A National Strategy for Materials Research with Neutron Beams

A discussion paper for the Roundtable Meeting, "Canadian Neutron Initiative: Towards a National Neutron Strategy"

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CANADIAN NEUTRON INITIATIVE

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1 Executive summary and overview of a national strategy

Canada's social, environmental, and economic challenges require a complete twenty-first century scientific toolkit for research and innovation in materials. Because everything is made of materials, innovation in materials underpins nearly all technology advances for national priorities, such as:

A Clean Environment: Producing clean energy, whether by wind, solar, or nuclear power, and storing it effectively in an efficient electricity grid.

A Clean Growth Economy: Making parts for clean and energy-efficient, lightweight planes, ships, and cars using 3D printing or other advanced manufacturing technologies.

Safety and Security: Aiding nuclear non-proliferation, ensuring pipeline and rail safety, and determining fitness-for-service of naval ships.

Health and Food Security: Understanding the biological materials present in our bodies on the nanoscale, designing medical devices, and developing resilient crops.

Neutron beams are versatile and irreplaceable tools for materials research in Canada. Canadians have led in this field for over 70 years, applying these tools to make major socio-economic impacts. One particular impact—**saving hundreds of millions of dollars** by reducing downtimes of Canada's fleet of nuclear power stations—outweighed Canada's cumulative investments in neutron beam facilities to date. Another impact is elevating Canada's scientific reputation through excellent research, including major contributions to discoveries that were honoured by the 2016 Nobel Prize in Physics. Examples of impacts in each of the above priority areas, and how this research bolsters Canada's innovation economy, its scientific reputation, and training for Highly Qualified People, are explored in Appendix A.

The importance of neutron beams as research tools is recognized globally. Neutron beams provide insights about materials that cannot be obtained by other scientific techniques—the reason why Bertram Brockhouse, Canadian pioneer of neutron scattering for materials research, was honoured with the 1994 Nobel Prize in Physics. The continuing value of neutron beams to research is recognized by innovative nations that have already committed **over $8B in capital investments in the past 20 years** for neutron facilities around the world.

Neutron beams are now missing from Canada's scientific toolkit. Canada lost access to these irreplaceable tools in 2018, when the country's only major neutron source, the NRU reactor in Chalk

Neutron beams were critical to explain, and prevent downtime from, cracking issues at Canada's fleet of nuclear power reactors.

"Research using neutron beams provided critical knowledge needed by operators of [Canada's nuclear] power plants… [which] led to public benefits in several forms: the radiation dose to inspection workers was significantly reduced by minimizing their time spent near the reactor face. Plant downtime was decreased while maintaining safety margins, resulting in financial savings. Power utilities in other countries using Canadian technology were provided knowledge to support the safe, reliable, and economic operations of their plants as well, thereby enhancing the cooperative relationships."
– Paul Spekkens, former Vice-President—Science and Technology Development for Ontario Power Generation (2004–2016)

What Are Neutron Beams?

Just like beams of light are used in a microscope to learn about materials on a small scale, beams of neutrons scatter from materials in different ways to reveal certain details about atomic structures and molecular motions on the nanometre scale—details that simply cannot be "seen" with other scientific tools or methods.

River, was closed permanently with no plan for replacement. At that time, **about 800 scientists, engineers, and students** from universities, government, and industries in Canada and around the world relied on access to its neutron beams. That same year, Canada's only arrangement for access to a foreign neutron source expired. Unless access is restored, many of Canada's programs that require neutrons will cease, while the remainder will progress at a much slower pace using only two beamlines at the lower-brightness McMaster Nuclear Reactor or using very limited access to American sources for the time that Canadians remain welcome.[1] Students will miss out on the effective training experience of using neutron facilities. Not only is Canada's leadership in this field quickly eroding, but its **long-term ability to innovate to meet its social, environmental, and economic challenges will be hindered** as its researchers cease making progress on problems that require these irreplaceable tools to solve.

A new strategy is urgently needed. While we value and learn from our past, we must also look ahead to the future. The world has changed since the pioneering days of the 1940s and 1950s, when Atomic Energy of Canada Ltd. (AECL) built two world-leading neutron sources and developed their applications, largely on its own. Since then, the technology for neutron sources and instruments has greatly expanded the applications for neutron beams, and many industries—not just nuclear—are benefitting from their insights. The neutron beam user community is well distributed across Canada and has a strong global reputation, and leading neutron facilities around the world are inviting Canada to partner with them. At the same time, bright neutron sources have become increasingly challenging to build, and, like Canada, Europe and the US are especially grappling with the challenge to provide sufficient access to neutron beams for the long term. Multinational frameworks have emerged in Europe to encourage or require cooperation on building and operating neutron sources. At home, Canada's framework has broken down: Both AECL and the National Research Council, which were historically responsible for providing neutron beams for research, have been restructured, leaving this role open to the initiative of others.

Canadian universities are leading the way to address this challenge through the Canadian Neutron Initiative (CNI). The CNI working group was formed in 2016 in order to secure government support for a national program to provide neutron beams beyond 2018. The CNI is led by executives from the University of Saskatchewan, McMaster University, the University of Windsor, and the Canadian Institute for Neutron Scattering (CINS). The CNI is an executive-level forum for strategy development and coordinating action. Its funding request for a national framework was endorsed by the House of Commons Finance Committee in 2017 and 2018.[2] It has gathered support from 23 institutions across the country because neutron beams contribute to so many areas of research and innovation, as described earlier. Through consultation with stakeholders over the past few years, **the CNI has identified four key objectives that are essential for a national neutron strategy** to rebuild Canadian capacity for materials research with neutron beams.

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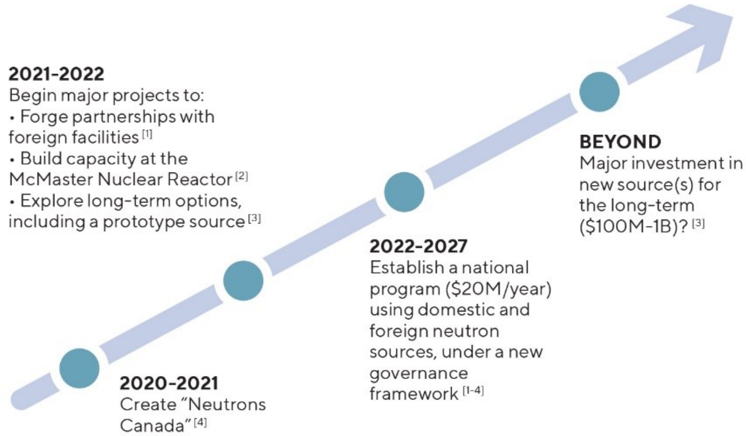
[1] In a survey of CINS members in 2020, 93% agreed that neutron beams are important for their research, but since Canada's source closed, only 16% have received sufficient beam time. Many have not accessed neutron beams at all, and even fewer are planning experiments. Survey results regarding reduced access are explored in section 4.4.
[2] See House of Commons Finance Committee reports on its consultations for the 2018 and 2019 budgets, available at: http://cins.ca/docs/HC_FINA_report_2017_12.pdf and http://cins.ca/docs/FINA_2018.pdf.

Figure 1. Simplified timeline to rebuild Canadian capacity for materials research with neutron beams. Identified activities align with the numbered objectives.



These objectives, with their activities and associated timelines (illustrated in Figures 1 and 2), are:

1. Forge partnerships with high-brightness neutron sources in other countries;
2. Build on existing domestic capabilities, including full exploitation of the McMaster Nuclear Reactor (MNR), a medium-brightness neutron source;
3. Explore and invest in developing new neutron sources for the long term; and
4. Create a new, national governance and management framework for these activities.

