBC by Province**  
(% of Total Student Researchers)



**Figure 49 – Distribution of International Student Researchers at the CNBC by Country**  
(% of Total Student Researchers)



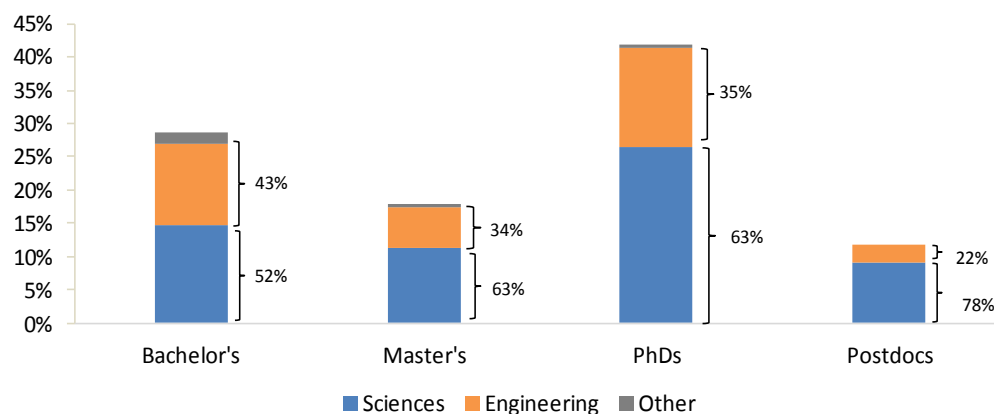
Source: Strapolec analysis

In all, 60% of Canadian student researchers came from universities in Ontario, 24% came from universities in Quebec, and 16% came from universities in the rest of Canada. Of all international student researchers, 44% came from the U.S., 24% came from the U.K., and the remainder came almost equally from the rest of Europe<sup>70</sup> and East Asia.<sup>71</sup>

### *Fields of Study*

Knowing the fields of study in which the student researchers were enrolled during their time at the CNBC is important to the discussion of the CNBC's contribution to HQP development in Canada, because both HRST and the Innovation Index score are dependent on the deployment of scientists and engineers.<sup>72</sup> Figure 50 shows the fields of study in which the student researchers were enrolled while attending the CNBC.

**Figure 50 – Fields of Study of CNBC Student Researchers by Degree Pursued While at the CNBC**  
(% of Total Student Researchers)



Source: Strapolec analysis

With respect to field of study, the majority of student researchers were pursuing Engineering or Science degrees while at the CNBC; less than 1% were pursuing degrees in other fields. These student researchers were in all stages of post-secondary education: About half were Bachelor's and Master's students, while the other half were either pursuing a PhD or were engaged in post-doctoral research.

### *Duration of Student Researcher Engagement*

Student researchers typically attended the CNBC to conduct experiments in support of their research theses. Some student researchers also attended summer and orientation programs at Chalk River, often as undergraduates. Most of the student researchers' time at the CNBC was devoted to data collection, after which they would return to their sponsoring universities to interpret and analyze the data. Generally, student researchers spent no more than a few weeks at

<sup>70</sup> Other European countries include: France, Belgium, Germany, Norway, Denmark, Russia, Armenia, Netherlands, Switzerland, and Italy.

<sup>71</sup> East Asia includes: China, South Korea, Taiwan, Japan; Other includes Australia and Mexico.

<sup>72</sup> While over 600 student researchers were identified as having attended the CNBC, internet research of publicly available data only uncovered the academic and employment histories of 230 of these students.

the CNBC facility. However, their engagement with the CNBC could last longer depending on their initial orientation and any further consultations or experiments they may have had with the CNBC.

Figure 51 summarizes the amount of time the student researchers spent engaged with the CNBC as a function of the level of degree they were pursuing while at the CNBC.

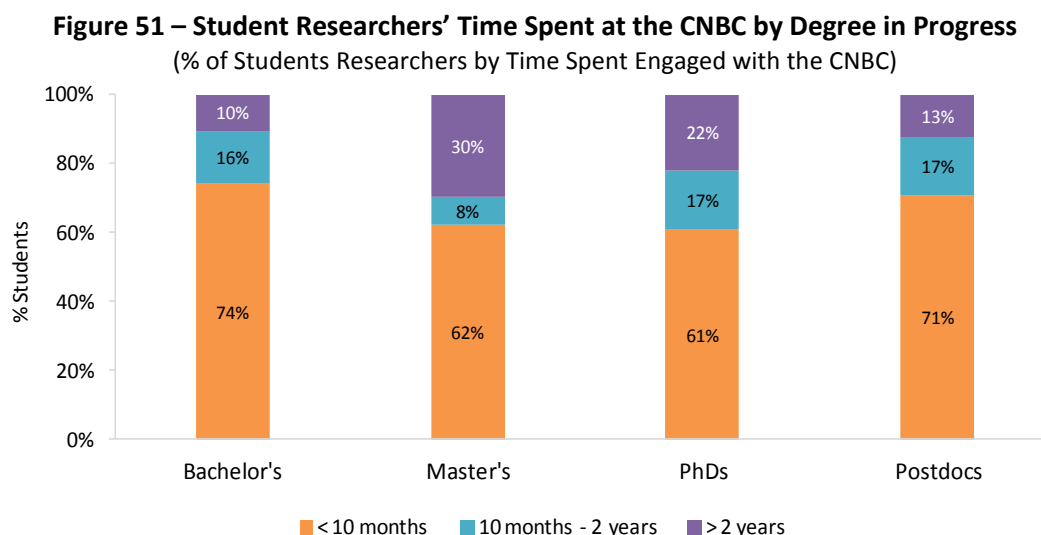


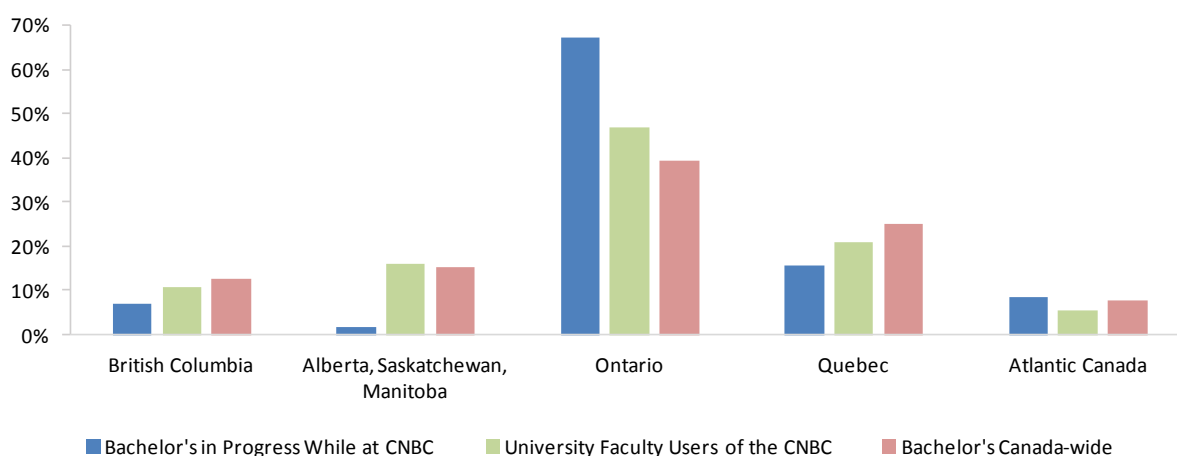
Figure 51 shows that the majority of all student researchers were engaged with the CNBC for less than 10 months. This suggests that their engagement focused on a single project that perhaps spanned an academic school year or less. In contrast, 38% of student researchers pursuing Master’s degrees and 39% of student researchers pursuing PhDs were engaged with the CNBC for more than 10 months, with the majority of these individuals engaged for more than two years, presumably because research becomes more specialized and complex for graduate level projects.

## 7.2 Regional Distribution of CNBC Student Researchers

The majority of Canadian student researchers came from sponsoring universities in Ontario, as illustrated in Figure 48. However, this subsection examines the regional distribution of the student researchers according to the degree they were enrolled in while at the CNBC, and finds that the graduate student researchers reflect a more proportionate distribution of the universities across Canada.

Figure 52 illustrates the regional distribution of Bachelor’s student researchers at the CNBC in contrast to the distribution of university faculty researchers at the CNBC, as well as the overall distribution of Bachelor’s students nationwide.

**Figure 52 – Regional Distribution of Bachelor’s Student Researchers at the CNBC vs. University Faculty Researchers at the CNBC and Bachelor’s Students Canada-Wide**  
(% of Total)



Source: CNBC, Statistics Canada Table 37-10-0030-01, Strapolec analysis

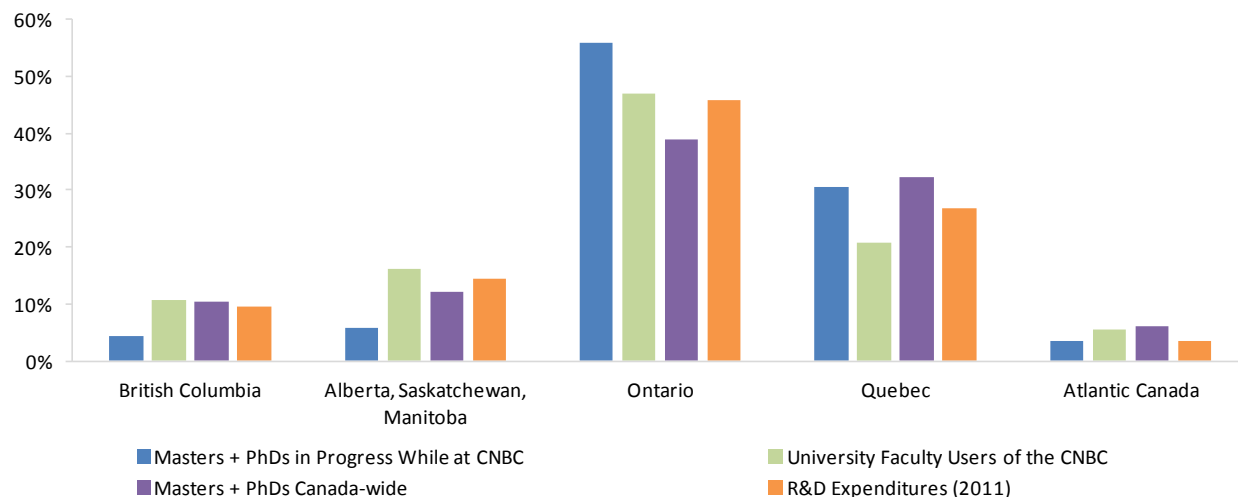
The results show that Bachelor’s students from Ontario universities were more likely to attend the CNBC as compared to Bachelor’s students from other regions in Canada, despite the fact that university faculty users of the CNBC were more proportionately represented from across Canada.

Bachelor’s students typically have less available time during the school year to travel for research, and university faculty have fewer budget resources to support travel for Bachelor’s students.<sup>73</sup> The regional bias towards Ontario Bachelor’s students may be due to their relatively close proximity to Chalk River, whereas it would be more difficult and expensive for Bachelor’s students from other provinces or territories to travel there.

When just Master’s and Doctoral student researchers are considered, the pattern aligns more directly with Canada’s regional distribution of students in general. Figure 53 illustrates the regional distribution of graduate student users of the CNBC as compared to university faculty users of the CNBC, along with the distribution of all Master’s and PhD graduates and of R&D expenditures across Canada.

<sup>73</sup> However, these two factors are not as limiting for graduate students.

**Figure 53 – Regional Distribution of Master’s and PhD Student Researchers at the CNBC vs. University Faculty Users of the CNBC vs. Master’s and PhD Graduates and R&D Expenditures Canada-Wide**  
(% of Total)



*R&D Expenditures include only R&D in Natural Sciences and Engineering.*

*Source: Statistics Canada Table 37-10-0030-01 (2011 data) and Table 27-10-0273-01 (2011), Strapolec analysis*

Two interesting observations are apparent in Figure 53. First, the distribution of university faculty users of the CNBC tracks the regional distribution of R&D expenditures in Canada’s economy, with the notable exception of Quebec, which could be considered underrepresented in terms of university faculty researchers at the CNBC.

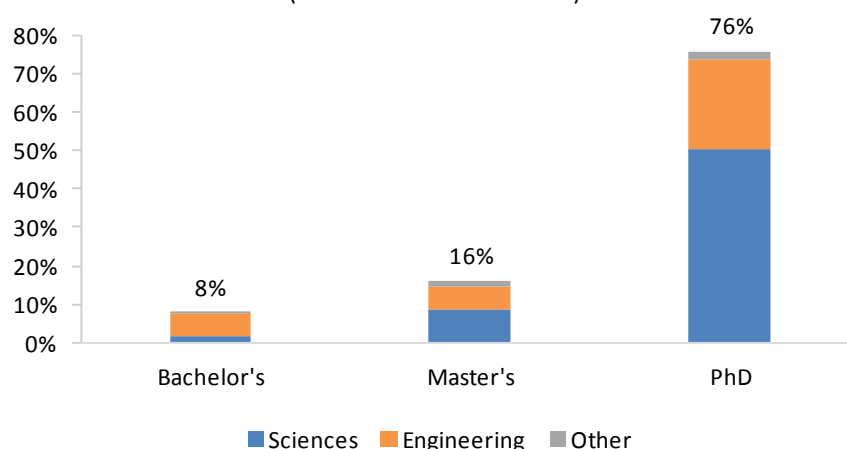
Second, the distribution of graduate degree holders in Canada is also somewhat reflective of R&D spending across the country, with the distribution of CNBC university faculty researchers somewhat informing the distribution of CNBC student researchers. Quebec is home to a high proportion of graduate degree holders, which matches Canada’s high R&D spending in that province and which could also contribute to Quebec’s higher than expected number of student researchers at the CNBC. Similarly, the CNBC’s lower uptake of graduate student researchers from Western Canada is in sync with lower R&D expenditures as compared to university faculty researchers at the CNBC and is likely also related to university faculty having to consider the higher cost of sending their students to the CNBC. The underrepresentation of CNBC graduate student researchers from Western Canada may also be indicative of the opportunity to pursue materials research at TRIUMF in Vancouver or the CLS in Saskatchewan. By contrast in Atlantic Canada, there is no such national facility for materials research comparable to the CNBC, TRIUMF, or the CLS, and graduate students from Atlantic Canada use the CNBC at a higher proportion than would be predicted by the R&D expenditures or by the distribution of all Master’s and PhD graduates. These observations suggest that university faculty researchers use the CNBC, as well as TRIUMF and the CLS, to assist in the hands-on training of their students because such facilities offer research capabilities not available elsewhere.

### 7.3 Fields of Study and Educational Attainment of CNBC Student Researchers

This section examines the educational progression of CNBC student researchers and looks at the fields of study they tended to pursue.

Figure 54 illustrates the highest degree attained by CNBC student researchers, regardless of the degree in progress at the time of their attendance. The results show that 76% of CNBC student researchers eventually attained a PhD, predominantly in Sciences or Engineering. Another 16% earned a Master's degree as their highest degree, and only 8% earned a Bachelor's degree as their highest degree. Further, 82% of Science student researchers eventually obtained a PhD, and 60% of Engineering student researchers obtained a PhD.