The urgent priority is to restore some access to neutron beams for Canadian researchers as soon as possible through foreign partnerships (Objective 1). Several such facilities have already "knocked on Canada's door" to discuss partnerships, and Canada needs a framework that can enable a national response. McMaster University has led a 'national' CFI proposal ("Building a Future for Canadian Neutron Scattering") that would make a valuable start toward investing in foreign partnerships through a one-time infrastructure contribution of $11M to be leveraged for some access to neutron beams at two US neutron facilities over six years. About five times this level of investment in foreign partnerships will be needed to meet the national need for beam time over the next several years.

Completion of the neutron beam laboratory at the MNR should begin immediately to provide more domestic capacity for the medium term (Objective 2). "Building a Future for Canadian Neutron Scattering" would also complete the neutron beam infrastructure at the MNR that will be operated under the new governance framework. This capital investment would be a major step forward, opening the possibility for full exploitation of the MNR through operational investments in the form of (i) $2–3M per year to operate the neutron beam lab as a national user facility; and (ii) $7M per year to double the available beam time and to maximize the quality of the beams. When fully exploited for neutron beams, the MNR could serve up to half of Canadian requirements, enabling high-demand 'workhorse' applications for which broad-band, continuous neutron intensities are appropriate. The MNR would specialize in neutron diffraction; any experiments requiring pulsed or cold neutrons or a high neutron brightness, including neutron spectroscopy, could not be conducted there.

"World-class research and innovation require large, national-scale science facilities that are accessible and maintained at the state-of-the-art. Neutron beam facilities are critical tools for materials research and technology development in areas such as clean energy, clean transportation, health, and food security. The Canadian Neutron Initiative proposes a single program for orderly stewardship of Canadian access to neutron beam facilities."
– Prof. Art McDonald, Nobel Laureate in Physics (2015), Queen's University

Exploration of long-term options for new neutron sources should continue in parallel with the development of the MNR (Objective 3). The global community is implementing, and planning for, reinvestments in new neutron sources to address the shrinking supply of neutrons as facilities age and close down. Canada must determine how to contribute to and complement these plans by developing its own scientific and business case to invest in one or more long-term options, namely: (i) major contributions to new multinational sources; (ii) a new domestic facility, which could range from a $500M dedicated neutron beam reactor to $1–2B for a multipurpose research reactor; and (iii) development of a compact accelerator-based neutron source (CANS), which could provide capabilities that the MNR cannot. Research led by the University of Windsor aims to determine whether CANS technology could provide a new source of neutrons to meet much of Canada's need for $100–$200M. Outcomes of such activities will inform decisions about major investments for the long term.

A new entity, Neutrons Canada, should be established without delay to manage all strategic activities as part of a unified national program, which could reach a scale of $20M per year (Objective 4). Creation of such an entity, with universities as institutional members, was considered and endorsed by a Roundtable Meeting with Vice-Presidents of Research and Associate Vice-Presidents from 16 universities across Canada in January 2020.[3] Neutrons Canada would govern, manage, and represent Canada's program for materials research with neutron beams. It will be needed to negotiate foreign partnership agreements on behalf of Canada; support user access to the foreign outstations; operate the neutron beam lab at the MNR as a national user facility; develop technology for a new neutron source; conduct science outreach; engage industry to maximize impact; and generally manage the program.

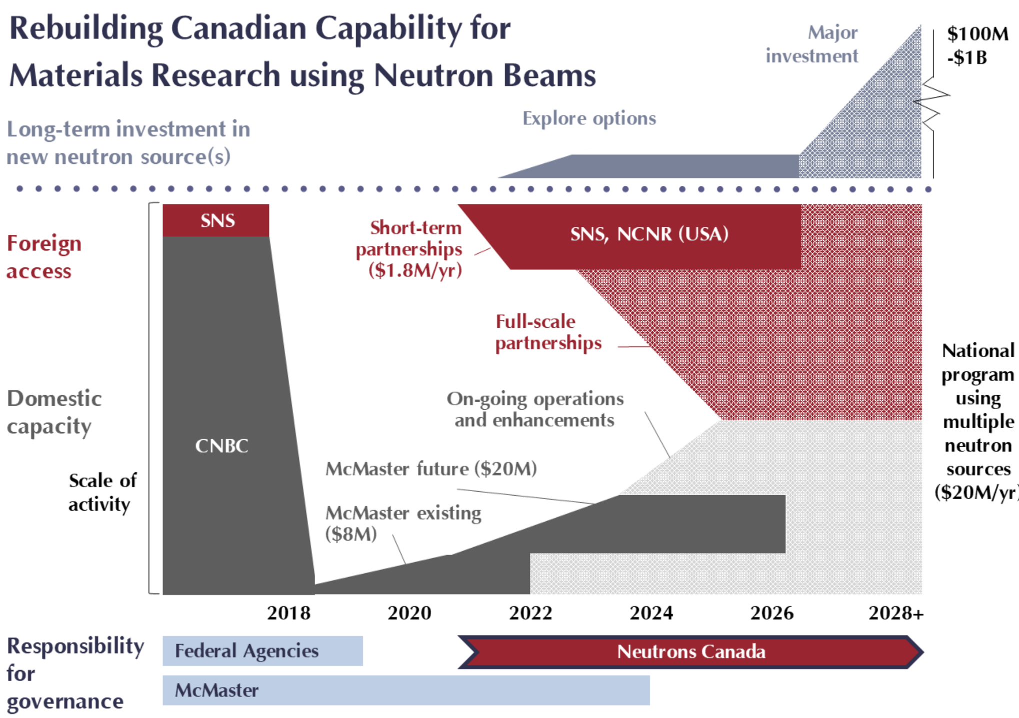


Figure 2. Activities in a coherent strategy to sustain and rejuvenate Canada's capabilities in this research field. Acronyms: CNBC = Canadian Neutron Beam Centre; SNS = Spallation Neutron Source (US); NCNR = NIST Center for Neutron Research (US).

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[3] Canadian Neutron Initiative. Canadian Leadership in Materials Research with Neutron Beams: Report on a Roundtable Meeting towards the establishment of "Neutrons Canada". Available from: https://fedorukcentre.ca/resources/canadian-neutron-initiative-cni.php

2 Consultation on the strategy

While there are ongoing activities aligned with each of the four objectives, the present consultative process focuses on the national neutron strategy as a cohesive whole. The strategy discussed in this document has grown out of consultations with universities across Canada, government agencies, industry, and potential foreign partners, as well as with researchers individually and collectively through the Canadian Institute for Neutron Scattering (CINS). Researchers have been engaged through forums such as the CINS Annual General Meetings since 2015, and the "Neutrons@Mac" meeting,[4] a strategic gathering of researchers at McMaster in May 2018. Further, it builds on CINS's long-term strategic planning work[5] and surveys to define user needs in 2017 and 2020; on McMaster's experience with a foreign partnership at the Spallation Neutron Source; and on the former CNBC's extensive experience of operating a national neutron beam user facility at Chalk River.

Stakeholders are invited to review this discussion paper and provide input on any aspect of the strategy in anticipation of the associated virtual roundtable meeting, "Canadian Neutron Initiative: Towards a National Neutron Strategy" to be held in December 2020. The Roundtable will engage a cross-section of stakeholders and leading scientists to shape a national neutron strategy to rebuild Canadian capacity for materials research with neutron beams. Ideas and feedback will be sought on key elements of the strategy, including the needed infrastructure and associated programs, domestic and foreign, on multiple time scales.