**Figure 54 – Highest Degree Attained by CNBC Student Researchers by Field of Study**  
(% of Student Researchers)



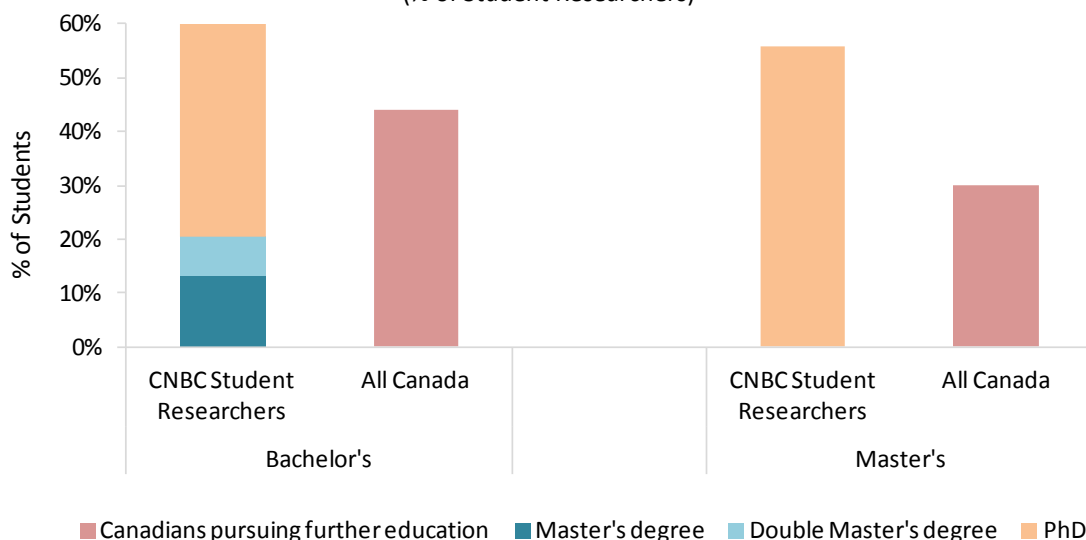
Source: Strapolec analysis

Figure 54 shows that over 90% of the CNBC student researchers eventually earned a Master's or PhD degree, even though about half were Bachelor's or Master's students at the time they came to the CNBC, as shown in Figure 50. This is a strong reflection of the higher educational aspirations developed by those who were exposed to the research environment at the CNBC.

Figure 55 examines these higher aspirations among the student researchers who were Bachelor's or Master's students at the time they came to the CNBC. Of the Bachelor's students, 60% earned a graduate degree. In fact, many went beyond a single Master's degree: 40% of the Bachelor's students who attended the CNBC later achieved a PhD, and another 14% earned two Master's degrees. These rates of academic achievement are far higher than is typical for Canada as a whole: Only 44% of all Bachelor's students in Canada who are surveyed upon graduation stated intention to pursue further education of any kind (as shown in Figure 55), and the percentage of such students who do end up attaining higher degrees is expected to be much lower.

Similarly, of the student researchers who were Master's students at the time they came to the CNBC, 56% later earned a PhD. In contrast, only 30% of all Master's students in Canada who are surveyed upon graduation state intention to pursue of any kind (as shown in Figure 55),

**Figure 55 – Highest Degree Attained by CNBC Student Researchers with Bachelor's or Master's Degrees In Progress While at the CNBC**  
(% of Student Researchers)



Source: Statistics Canada Table 37-10-0030-01, Strapolec analysis

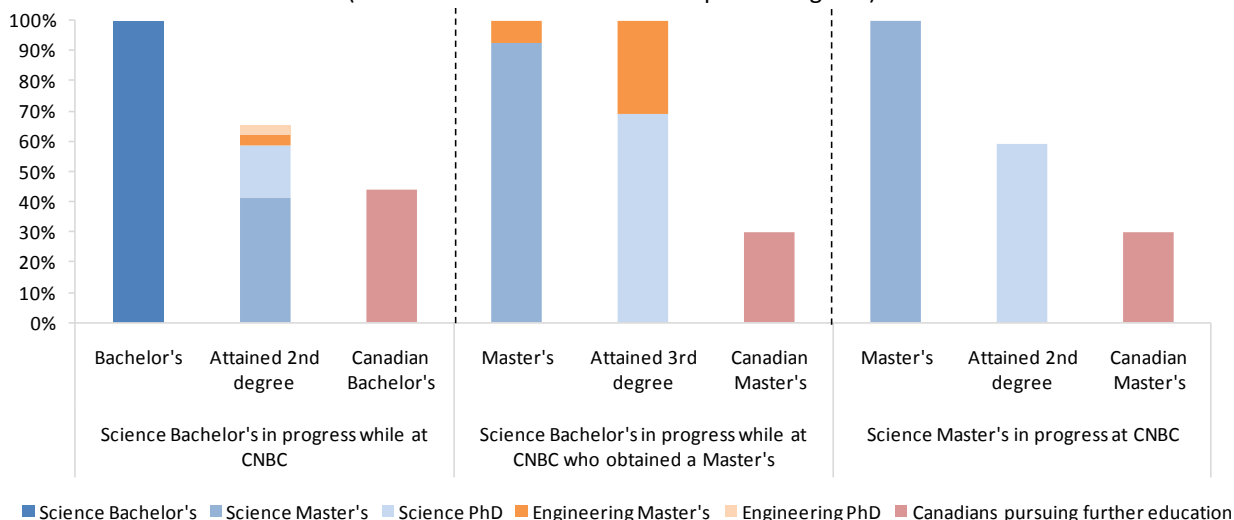
\* Canada-wide data is an average of Canadian Bachelor's and Master's graduates saying they intend to pursue further education 2000, 2005, and 2010.

Figures 56 and 57 examine the higher educational aspirations of these students in more detail. They illustrate the career progressions of Engineering and Science student researchers, respectively, grouped by the degrees they were pursuing during their time at the CNBC. The data shows that for CNBC student researchers pursuing their Bachelor's degrees while at the CNBC, some Science students changed streams and pursued a Master's of Engineering, and some Engineering students went on to pursue a Master's of Science. Changing streams was significantly more common among Bachelor of Engineering student researchers; however, in this sample, those Engineering students who switched to a Master's of Science did not tend to obtain a PhD in Science.

Of the student researchers who (1) attended the CNBC while earning a Bachelor of Science degree and then (2) proceeded to earn a Master's degree, 100% went on to obtain a third degree, either a second Master's degree (31%) or a PhD (69%)—which is well above the Canadian educational norm. In contrast, of the student researchers who (1) attended the CNBC while pursuing a Bachelor of Engineering degree and who then (2) attained a Master's degree, only 25% ended up progressing to a PhD.

Considering students who were in Master's programs while visiting the CNBC, more Master of Science students than Master of Engineering students advanced to obtain a PhD, but both groups significantly exceeded Canadian norms in terms of the number that went on to pursue Doctorate degrees.

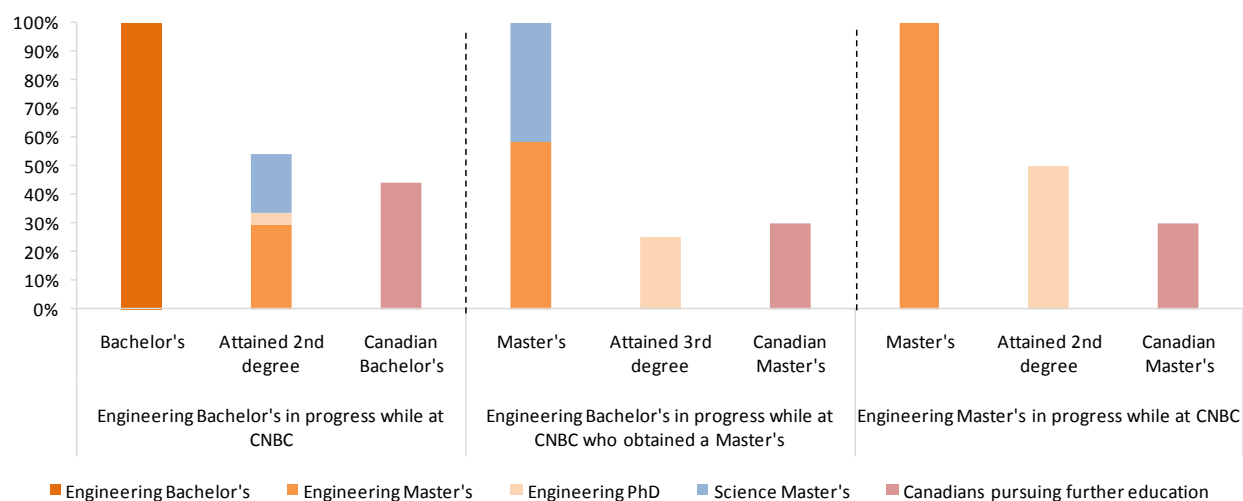
**Figure 56 – Degree Pathways for Science Student Researchers Who Attended the CNBC**  
(% of Student Researchers with Specific Degrees)



Source: Statistics Canada Table 37-10-0030-01, Strapolec analysis

\* Canada-wide data is an average of Canadian Bachelor's and Master's graduates saying they intend to pursue further education 2000, 2005, and 2010.

**Figure 57 – Degree Pathways for Engineering Student Researchers Who Attended the CNBC**  
(% of Student Researchers with Specific Degrees)



Source: Statistics Canada Table 37-10-0030-01, Strapolec analysis

\* Canada-wide data is an average of Canadian Bachelor's and Master's graduates saying they intend to pursue further education 2000, 2005, and 2010.

## 7.4 Deployment of CNBC Student Alumni in Canada's Economy

This section summarizes the current employment of CNBC student alumni (i.e., former CNBC student researchers) and describes how that employment relates to measures of an innovative economy. It also tracks the progression of the alumni's education and career trajectories since their time at the CNBC.

The results are presented from three perspectives:

- HRST deployment in Canada and globally;
- Deployment of CNBC-trained HQP generally; and
- Deployment of CNBC-trained HQP in Canada's R&D-intensive sectors.

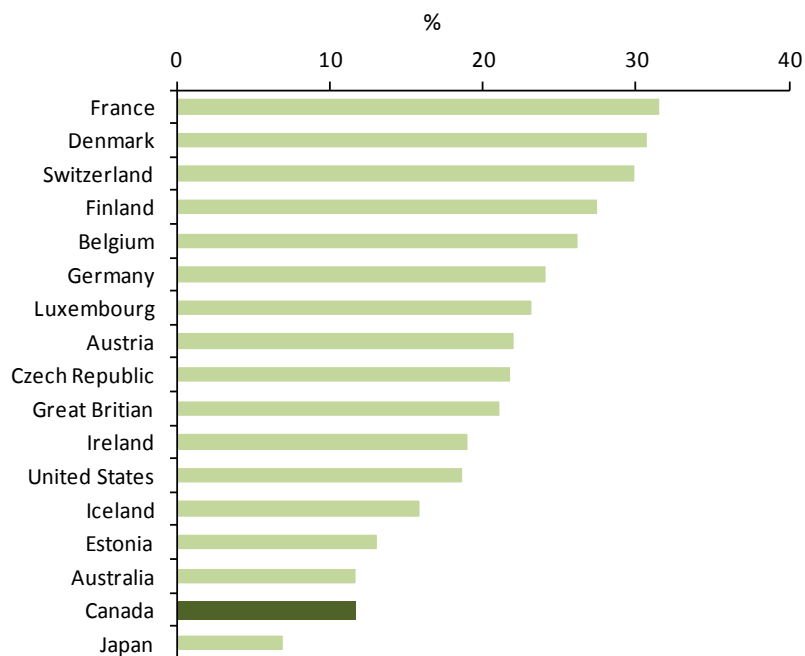
### *HRST Deployment in Canada and Globally*

The availability of scientists and engineers to explore advances that enable innovation is a vital element of an innovative economy and its economic growth. The WEF uses the employment of HRST as an element of its Innovation Index.<sup>74</sup>

Figure 58 summarizes the Organisation for Economic Co-operation and Development's (OECD) S&T Scoreboard<sup>75</sup> for HRST deployment. HRST employees represent 11.5% of total employment in Canada's manufacturing sector, putting Canada in twenty-fourth place, among the lowest of all OECD countries.

**Figure 58 – Manufacturing HRST in OECD Countries, 2008**

(% of Total Manufacturing Employment by Country)

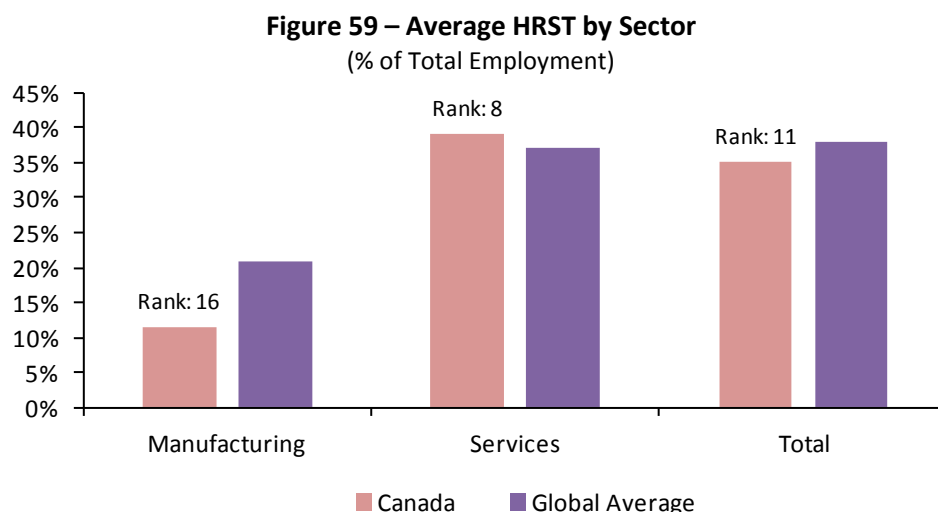


Source: OECD 2013

<sup>74</sup> HRST is defined as persons who graduated at the post-secondary level of education or who are employed in an S&T occupation for which a high qualification is normally required and innovation potential is high. In terms of occupational data, HRST comprises Professionals (ISCO Group 2) and Technicians and Associate Professionals (ISCO Group 3) in physical and engineering science, life sciences and health, teaching, and other areas.

<sup>75</sup> OECD 2013.

Figure 59 shows that in Canada, the deployment of HRST is dominated by employment in the services industry, in which 39% of human resources are HRST. A higher concentration of HRST employees in the services industry is common across all OECD countries. Canada does not lack an educated workforce; however, low HRST deployment within the manufacturing sector in Canada impacts the nation's effectiveness as an innovative economy.



The ongoing development of future HQP contributes to sustaining a nation's HRST. Both innovation and economic growth are dependent on a stock of highly skilled human capital that supplies the labour market and helps in the diffusion of advanced knowledge.<sup>76</sup> Therefore, the fact that 80% of CNBC student alumni attained a PhD – see Figure 54 – means that the CNBC provides a significant contribution to HQP development in Canada.

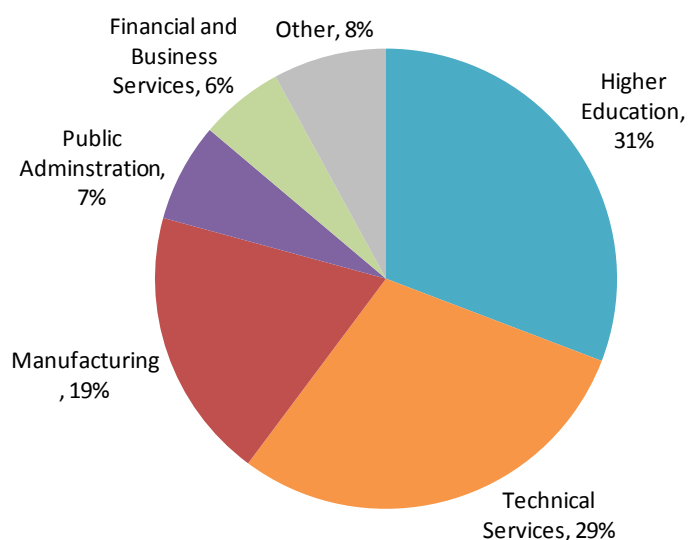
#### *Deployment of CNBC-Trained HQP*

Figure 60 summarizes where CNBC student alumni are currently employed. Almost 80% of all alumni enter three career areas: 31% are employed in higher education/academia; 29% are employed in Technical Services<sup>77</sup>; and 19% are employed in manufacturing. The remaining 21% are employed in other areas of the economy. Of the alumni who are not employed in academia, almost 30% are employed in manufacturing.

<sup>76</sup> McKenzie, M. (Statistics Canada) 2008.

<sup>77</sup> Technical Services is defined for the purposes of this report as a grouping of three industries in the North American Industry Classification System: Architectural, engineering and related services (NAICS 5413), Management, scientific and technical consulting services (NAICS 5416), and Scientific research and development services (NAICS 5417).