This paper explores each of the four strategic objectives in dedicated sections. To prepare for this exploration, Canada's present foundation for the future is described in the next section. A fiscal model of the new framework is provided in section 13. Extensive discussion of the value of materials research and the record of the Chalk River Laboratories are in Appendices A and B. Appendices C and D provide a stakeholder analysis and list the CNI working group leaders and supporting institutions.

The following Discussion Questions are intended to encourage ideas and feedback and are associated with each of the four strategic objectives.

Forging foreign partnerships (Objective 1)

1. *How can Canada best support the full range of users, including expert and non-expert users from universities, government labs, and industry, to access foreign neutron beam facilities? How do their needs differ?*
2. *What activities to support access to foreign neutron sources should be conducted within a Canadian program, as opposed to outsourcing to a foreign partner?*
3. *How should Canada make decisions on foreign partnerships? What criteria should be used to select the partners? What should be the process for this selection and for decisions about the amount of investment in each?*
4. *What role should Neutrons Canada, which is to be established as a national organization with institutional members, play in such decisions and in negotiating the arrangements with the partners?*

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[4] Update on the Canadian Neutron Initiative and the "Neutrons@Mac" meeting. http://cins.ca/2018/06/11/cni-update/

[5] For example, through the CINS's long-range plan: "Planning to 2050 for Materials Research with Neutron Beams in Canada" (updated in 2015). http://cins.ca/docs/CINS_LRP_2015.pdf

Building on domestic capabilities (Objective 2)

5. *What are the benefits of fully exploiting the McMaster Nuclear Reactor for neutron beams that would be more difficult or impossible to acquire if Canada relied exclusively on foreign neutron sources instead?*
6. *How can Canada best retain, leverage, and plan for succession of its scientific and technical expertise in neutron beam instrumentation and methods?*
7. *In what other ways can Canada build on its domestic capabilities for materials research with neutron beams?*
8. *What role should Neutrons Canada play in fully exploiting the McMaster Nuclear Reactor, in fostering domestic expertise, and in otherwise building Canada's domestic capabilities?*

Exploring new neutron sources for the long term (Objective 3)

9. *What are the benefits of participating in multinational consortia to plan and build new neutron sources, in addition to gaining access to beam time in the future?*
10. *What are the benefits of developing a new domestic neutron source that are not achievable through such participation in multinational consortia?*
11. *How can the Canadian neutron beam community prepare to participate in national decision-making processes about new neutron sources, as a coherent constituency alongside the nuclear power and isotope production communities?*
12. *What role should Neutrons Canada play in planning for new neutron sources for the long term? Or in research, development, and demonstration projects for such sources?*

Creating a new framework (Objective 4)

13. *What benefits arise from having a national organization, Neutrons Canada, to perform functions such as:*
    a. *Planning and shepherding major neutron initiatives through decision-making processes and implementing major neutron initiatives?*
    b. *Governing and managing a national program for user access to neutron beam facilities, both domestic and foreign?*
    c. *Negotiating with foreign facilities?*
    d. *Maintaining the continuity of expertise needed to support both (i) the operations of neutron facilities, and (ii) the implementation of capital projects?*
14. *What is the potential value of centralized efforts to engage industry in (i) applying neutron beams, (ii) supplying services to develop neutron beam facilities, and (iii) spinning-off technologies?*
15. *What value can a neutron beam program contribute to science outreach to youth and the general public?*

Equity, Diversity and Inclusion

16. *What role can a national neutron strategy play in promoting equity, diversity, and inclusion, recognizing that groups such as women, racial and ethnic minorities, Indigenous communities, and persons with disabilities are presently underrepresented in the neutron beam community?*

17. *What role can a national neutron strategy play in fostering expertise among atypical users, such as researchers from less research-intensive institutions, including smaller, rural, and Northern universities, colleges, and polytechnics? How can we ensure that the needs of these users are considered?*

18. *How can Canada ensure equity, diversity, and inclusion in the neutron beam user community while relying on access to foreign facilities?*

19. *When new neutron beam infrastructure is to be constructed in Canada, how can local and Indigenous communities be engaged to ensure a meaningful partnership?*

3 The present: A strong foundation for continued excellence

The national strategy will build on Canada's capabilities, established over the past 70 years of global leadership in materials research using neutron beams. Specifically, Canada has (1) a base of about 100 Canadian principal investigators at universities, in addition to experts within industry and government labs; (2) expertise in neutron sources and instruments; (3) a medium-brightness neutron source, the McMaster Nuclear Reactor (MNR), that has been prepared to operate for decades into the future; and (4) the strong reputation needed to attract partnerships, collaborations, and expertise. Indeed, after the closure of the NRU reactor was announced, several world-leading neutron facilities reached out to Canada to offer partnership opportunities. Key aspects of this foundation for future excellence are reviewed below. Further, we value and learn from our past, recognizing that much of the present foundation rests on the record of Canada's previous program for materials research using neutron beams that was centred on the neutron beam capabilities at Chalk River Laboratories. This historic record is explored in Appendix B.

3.1 The Canadian neutron beam user community

About 800 scientists, engineers, and students from universities, government labs, and industry participated in research at the Canadian Neutron Beam Centre (CNBC), located at the NRU reactor at Chalk River, during the CNBC's last five years of operation. About 360 of these research participants represented 64 departments in 30 Canadian universities, and 430 represented over 100 institutions in 22 foreign countries (Figure 3). Research was also conducted at foreign neutron facilities by Canadian scientists, some of whom are not captured in CNBC user statistics. The balance between the number of Canadians accessing facilities in the US and American researchers accessing the CNBC was about equal.

Figure 3. Left: Geographic distribution of 30 participating universities, as well as 22 countries of foreign institutions (represented by flags). Right: Distribution of beam time by user type over the last five years of the CNBC's operation (2013–2018).

3.1.1 Universities

Universities generate new knowledge and train students using neutron beam facilities. As of the closure of the CNBC, Canadian users of neutron beams, whether in Canada or abroad, included 100 principal investigators from nearly every major university in Canada, as well as some smaller ones. Universities are continuing to build capability in this field despite the setbacks of the CNBC's closure and the expiry of Canada's only agreement with a foreign neutron source (i.e. the SNS in the US). Notably, within the last three years, Canadian universities have hired eight professors who use neutron beams: Meigan Aronson, Alannah Hallas, Dimitry Sediako, and Emily Cranston (UBC); Benjamin Tutolo (U. Calgary); Drew Marquardt (U. Windsor); Sarah Dunsiger (Simon Fraser U.); and Levente Balogh (Queen's U).

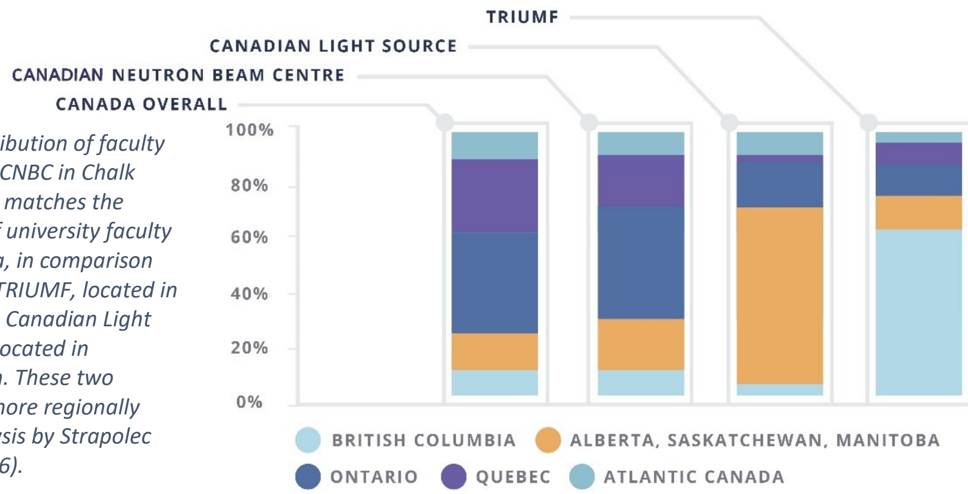

Figure 4. Distribution of faculty who used the CNBC in Chalk River, Ontario matches the distribution of university faculty across Canada, in comparison with users of TRIUMF, located in BC, and of the Canadian Light Source (CLS), located in Saskatchewan. These two facilities are more regionally aligned. Analysis by Strapolec (see footnote 6).