**Figure 60 – Most Recent Employment of CNBC Student Alumni by Economic Category**  
(% of Student Alumni)



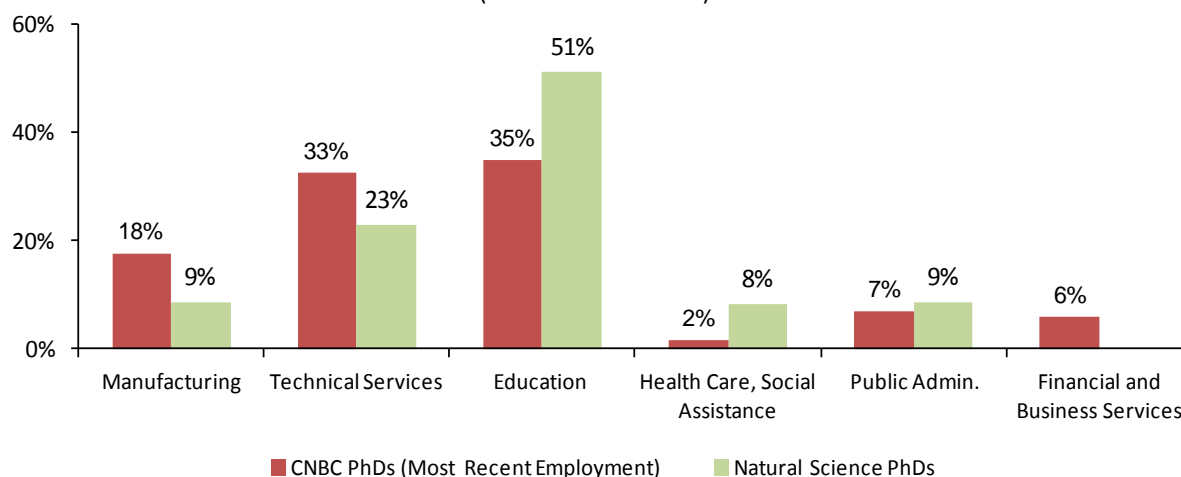
*Source: Strapolec analysis*

Figure 61 shows that the employment of CNBC student alumni with PhDs differs from the population of natural sciences PhDs in Canada overall.<sup>78</sup> Over half of all Canadian PhD graduates seek careers in education, including academia, and 32% pursue employment in Manufacturing or in Technical Services. In contrast, only 35% of CNBC alumni with PhDs have pursued careers in Education,<sup>79</sup> while 51% are employed in Manufacturing or in Technical Services.

<sup>78</sup> The categories of employment for CNBC student alumni used in Figure 60 were slightly altered from those used in Figure 59 to better match those used by Statistics Canada. The Other category was broken up to expand the Higher Education category into Education in general and to create a category for Health Care and Social Assistance.

<sup>79</sup> The vast majority of CNBC student alumni in education are employed in post-secondary education/academia specifically ('Higher Education'), as Figure 59 suggests.

**Figure 61 – Distribution of CNBC Student Alumni PhDs vs. All Natural Science PhDs by Industry of Employment**  
(% of PhD Graduates)

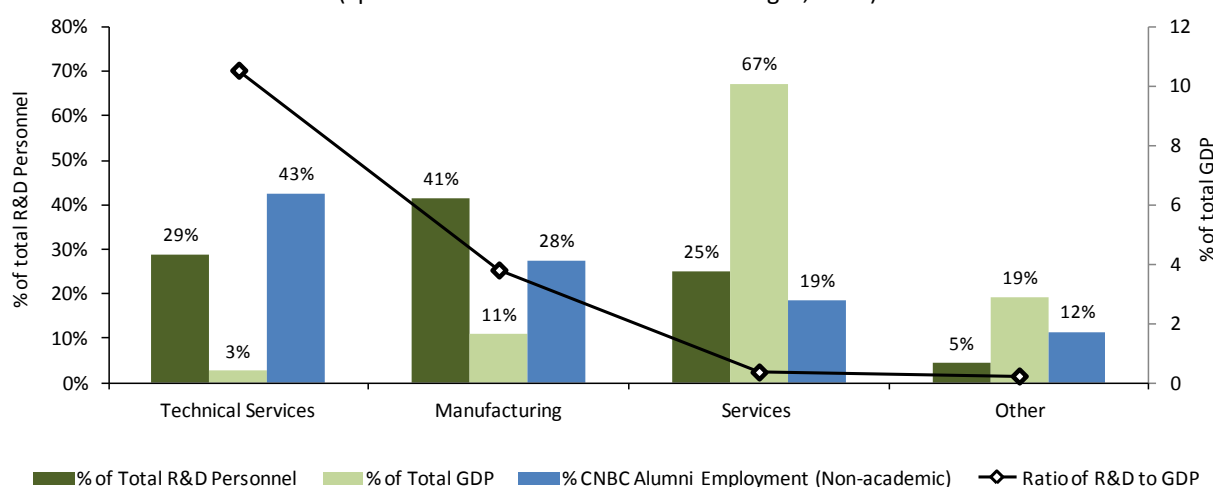


Source: Statistics Canada, National Graduates Survey (Class of 2005) (Figure reproduced from Desjardins and King 2011), Strapolec analysis

### *CNBC-Trained HQP Deployment in Canada's R&D-Intensive Sectors*

Another aspect of measuring the effectiveness of HRST is the employment of R&D personnel in the economy. Figure 62 shows that in 2011, manufacturing employed 41% of total R&D personnel in Canada, even though it represented only 11% of total Canadian GDP. Technical Services represented 29% of total R&D personnel, but less than 3% of GDP. Services represented 25% of total R&D personnel, but 67% of GDP.<sup>80</sup>

**Figure 62 – R&D Personnel by Sector in Canada**  
(Specific Sectors of Canadian R&D Strength, 2011)



Source: Statistics Canada Table 27-10-0002-01 and Table 27-10-0273-01, Strapolec analysis

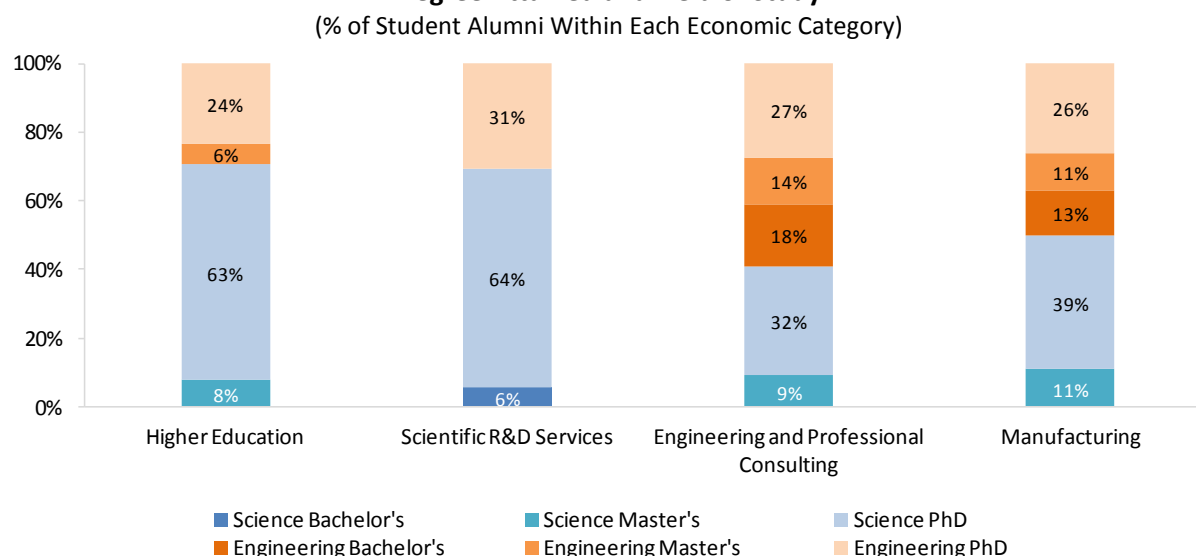
<sup>80</sup> Other refers to: Agriculture, forestry, fishing and hunting; mining and oil and gas extraction; total utilities; and construction

As Figure 62 shows, CNBC student alumni have gravitated to where Canada needs R&D skills the most: Technical Services, as well as manufacturing. These results clearly show that the CNBC has been an important provider of HRST to Canada's industrial R&D infrastructure.