The geographic distribution of the faculty who used the CNBC closely matches that of all faculty across Canada (Figure 4). This community has also been strong in both scientific stature and engagement with industry. Key indicators of this strength are shown in Figure 5.[6] Further, a 2014 study found that over 6% of all NSERC-funded industry-university collaborations involved users of the neutron beams or other facilities at Chalk River, even though these users represented only about 1% of all NSERC-funded faculty.[7] Materials research with neutron beams is one of the few areas of strength in academic-industry collaborations in Canada, where Canada otherwise ranks weakly when compared internationally.

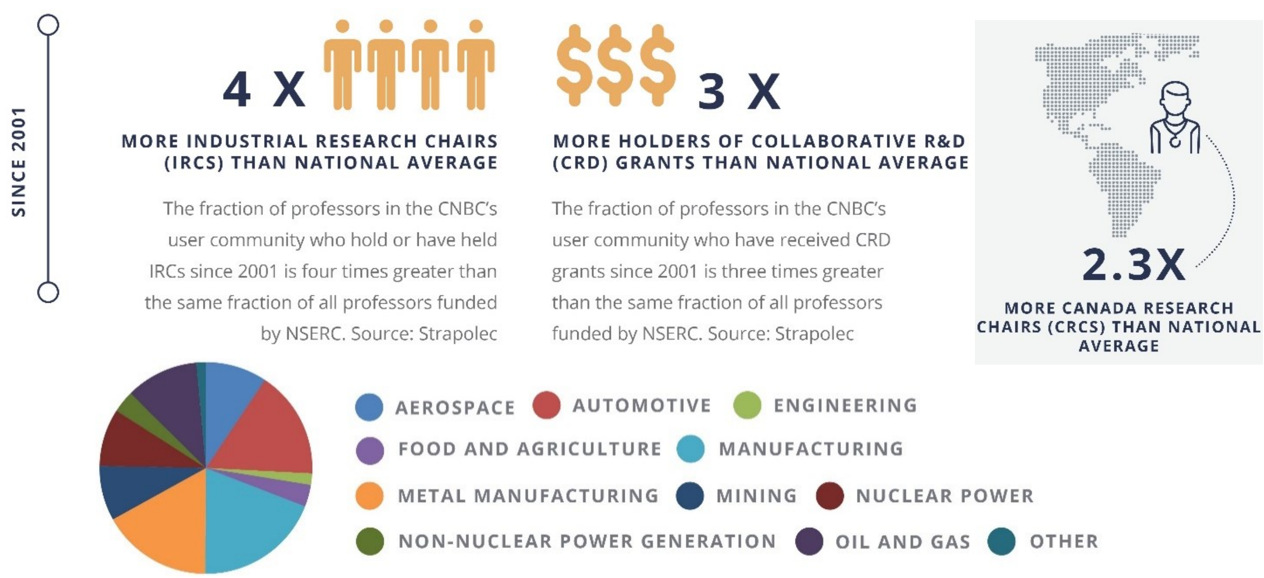

Figure 5. Rates of Canada Research Chairs, Industrial Research Chairs, and Collaborative R&D grants, and distribution of $40M in industry sponsorship among sectors for the CNBC's user community for 2001–2018. Analysis by Strapolec (see footnote 6).

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[6] Strapolec. "Study of CNBC Performance and Impacts" (Feb 2019). Available from: http://cins.ca/resources/cnbc/
[7] KPMG. "A Report on the Contribution of Nuclear Science and Technology (S&T) to Innovation." Final report prepared for Natural Resources Canada. Fall 2014.

"Canada, centred around the Chalk River reactor, has been pioneering in the techniques and applications of neutron scattering for over 50 years from the early development of triple-axis spectroscopy to the later industrial exploitation in engineering problems. Although the reactor closed in 2018, the ongoing value of the skills base in institutes and universities that has grown up over that period, for both basic research and industrial applications, should not be underestimated."
– Robert McGreevy, Director of the ISIS Neutron and Muon Source (United Kingdom)

3.1.2 Industry and government

Industry users tend to come from risk-sensitive, heavy industries where precise knowledge of the properties of key materials is needed to ensure reliability and meet regulatory requirements: nuclear power, aerospace, automotive, oil and gas, primary metal production, and other manufacturing sectors (for specific examples, see Appendix A). These industries pay the full cost of access to neutron beams for failure analysis, prototyping, and other R&D activities to improve their manufacturing methods or satisfy regulators. Paid projects tend to be urgent, high-impact, and proprietary one-offs. Longer-term involvement with industry typically arises when industries pool resources (e.g. through the CANDU Owners Group) and sponsor academic or government labs to solve materials problems that may benefit an entire sector (see above for a discussion on academic sponsorship).

Canadian Nuclear Laboratories[8] (CNL), the private sector operator of the government-owned Chalk River Laboratories, was the CNBC's largest client outside of academia, using nearly 20% of the CNBC's beam time in its last five years. The end users of the knowledge generated for many CNL projects have been the Canadian nuclear power industry, government departments that pay CNL to conduct nuclear science and technology projects, and regulatory bodies (e.g. the Canadian Nuclear Safety Commission, Health Canada). Other projects have addressed CNL's operational needs as a nuclear site. Projects over the final few years of the CNBC included nuclear forensics, nuclear waste management, and quality assurance and analyses of fuel produced by CNL, as well as studies on hydrogen in CANDU pressure tubes, fuel failure, the reliability of welding methods, super-critical water reactors, and the biological effects of radiation. Over the final 15 years of the CNBC's operation, CNL frequently sought access for nuclear fuel analysis and stress measurements in feeder tubes and feeder welds.

In addition to government clients that accessed the CNBC indirectly through CNL, direct government clients included CanmetMATERIALS, the National Research Council (NRC), and Defence R&D Canada (DRDC). CanmetMATERIALS and the NRC typically accessed the CNBC to advance their R&D work with industry. DRDC typically accessed the CNBC for its own operations (e.g. investigating the strength of welds on military ship hulls to manage the aging of the fleet).

"Neutron beams are essential and unique tools for evaluating the reliability of critical components for the automotive industry."

– Glenn Byczynski, R&D and Engineering Manager for the US and Canada, Nemak

[8] The references to CNL in this section include Atomic Energy of Canada Ltd. (AECL) prior to 2015, at which time the operations of AECL's research arm at Chalk River Laboratories was transferred to Canadian Nuclear Laboratories.

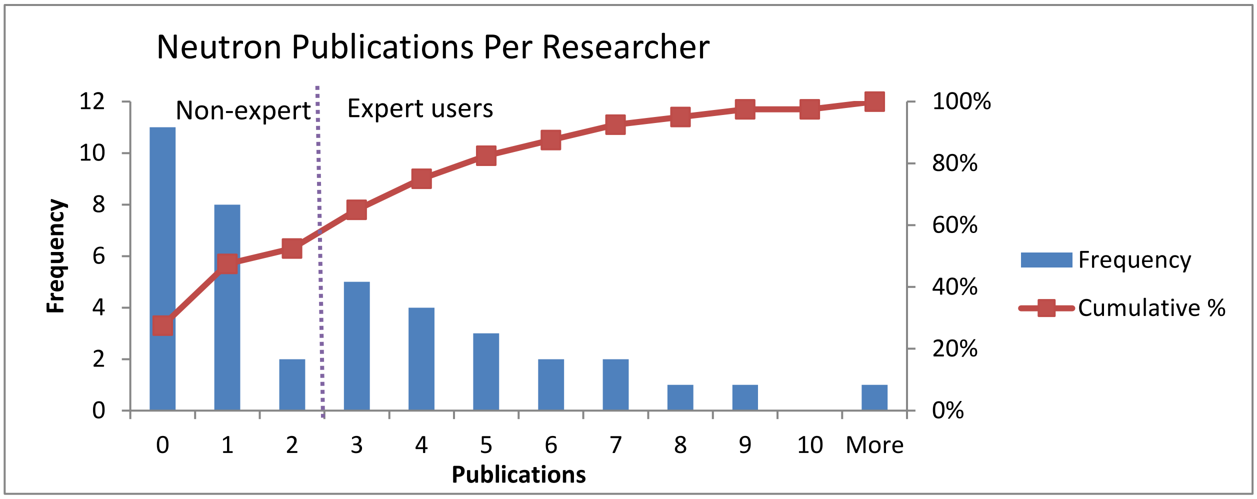

Figure 6. Histogram of the frequency of neutron beam publications in the two years following the closure of the CNBC among 40 neutron beam users, primarily Canadian faculty researchers. Source: CINS-CNI 2020 survey.

3.1.3 Expert vs. non-expert users

The neutron beam user community can be divided into two categories—"expert users" and "non-expert users"—based on the centrality of neutron methods in a user's research program, as reflected by the frequency of neutron experiments or neutron publications. As shown in Figure 6, a natural division appeared in a survey of neutron beam users between those who published two or fewer papers in the two years following the CNBC's closure ("non-expert users") and those who published three or more papers, thus demonstrating a greater specialization in neutron beam experiments ("expert users").[9] Extrapolating from the survey results (in which non-experts were less likely to respond), and comparing data from the CNBC on numbers of experiments per user in 2008-2017, it is estimated that the division of expert to non-expert users in Canada is about 20% expert users and 80% non-expert users.

Expert users most often have programs in biological materials or quantum materials. Non-experts appear in all fields, but users in industry and Canadian government labs, as well as university users in materials science and engineering, are generally non-experts. Non-expert users access neutron beams when needed to solve a particularly challenging problem or to complement other techniques they use more frequently. For instance, researchers who study engineering materials benefit greatly from the penetration depth of neutrons into metals and alloys when safety and reliability are vital.

Non-experts tended to rely heavily on the domestic facility for training their students. As such, facility staff provided the scientific expertise that was essential for effective planning, execution, and analysis of neutron beam experiments by non-experts and first-time users.

[9] Following the method of the Danish user community, CINS has previously categorized expert users as those who publish at least four papers in two years [Banks D and Harroun TA. 2019. Seventy years of scientific impact using neutron beams at the Chalk River Laboratories. FACETS 4: 507–530. doi:10.1139/facets-2019-0003]. Even though many of the newly published papers would still be based on data collected at the CNBC, it is now much more difficult to complete neutron beam experiments (even for expert users in Canada as was shown in the CINS-CNI 2020 Survey), and thus the threshold for our purposes has been adjusted to those who publish at least three papers in two years.

The effect of the increased difficulty in accessing neutron beams in Canada is different for expert vs. non-expert users, as was observed in the 2020 survey of neutron beam users (Figure 7):

- Expert users who find that it is more difficult to succeed in competitions for beam time at foreign facilities are getting much less beam time than before the CNBC closed; about 80% of such respondents are no longer receiving enough beam time to meet their research objectives.
- Non-expert users (except for a few who were already not using the CNBC) find that it is much more difficult to obtain beam time and are deterred from applying; only 25% of non-expert respondents applied in the last two years, and 60% of those did not receive enough beam time to meet their research objectives.

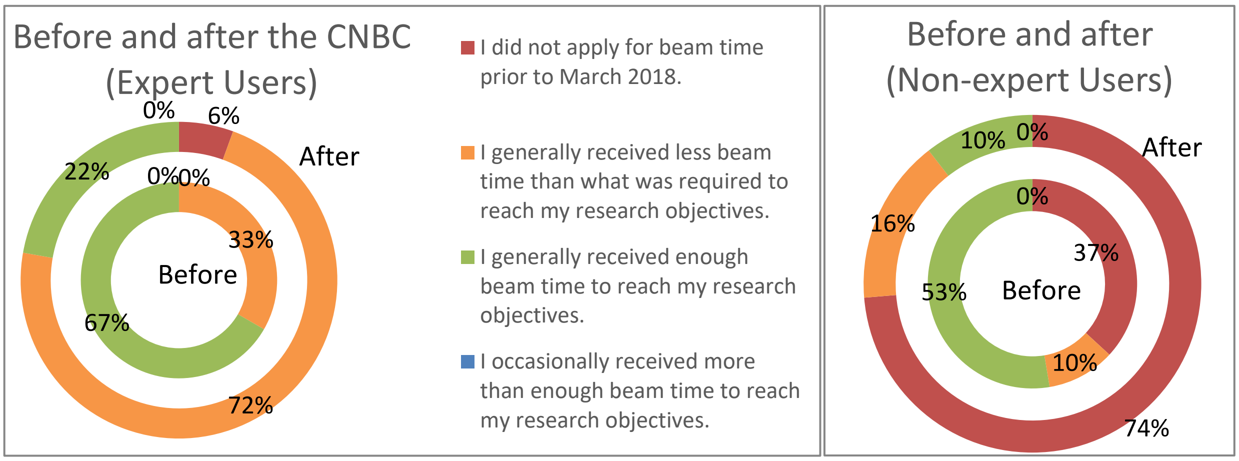

Figure 7. Sufficiency of beam time in the two years before and after the CNBC closed, for expert users (left) and for non-expert users (right). Expert users were defined as those who reported three or more publications in the past two years. For further discussion of the ongoing decline in access to beam time, see section 4.4. Source: CINS-CNI 2020 survey.

3.2 McMaster University

In 1962, Bertram Brockhouse joined McMaster University, where he developed the institute now known as the Brockhouse Institute for Materials Research. Under his leadership, the McMaster Nuclear Reactor (MNR) developed its beam capabilities, and its two neutron diffraction beamlines were available for materials research until the 1990s. At that time, the neutron diffraction beamlines were decommissioned, as the reactor was slated for closure. However, it is still operating today because a medium-flux reactor at a Canadian university is an irreplaceable asset, and modernizing the MNR's capabilities has been a key element of McMaster's institutional strategy. About $25M in capital was invested in the MNR and associated labs between 2000 and 2012 through Canada Foundation for Innovation (CFI) projects and the Knowledge Infrastructure Program, enabling the MNR to operate throughout the coming decades.

Today, the MNR is Canada's only neutron source that is sufficiently bright for a domestic neutron diffraction program. It has neutron beamlines for imaging and neutron activation analysis, operated primarily for commercial purposes. Rebuilding its neutron diffraction capabilities began with a single-crystal diffractometer, known as the McMaster Alignment Diffractometer (MAD), completed in partnership with the CNBC. This instrument opened to users in mid-2017, and in its first year it operated at 50% capacity for 13 experiments conducted by 20 users from 5 universities and 1 private sector firm—an auspicious beginning toward a neutron user program. The MAD is used for (1) preparing for neutron measurements at the Spallation Neutron Source (SNS) in the US, as success rates in the SNS's oversubscribed competitions are much higher if basic neutron characterizations are already complete; and (2) for scientific and educational programs.