## 7.5 Career Progression of CNBC Student Alumni

Figure 63 illustrates the current employment of CNBC student alumni across the three main sectors in which they are typically employed and indicates the differences between their highest degree earned and their general field of study (Science versus Engineering). The figure has split the Technical Services sector into two groups: (1) Engineering and Professional Consulting, and (2) Scientific Research and Development (R&D) Services.<sup>81</sup>

**Figure 63 – Breakdown of Most Recent Employment Category for CNBC Student Alumni by Highest Degree Attained and Field of Study**



Source: Strapolec analysis

Figure 63 shows a marked difference in the mix of CNBC alumni who seek employment in these three main sectors. Of all the CNBC alumni employed in higher education/academia or in Scientific R&D Services, about 70% were Science graduates. Of the alumni employed in Engineering and Professional Consulting, 60% were Engineering graduates. Manufacturing is nearly an even split between Science and Engineering graduates.

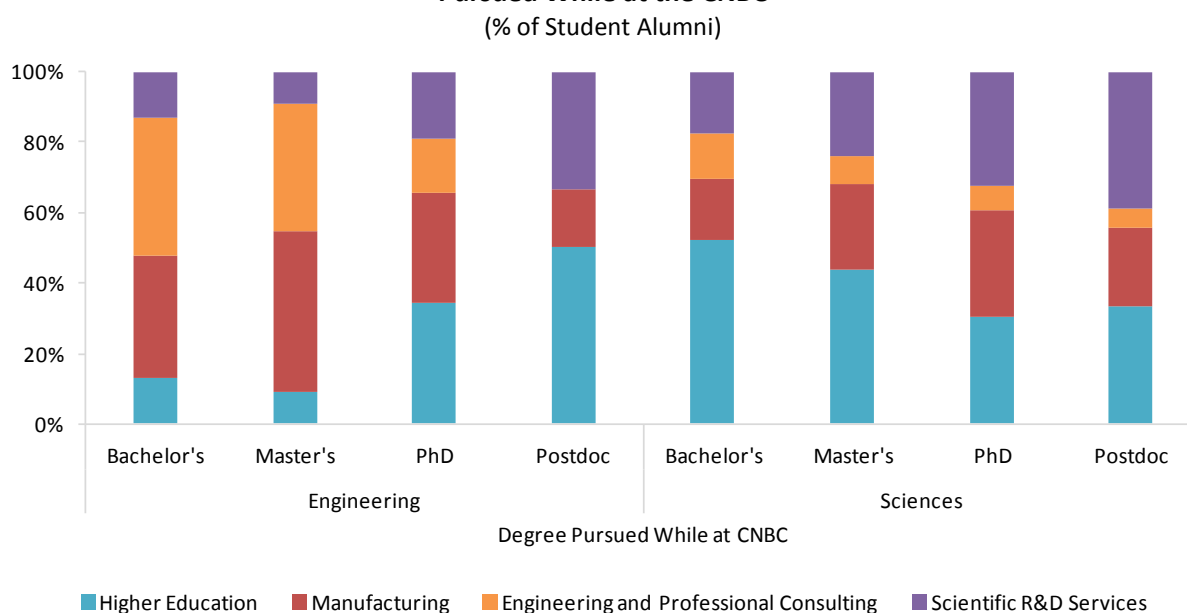
CNBC alumni who work in higher education/academia or in Scientific R&D Services predominately have a PhD, which is the case for both Science and Engineering graduates. The Engineering workforce in both Engineering and Professional Consulting and manufacturing captures all undergraduate Engineering alumni and most Master's Engineering alumni.

<sup>81</sup> Engineering and Professional Consulting for the purposes of this report consists of NAICS 5413 – Architectural, engineering and related services and NAICS 5416 – Management, scientific and technical consulting services. Scientific R&D is NAICS 5417 – Scientific research and development services.

Figure 64 examines the breakdown of alumni employment as a function of the degree they were pursuing while at the CNBC, with a focus on the three major areas in which alumni are employed.<sup>82</sup> Alumni who were pursuing a Bachelor's or Master's degree in Engineering while at the CNBC tend to find employment in industry, which is perhaps reflective of the applied science nature of Engineering studies. In contrast, alumni who were pursuing a Bachelor's or Master's degree in Sciences demonstrate a bias towards finding roles in higher education/academia, perhaps indicative of the pure science focus of Sciences programs. Interestingly, employment trends for alumni who were engaged in PhD and postdoctoral research while at the CNBC are the reverse, with a greater percentage of Engineering alumni seeking employment in academia as compared to Science alumni.

Figure 65 summarizes the level of seniority of the most recent employment positions attained by CNBC student alumni as a function of the number of years that have passed since they attended the CNBC. As would be expected, alumni with greater years of experience tend to fill more senior positions, while more recently graduated alumni have a greater share of non-supervisory positions.

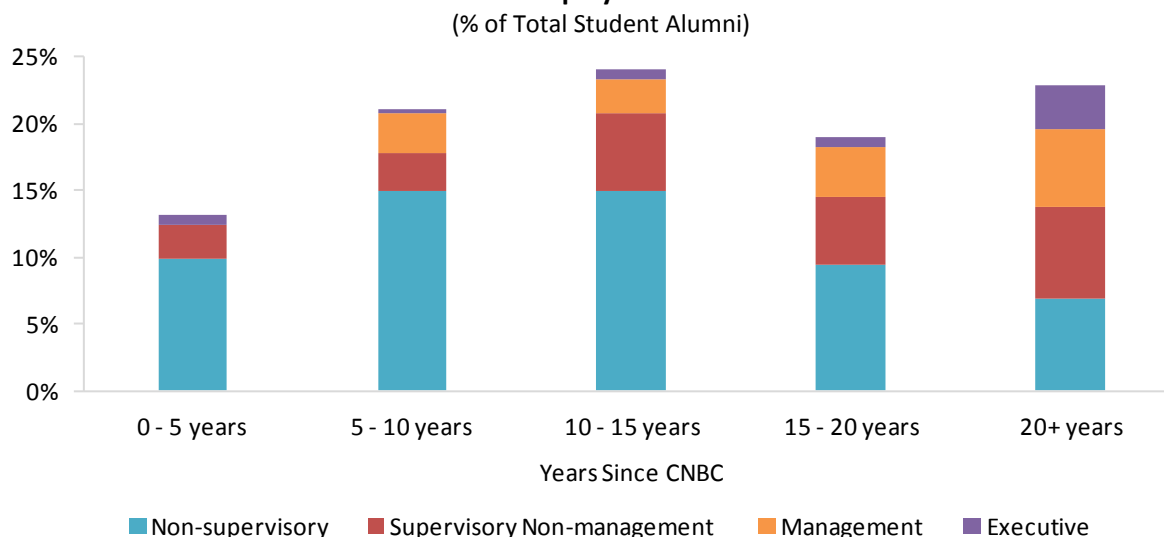
**Figure 64 – Breakdown of Most Recent Employment Category for CNBC Student Alumni by Degree Pursued While at the CNBC**



Source: Strapolec analysis

<sup>82</sup> Again, the figure has split the Technical Services sector into two groups: Engineering and Professional Consulting and Scientific R&D Services.

**Figure 65 – CNBC Student Alumni by Years Since Attending the CNBC and Seniority at Most Recent Employment**



Source: Strapolec analysis

## 7.6 Interviews with CNBC Student Alumni

A number of student alumni were interviewed to gain insight into how their careers have been impacted by their experience at the CNBC. Alumni were selected to cover a broad mix of backgrounds, career paths, and timeframes. From these interviews, several common themes emerged, as well as specific insights that highlight the impact of their CNBC experience. The specific insights are captured in student alumni profiles (see Section 7.6.2).

### 7.6.1 Common Themes from Interviews

During the course of the student alumni interviews, several features of the CNBC emerged as having been impactful.