McMaster is now building a second diffraction beamline: a 24-metre small-angle diffractometer—a $9M CFI-funded project expected to be complete by the end of 2020. The university contributed $2M to this project to expand the external beam hall to provide room for more beamlines. To execute this project, a partnership was established between McMaster and Canadian Nuclear Laboratories for the CNBC to provide scientific consultation, project management, and design.

McMaster has also been a leader in materials research using neutron beams in Canada. It has the largest concentration of expert neutron beam users in Canada, and has maintained a succession of world-leading researchers, from Brockhouse to Malcom Collins to Bruce Gaulin, who is now the Brockhouse Chair in the Physics of Materials. Gaulin remains the only President of the Neutron Scattering Society of America to have been elected from outside the US. Compared to other Canadian institutions, McMaster has been the most frequent user of the CNBC and the SNS: 18% of all papers arising from the CNBC since 1980 were authored or co-authored by McMaster users. Of all papers arising from the SNS up to 2018 with at least one Canadian author, about half had an author from McMaster. McMaster has also held key roles in securing funds for the Canadian neutron beam user community: Collins and Gaulin have led many of the multi-institutional NSERC grants that built beamlines at Chalk River and maintained the Chalk River facility in a state of readiness for user access; further, they were both leaders of the Canadian Institute for Neutron Scattering for many years. Gaulin also led the CFI project “Canadian Participation at the SNS” to enable Canadian access to a new world-leading foreign facility (section 4.2).

3.3 Other neutron beam capabilities and interests

In addition to the resources at McMaster, as well as the user community (which is well distributed across Canada, as described in section 3.1), there are other key capabilities and interests in Canada that form part of the foundation for a successful national strategy:

- Canadian Nuclear Laboratories (CNL) retained a large portion of the CNBC’s scientific and technical expertise beyond the CNBC’s closure to advance CNL’s own research capabilities, especially for materials research for the nuclear sector—expertise that could be applied to neutron beam development projects on a commercial basis. CNL is also responsible for the disposition of much of the former CNBC’s equipment, some of which could be reused at neutron sources elsewhere.
- At the University of Saskatchewan, there is strong interest in growing neutron beam capability. In 2009, the university and the provincial government offered $200M towards a partnership with the federal government to build a neutron beam reactor on campus, where it would complement the Canadian Light Source, a major user facility for materials research using x-rays. In 2011, the Sylvia Fedoruk Canadian Centre for Nuclear Innovation (“Fedoruk Centre”), a not-for-profit corporation located at the university, was established to help place Saskatchewan among global leaders of nuclear research, development, and training through investment in partnerships with academia and industry. The Fedoruk Centre has retained some of the CNBC’s expertise in (1) strategic planning, and (2) developing neutron beam infrastructure. The first enables the Fedoruk Centre to support the CNI working group in a knowledgeable secretariat role, securing resources and partners for the working group, while the second enables the Fedoruk Centre to offer design and project management support for neutron instrument projects such as completing the small-angle diffractometer at the MNR.

- The University of Windsor has partnered with TRIUMF, Canada's particle accelerator centre, to explore the feasibility of accelerator-based neutron sources as one long-term option for Canada (discussed further in section 6).

Other potential stakeholders in the development of this national strategy include: government funding agencies; communities that rely on neutrons for purposes other than materials research (e.g. isotope production, nuclear power for testing fuels and components in a reactor environment); and other major research facilities, including those with expertise in accelerators and neutron production. A brief stakeholder analysis is provided in Appendix D.

4 Forging foreign partnerships

In this section, we briefly review the global context and Canada's past participation in foreign neutron sources, and then explore Canada's need for new partnerships as part of a coherent national strategy.

Strategy Objective 1: Forge partnerships with high-brightness neutron sources in other countries.

4.1 Global renewal of advanced neutron sources

To take advantage of developments in accelerator-based neutron sources (and to replace older reactors), foreign reinvestments in neutron beam facilities gained momentum in the 1990s and 2000s with the building of the FRM-II reactor in Germany, the Second Target Station at the ISIS pulsed neutron source in the UK, and the Spallation Neutron Source (SNS) in the US. Other major new facilities around the world include the Japan Spallation Neutron Source, the OPAL Reactor in Australia, the China Spallation Neutron Source and the China Advanced Research Reactor, and the European Spallation Source, which plans to open its first instruments for users in 2023. Since the year 2000, such reinvestments globally have totalled about $8B in capital expenditures for new and upgraded sources. The new sources have projected lifetimes of about 50 years and have enhanced figures of merit for neutron experiments by factors of up to 100. At these facilities, neutron beams can be applied to an even more diverse set of materials problems, including problems which were impossible to solve even a decade ago, such as spectroscopy in small (e.g. 20 mg) single crystals, which is essential to solving many research questions in quantum materials research.

4.2 Canadian participation at the Spallation Neutron Source (2008–2018)

Canada played a small but successful role in establishing leading-edge neutron capabilities at a new world-leading facility, the SNS at Oak Ridge National Laboratory, by contributing $15M awarded from the CFI International Access Fund for "Canadian Participation at the SNS" in 2002. This award to McMaster University allowed Canadian researchers to take part in overseeing the design and construction of two forefront instruments at the SNS: a neutron diffractometer (VULCAN) and a chopper neutron spectrometer (SEQUOIA). These instruments remain the world-leading neutron instruments in their class, enabling clear advancements in science on the international scale. In return, Canadian scientists gained access to the equivalent of 30% of one instrument's beam time, distributed between these and other SNS instruments, for 10 years, ending in 2018. This access enabled Canadian researchers to remain at the forefront of materials research, with 88 Canadian students and post-docs producing at least 106 papers. These publications represent a publication rate 2.3 times that of the SNS as a whole, at a cost 3.5 times lower.[10] The enabled research continued to build Canada's highly respected international reputation, as evidenced by (1) the awards granted to two McMaster PhD students, who were awarded the 2014 and 2018 Outstanding Student Research Prizes from the Neutron Scattering Society of America; and (2) Gaulin's chairmanship of the 2017 Gordon Research Conference on Neutron Scattering in Hong Kong. As a result of Canada's reputation enabled by investments at Chalk River and the SNS, several world-leading international neutron sources have reached out to the Canadian neutron community to invite partnerships.

[10] The CFI's 100% share of the $15M investment leveraged the equivalent of 30% of one beamline for 10 years, beginning in 2008. The Canadian publication rate is thus equivalent to 35 publications per beamline-year—more than double the rate of the SNS as a whole at 15 publications per beamline-year over the same period. The CFI's cost per Canadian publication, $141,500, was 3.5 times lower than the cost of publications from the SNS as a whole at $500,000 per publication.

4.3 Shrinking supply of neutrons

Despite the $8B that has been invested globally in new and upgraded facilities since 2000, the overall global supply of neutron beams is decreasing. Many older neutron sources are shutting down due to age—most of the sources are aging reactors built within 20 years of Canada's recently shut down NRU reactor—as well as due to public perceptions about the safety of nuclear reactors. Remaining reactor sources face pressure to eliminate highly enriched uranium fuel, which could lead to more closures or to reductions in neutron brightness. In Europe, three reactors closed in 2019: the BER-II at the Helmholtz-Zentrum Berlin (Germany); the Orphée reactor at the Laboratoire Léon Brillouin (France); and the JEEP II reactor (Norway). Of Europe's remaining nine major facilities, there may be only five left by 2028, representing a net decrease in available beam time since 2018 of as much as 50%, even after the new $3B European Spallation Source is ramped up by 2028 (Figure 8).[11] Similarly, the US has ramped up its new $2.2B flagship facility, the SNS, and expanded capacity at its two older, NRU-vintage facilities. Still, the US continues to struggle with reduced access to neutron beams[12] because two of its facilities have closed in the last 20 years, and a third became unavailable to users in 2014. The US is continuing to upgrade the SNS and is planning a further $1B investment to add a second target station there. Yet this investment will not be enough to replace both of its reactor sources when they eventually close—a major reason why the US is exploring conceptual designs for a new low-enriched uranium reactor.

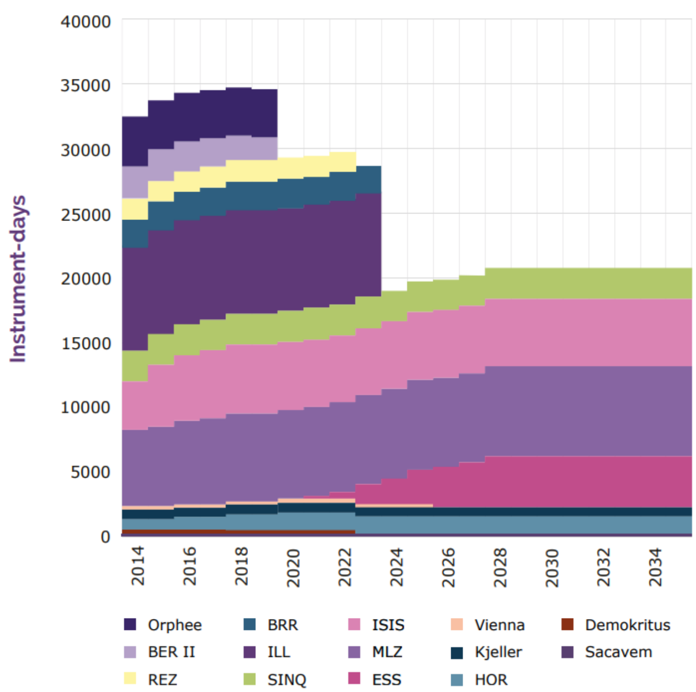

Figure 8. The predicted delivery of instrument-days at the various European neutron sources in a "baseline scenario," showing a 40% drop from 2018 levels in the near future. Source: ESFRI (see footnote 11).

[11] ESFRI Physical Sciences and Engineering Strategy Working Group: Neutron Landscape Group. "Neutron scattering facilities in Europe—Present status and future perspectives." ESFRI Scripta Vol. 1. https://www.esfri.eu/esfri-scripta-vol1-neutron-scattering-facilities-europe-present-status-and-future-perspectives. See also: ESFRI Roadmaps: roadmap2018.esfri.eu/ (2018); esfri.eu/roadmap-2016 (2016).
[12] American Physical Society Panel on Public Affairs. Neutrons for the Nation. American Physical Society (July 2018).

4.4 Reduced access for Canadians

There are about 15 world-class neutron beam facilities around the globe, each with its own strengths. Even while the CNBC was operating, some access to foreign facilities was needed for capabilities unavailable in Canada, such as cold or pulsed neutrons. A fundamental hindrance to Canadian access has been that all neutron beam facilities are heavily oversubscribed[13]—a major reason for the partnership with the SNS, which gave Canadians preferred access to a portion of the SNS's beam time. Oversubscriptions have recently been made worse by closures of facilities and user programs in Europe and the US, as well as in Canada. Most facilities outside the US restrict access in order to favour countries that help pay for their operations. The Institut Laue-Langevin in France (ILL)—the world's brightest reactor neutron source—does not accept proposals in their beam time competitions unless two-thirds of the scientific team is from paying countries. The European Spallation Source will have similar requirements when it opens. Some facilities, particularly in the US, have accepted Canadian scientists on an informal *quid pro quo* exchange of access to neutron facilities.[14] Now, having lost the CNBC, there is no longer a basis for such an exchange, although Canadians have remained welcome so far; in the last two years, Canadian users have accessed facilities in the US for 80% of their beam time. [15] Facilities outside the USA continue to welcome Canadians within the limits of their policies to prefer

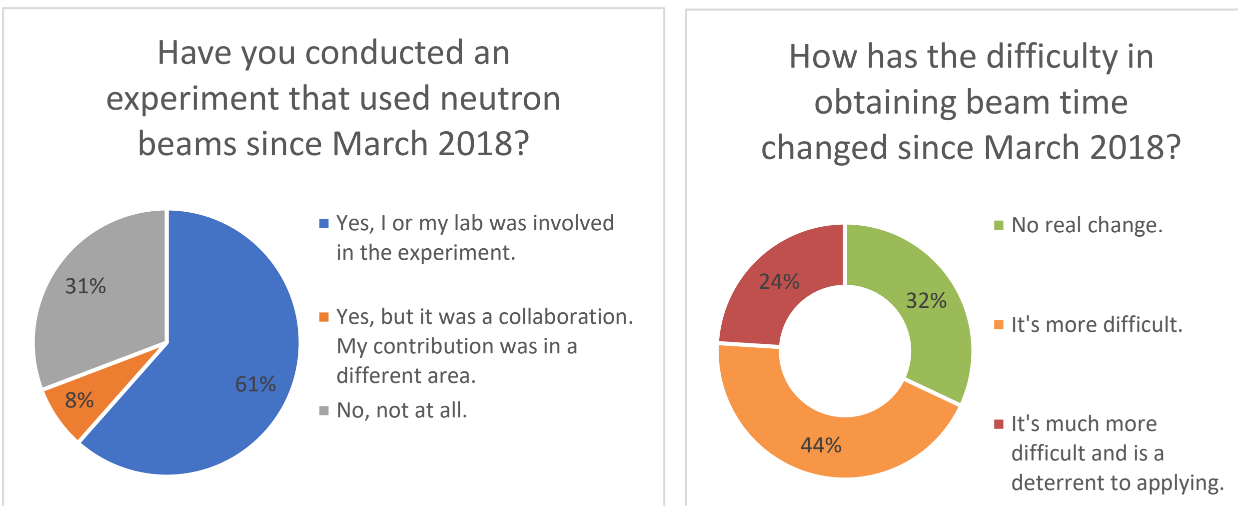

Figure 9. Fewer researchers have accessed neutron beams in the two years following the CNBC's closure in March 2018, and those who did reported that it was much more difficult. Left: Fraction of respondents who have continued their use of neutrons in the last two years. Right: Fraction of respondents who have experienced changes in difficulty in obtaining beam time; those who reported no real change in difficulty in getting beam time consist of only those who, in the past two years, have only used capabilities that the CNBC did not provide (e.g. small-angle neutron scattering, cold neutrons, time-of-flight methods, or spin echo neutron scattering). Source: CINS-CNI 2020 survey (footnote 15).

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[13] For example, each of the neutron user programs in the US are oversubscribed by a factor of 2 to 3 [APS Panel on Public Affairs. Neutrons for the Nation. July 2018]. Oversubscription rates of 3 or more are strong deterrents from applying [APS Committee on International Scientific Affairs. Access to Major International X-Ray and Neutron Scattering Facilities. April 2009].

[14] There had been an approximately equal balance, with over 100 foreign researchers participating in research at the CNBC each year, while a survey of American facilities in 2012 reported over 90 research participants from Canada. A research participant during a given year is defined as an individual who was a user during that year, or who is a co-author of a paper resulting from work carried out at the CNBC that was published during the year. This is a standardized measure for North American neutron facilities.