#### 1. A complex, prestigious national laboratory environment

Alumni found the CNBC to be a prestigious national laboratory, with highly skilled researchers from around the world engaged in using large-scale state-of-the-art facilities to perform novel experiments. The alumni highlighted the high quality of science they saw at the CNBC. They learned from the CNBC staff's approach to operating in a complicated research facility, and they brought that knowledge with them into their careers.

#### 2. Specialized materials research tools and techniques

Experience at the CNBC taught alumni valuable skills and knowledge about materials research. Use of tools and techniques that were only available at the CNBC contributed materially to their theses, often in a manner that was vital to their successful completion.

### **3. Disciplined skills**

The exposure to disciplined scientific research methods, the focus on attention to detail, and the necessity of thoughtfulness while preparing experiments for limited beam time carried forward in both the academic and private sector careers of alumni.

### **4. Focus on industry-centric research**

Many alumni felt that the exposure to professional scientists who were focused on industry-oriented research was a paradigm shift. Such a focus was not common in academic settings. This industry-oriented approach taught alumni the value of applied science in such a tangible manner that it shaped their approach to their jobs as they moved into the private sector.

### **5. Experience led to jobs**

While many factors in the alumni's educational experiences came into play to influence their final career decisions, many alumni identified a direct connection between their time at the CNBC and not only their first jobs, but also their entire career paths. Others commented that their PhD research using the CNBC directly led to jobs in fields related to that research. The remaining alumni conveyed that their experience at the CNBC became an asset after their studies and had an influence on their outlook for employment prospects.

### **6. A culture of safety and security**

The CNBC's culture of safety and security permeated the conduct of all activities at the facility. This was memorable to the alumni and remained with them afterwards. These skills were particularly valuable in a variety of industry sectors, including oil and gas and pharmaceutical manufacturing.

### **7. The people of the CNBC**

All alumni expressed gratitude for the experienced, professional, knowledgeable, and supportive CNBC staff members, who were recognized as being warm, respectful, and willing to help in all aspects of the alumni's attendance at the facility. Alumni reflected that the staff not only impacted the success of the experiments, but also enriched their entire experience. The alumni emphasized the level of respect between themselves and the CNBC scientists during their collaborations.

### **8. An unforgettable opportunity**

All alumni said their experience at the CNBC was positive and unforgettable, and they expressed pride for having attended the facility.

#### **7.6.2 Student Alumni Profiles**

The CNBC's impact on alumni varied depending on their path after education. Individual perspectives on the impact of the CNBC are provided in Figure 65. The interviewed alumni attended the CNBC at different times over its history and are currently employed in a broad range of sectors.

Figure 66 – Case Studies: CNBC Student Alumni

<b>Dr. Thomas Mason</b> At CNBC: 1987-1990 Director of a U.S. national laboratory Scientific R&D	Investments in the CNBC encouraged Dr. Thom Mason to attend McMaster University, which provided access to the CNBC. The knowledge he subsequently gained at the CNBC regarding materials research using neutron beams was crucial to his career. Mason used the CNBC again as a university faculty researcher. Later, new investments at Oak Ridge National Lab attracted him to the U.S. <i>"The CNBC had a big influence on my life and I wouldn't have become the scientist I am today without it."</i>	<b>Dr. Riaz Sabet-Sharghi</b> At CNBC: 1995-1999 VP of Technology Oil and Gas	Without access to the CNBC, Dr. Riaz Sabet-Sharghi's PhD "would not have been possible." His time at the CNBC remains relevant to his current research in non-destructive testing technologies for pipelines. Sabet-Sharghi says the CNBC taught him the importance of attention to detail in research and the need to take safety seriously. <i>"From a research perspective, the CNBC was a gold mine whose research capabilities are irreplaceable."</i>
<b>Prof. Chris Wiebe</b> At CNBC: 1997-2002 Professor and Tier II Research Chair Academia	Use of the CNBC's neutron facilities was important to Prof. Chris Wiebe's over 120 publications. CNBC experience taught him how to think critically, interpret data, and select research topics. The CNBC's closure puts Wiebe's research program at risk and results in a loss of assets for Canada's next generation of researchers. <i>"Every major industrialized country has a neutron source other than Canada, and Canadian scientists will be begging for access to overburdened international facilities."</i>	<b>Rebecca Toda Worden</b> At CNBC: 2008 Senior Manager Finance	Experience with neutron beam diffraction was an important asset that helped Rebecca Toda Worden gain a job in nuclear engineering after graduating from her Master's program. The skills and research method she developed at the CNBC have been useful in her later career in the financial sector. <i>"My time there is a marked chapter in my life that continues to make me proud."</i>
<b>Dr. Susan Burke</b> At CNBC: 2004 Director of Materials Science Pharmaceuticals/Healthcare	According to Dr. Susan Burke, the CNBC's neutron scattering capabilities were vital to Canadian product development by providing an irreplaceable perspective for materials research. Additionally, the CNBC's serious approach toward safety was highly influential to Burke's outlook in the private sector. <i>"It is a sad state for Canada if there aren't scientists working at the CNBC. Materials science research is important. Materials are in everything."</i>	<b>Dr. Jennifer Jackman</b> At CNBC: 1980-1983 Director of a national laboratory Scientific R&D	The CNBC and its staff facilitated Dr. Jennifer Jackman's pursuit of a doctorate at a time when only 3% of PhD graduates were female. The CNBC permanently changed its policy to allow Jackman and other pregnant women to safely conduct research. Without the knowledge and credentials she gained at the CNBC, Jackman would not have been able to become the Director of one of Canada's national laboratories. <i>"It is not a stretch to say the CNBC formed my path to becoming a senior scientist."</i>
<b>Dr. Matthew Harding</b> At CNBC: 2011-2012 Program Manager Aerospace	The CNBC taught Dr. Matthew Harding the value of neutron scattering to materials research. The significant role that the CNBC played in Canada's scientific research history was inspiring to Harding, and it led him to incorporate neutron scattering into his university teaching curriculum. Harding's research at the CNBC also contributed to his PhD, which ultimately led to his job in the aerospace industry. <i>"I wouldn't trade my time at the CNBC for anything."</i>	<b>Dr. Daniel Cluff</b> At CNBC: 2011-2013 Fuel R&D Scientist Scientific R&D	Neutron beams at the CNBC provided Dr. Daniel Cluff with research capabilities that x-rays at his university could not provide. The knowledge and skills he developed while at the CNBC have proved useful in his subsequent career in the private sector. <i>"It is a shame there will no longer be a neutron facility in Canada, as Canadian scientists will lose an essential source for valuable research."</i>
<b>Dr. Pablo Prado</b> At CNBC: 1992-1997 Co-Founder and President Professional Services	Neutron diffraction experiments at the CNBC were a key component of Dr. Pablo Prado's PhD. Additionally, observing how this sophisticated national laboratory co-ordinated and organized experiments in an efficient manner was beneficial to his career outlook. <i>"The CNBC taught me about neutron diffraction; the whole experience was positive."</i>		

Note: 'At CNBC' refers to the alumni's first and last dates of research.

### **7.6.3 Reflections on the Student Alumni Interviews**

The comments made by the interviewed alumni are well aligned with the findings described in earlier sections of this report.

#### *The Importance of the CNBC to Canada's Research Environment*

Earlier sections of this report highlighted the importance of the CNBC to materials research and noted that it had been one of the most advantageous resources in Canada. Alumni echoed this sentiment in their comments. With the CNBC's closure, Canada is now one of few major industrialized nations without a neutron beam user facility. Without access to such a facility, Canadian researchers will lose a valuable resource for conducting materials research.

Alumni emphasized that the CNBC's closure will likely lead to an exodus of scientists in Canada, who will travel elsewhere to conduct their research. Alumni were uncertain where Canada's next generation of students will go to gain such valuable industry-oriented research skills.

#### *The CNBC's Industry-Centric Perspective*

Section 6.0 identified that CNBC users were more highly engaged with industry collaboration than other Canadian researchers. The alumni's comments on how tangible that industry culture was underscores this unique feature of the facility. Losing this asset will impact the degree to which Canadian industry collaborates with academia.

Alumni also highlighted the likely loss of quality industry-oriented research. Many stated that, as an integral asset to student development, the CNBC provided graduate student researchers with a high-level research facility with capabilities that are unavailable at universities. It is expected that the closure of the CNBC will negatively impact student development and the quality of industry-oriented materials research in Canada. This is likely to degrade Canada's score on HRST deployment, which contributes to its status as an innovative economy.

#### *CNBC Alumni Deployment in Canada's R&D-Intensive Sectors*

Analysis of the career paths of former CNBC student researchers shows that alumni gravitated in larger than normal numbers to Canada's R&D-intensive sectors. The alumni's comments emphasized how instrumental the CNBC experience was to their chosen career paths. Without the CNBC's influence, the future supply of domestically trained HQP may tighten, and potential candidates may train in other countries and stay there after graduation.

### **7.7 Conclusion**

Most student researchers who attended the CNBC were from Canada and were pursuing Science or Engineering degrees. Students came proportionately from all areas in Canada, moderated only by the availability of local, complementary facilities in Western Canada and the cost to travel to the CNBC.

The CNBC contributed a number of positive impacts to its student alumni:

- Almost all CNBC alumni hold a Master's or Doctorate degree, which is a much higher level of educational achievement than is the norm in Canada, suggesting that the CNBC was a positive contributor to HQP development, the highest level of HRST, in Canada;
- The industry-centric approach of the CNBC offered student researchers a distinctly different environment compared to universities;
- CNBC alumni are currently deployed in Canada's academic, manufacturing, and scientific & professional service sectors, the core areas where R&D occurs in Canada and the sectors which contribute most directly to Canada's innovation economy;
- The industry-centric focus of the research that used the CNBC correlates with a higher proportion of CNBC alumni being deployed in industry versus pursuing academic careers than would be expected based on overall Canadian trends; and
- Alumni have achieved influential leadership roles in Canada and internationally.

All alumni interviewed expressed a sense of loss to Canada and to future student researchers upon learning of the closure of the CNBC. The closure may degrade Canada's score on HRST deployment, which contributes to Canada's status as an innovative economy.

## **8.0 Summary and Concluding Remarks**

The analysis of the CNBC's performance and impacts developed in this report assessed the CNBC against its peer facilities, within its research community, for its industry collaborators, and for the students whose university training included conducting research at the CNBC. The major findings of this analysis show that the CNBC has contributed positively to Canada's research capacity and outcomes in unique and distinct ways that augment Canada's effectiveness as an innovative economy. The major findings of this report include:

### *The CNBC and Its Place in Canada's Innovation Economy*

- 1) ***The CNBC Was a Specialized and Leading International Facility:*** The CNBC was a key element of Canada's research infrastructure. The CNBC's publication record and scientific impact, as measured by citation rates, are on par with comparable international facilities. The CNBC has been a valued source of collaboration with the U.S.
- 2) ***The CNBC Has Been a Key Element of Canada's Innovation Economy:*** The CNBC's contribution to innovation in Canada is framed by four fundamental observations:
  - a. Manufacturing's high level of BERD makes it a key element and indicator of a strongly innovative economy, because manufacturing relies on research;
  - b. Materials research underpins innovation in manufacturing, and the CNBC was an enabler of materials research in Canada;
  - c. Canada's publications in materials research are well regarded and contribute positively to Canada's overall research quality; and
  - d. The quality of research conducted at the CNBC is on par with leading global standards of excellence.
- 3) ***The CNBC Was an Essential Research Tool for Canada's Manufacturing Base:*** The CNBC enabled materials research fields that underpin advances in manufacturing, such as: enhanced steel pipe integrity for the oil and gas industry; better alloys for the automotive and aerospace sectors; and better materials for drug delivery.

### *The CNBC's Contributions to Academic Excellence*

- 4) ***The CNBC Was Canada's Most Valuable Research Asset:*** The CNBC was considered the most impactful research facility in this country by the international scientific community.
- 5) ***The CNBC Was a Nationwide Facility:*** The CNBC drew researchers from across the country, in numbers proportionate to where R&D is conducted in Canada, which made it the most broadly accessible and widely leveraged national user facility for materials research.
- 6) ***The CNBC Was Valued by Canada's Research Chairs:*** A high proportion of Canada Research Chairs made use of the CNBC, underscoring the breadth of the materials research applications of neutron beams and the importance of this facility to Canada's leading researchers.

- 7) ***The CNBC Facilitated Highly Valued Research Outcomes:*** Research outcomes from the CNBC in key areas of materials research, including research that informs energy and biomedical technologies, have had a higher scientific impact than similar research conducted without the CNBC. The CNBC was a positive contributor to Canada's overall record of research quality.

*The CNBC's Role in University–Industry Collaboration*

- 8) ***The CNBC Attracted Industry-Focused Research and Collaboration:*** Researchers who used the CNBC attracted a high proportion of collaborative industry research dollars from a broad cross-section of Canada's R&D investing sectors. The CNBC stood out as a highly industry-centric research institution.

*The CNBC's Contribution to HQP Development*

- 9) ***The CNBC Was an Engine of HQP Supply:*** The CNBC supported the development of highly qualified personnel deployed in Canada's academic, industrial manufacturing, and scientific R&D sectors. Almost all students who attended the CNBC eventually achieved a Master's or Doctorate degree—a much higher progression rate than is the norm in Canada. The industry-centric approach at the CNBC offered student researchers an environment that was distinctly different from that of universities; this industry focus corresponds to a higher proportion of CNBC student alumni being deployed in industry than in academia, which differs significantly from Canadian trends. CNBC alumni have achieved influential leadership roles in Canada and internationally.
- 10) ***Students Developed Valuable Experience and Skills at the CNBC:*** Student alumni identified how the portable skills they developed at the CNBC impacted their subsequent careers. These skills included:
- A disciplined approach to time pressures, as experiments used very limited and valuable resources, i.e., neutron beams;
  - An appreciation for applied science and industry-oriented research;
  - An awareness of the value of people who provide coaching and support to students in their development;
  - An appreciation of the importance of safety and security when conducting research, which is applicable in many other industries, such as pharmaceuticals and oil and gas.

These findings support the overall conclusion that ***the CNBC has had a positive impact on Canadian innovation, research, and industry, as well as on the development of highly qualified personnel in Canada; thus, the CNBC will be sorely missed.*** There is currently no replacement in Canada for the research capabilities that were offered by the CNBC. The findings of this report suggest that many research activities in Canada will cease, and the skills and expertise that have found their way into the Canadian economy from the CNBC may not be available in Canada in the future.

**Appendix A – List of Acronyms**

AECL – Atomic Energy of Canada Limited

ARC – Average Relative Citation

BERD – Business Enterprise Research and Development

CAGR – Compound Annual Growth Rate

CCA – Council of Canadian Academies

CDI – Citation Distribution Index

CFI – Canada Foundation for Innovation

CINS – Canadian Institute for Neutron Scattering

CLS – Canadian Light Source

CNBC – Canadian Neutron Beam Centre

CNL – Canadian Nuclear Laboratories

CRC – Canada Research Chair

CRD – Collaborative Research and Development Grant

CRL – Chalk River Laboratories

DoE – Department of Energy (U.S.)

EPO – European Patent Office

GDP – Gross Domestic Product

HFIR – High Flux Isotope Reactor

HQP – Highly Qualified Personnel

HRST – Human Resources in Science and Technology

ICR – International Collaboration Rate

ICT – Information and Communications Technology

ILL – Institut Laue-Langevin

IP – Intellectual Property

IRC – Industrial Research Chair

LANSCe – Los Alamos Neutron Science Center

LLB - Laboratoire Léon Brillouin

NCNR – NIST Center for Neutron Research

NIST – National Institute of Standards and Technology

NRC – National Research Council

NRCan – Natural Resources Canada

NRU reactor – National Research Universal reactor

NSERC – Natural Sciences and Engineering Research Council of Canada

OECD – Organisation for Economic Co-operation and Development

R&D – Research and Development

S&T – Science and Technology

SI – Specialization Index

SMR – Small Modular Reactor

SNO – Sudbury Neutrino Observatory

SNS – Spallation Neutron Source

STFC – Science and Technology Facilities Council

WEF – World Economic Forum

WoS – Web of Science

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