[15] Summary of Results from the CINS-CNI 2020 Survey. Oct 5, 2020. Available from: https://fedorukcentre.ca/documents/resources/cni/cins-cni-survey-2020-report.pdf

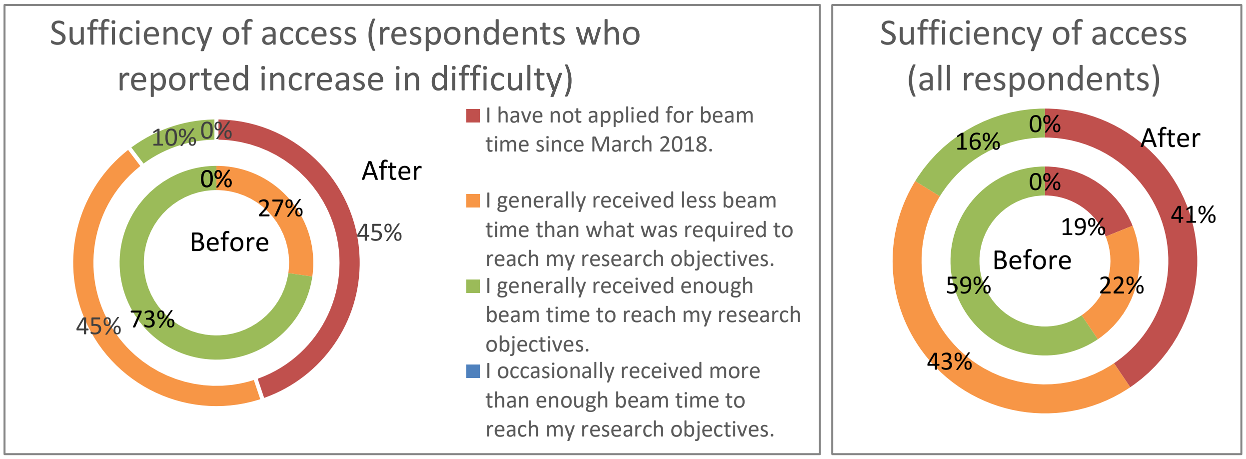


Figure 10. The change in access levels is dramatic for those who have been affected. The figure illustrates the sufficiency of beam time in the two years before and after the CNBC closed in March 2018, for those who reported an increase in difficulty (left), and for all respondents (right). Of those who have been affected, only 10% are getting enough beam time since the closure, whereas previously 73% received sufficient beam time. Nearly half (45%) have applied for beam time but have received insufficient amounts (none or too little), while an equal number (45%) have been deterred from even applying. Furthermore, the fraction of all respondents who did not apply in a two-year window doubled from 19% to 41% after the CNBC closed. Source: CINS-CNI 2020 survey (footnote 15).

paying countries. Over the past 10 years, the ILL provided access to neutrons for 79 experiments by teams that included 74 unique Canadian researchers (including students and post-docs). The ILL continues to be the most sought-after facility outside North America (see section 4.5).

In the two years following the CNBC's closure and the expiry of the agreement with the SNS, Canadian researchers have faced severe reductions in access to neutron beams, which was clearly shown in a survey of neutron beam users in 2020 (Figure 9 and Figure 10). The results show that Canadian researchers' capacity to apply neutron beams to their research is continuing to decline even now. As such, it may take several more years before the full extent of the reduction in capacity can be clearly identified and fully appreciated. The survey found that the number of *planned* experiments for the next 12 months was 24% below the number of *actual* experiments conducted in the past 12 months, and given the reduced access to—and oversubscription rates for—neutron facilities, many planned experiments will not succeed in their beam time competitions. Furthermore, oversubscription rates and policy barriers to Canadian participation will only worsen with the increasing scarcity of neutrons, and Canada cannot expect to access foreign facilities for long without making a financial contribution.

For the last decade, Canadian researchers have enjoyed advantages provided directly and indirectly by the CNBC and SNS, and these advantages have helped Canadians to be competitive in beam time competitions: Canadian scientists and their students and post-docs have received valuable training and experience, and have collected data and published papers that can be cited as relevant prior research. Some such users have become leaders in their scientific fields and have attracted international collaborators, who now in turn assist them to access beam time at facilities in their home countries. Canadians have been welcomed to apply to facilities in the US, in part because of the above-mentioned *quid pro quo* scientific exchange, and because Canada made a major contribution to the construction of instruments at the SNS. Such residual advantages will decline over the next several years as (1) the backlog of projects that build on results from the CNBC and the SNS is cleared; (2) current students graduate, and training new ones in neutron beam techniques becomes harder; (3) Canadians' reputation in the field and their attractiveness as collaborators declines; (4) Canadian researchers divert their interests elsewhere in response to not getting enough beam time; and (5) the residual welcome of Canadian scientists at US facilities wears down.

Unless Canada restores access soon, many of its programs that require neutrons will cease, while the remainder will progress at a much slower pace using only the two beamlines at the MNR or limited access to American sources for the time that Canadians remain welcome. For students, the high likelihood of a failed proposal to one of these sources, which only accept proposals for beam time once or twice a year, can doom an entire MSc thesis or PhD thesis chapter, and they will miss out on the effective training experience offered by these facilities.

Table 1. Top six neutron facilities used by Canadian respondents, with the experiments planned at each facility as a percentage of beam days for all experiments planned by respondents. Source: CINS-CNI 2020 survey (footnote 15).

Neutron facility	Country	%
NIST Center for Neutron Research (NCNR)	USA	43
Spallation Neutron Source (SNS)	USA	24
High-Flux Isotope Reactor (HFIR)	USA	9.4
Institut Laue-Langevin (ILL)	France	8.7
ISIS Neutron and Muon Facility (ISIS)	United Kingdom	5.1
Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM-II)	Germany	2.9

4.5 Partnership opportunities

Partnerships are the only way to gain immediate access to the full range of neutron techniques that Canadians need. Partnering with foreign neutron facilities must be a permanent element of Canada's strategy. Partnering is critically needed immediately to maintain the continuity of Canadian research programs, but will still be very necessary even when the medium-brightness MNR is fully exploited. Most Canadian research programs will still require high neutron brightness for at least some of their experiments using neutrons. High brightness enables high-resolution in time, energy, momentum transfers, and space in the specimen—each of which is often necessary to solve problems in materials research. Further, even in the most optimistic long-term scenario for a new domestic source based on a reactor or compact accelerator (section 8), there will still be needed scientific capabilities that will only be available at world-leading spallation sources abroad.

Since 2015, when the closure date of Canada's facility was announced, at least six foreign facilities have reached out with partnership opportunities for Canada to invest in. Because the leading facilities in the US and Europe in particular offer distinct advantages that appeal to Canadian researchers, the Canadian program could partner with multiple facilities, determined by Canadian demand for specific capabilities.

Most of the neutron techniques that Canadians need immediately can be found at US sources. Partnership options in the US are: (1) the Department of Energy's Oak Ridge National Laboratory (i.e. the SNS and the High-Flux Isotope Reactor [HFIR]) in Oak Ridge, Tennessee; and (2) the Department of Commerce's NIST Center for Neutron Research (NCNR) in Gaithersburg, Maryland. These facilities are well known to expert Canadian users, and are reasonably accessible to them geographically. Building on precedents, a Canadian program could operate at these facilities through a combination of cash and in-kind contributions of expert personnel and equipment. For example, Germany's Jülich Centre for Neutron Science maintains an outstation at the SNS with Jülich Centre staff who support German users, while the CFI project "Canadian Participation at the SNS" was a cash contribution for bare access, without a program to support Canadians specifically.

"We would welcome a Canadian partnership, because attracting strong communities facilitates our mission as the world's flagship centre for neutron science. The Canadian research community has an excellent record of applying neutrons for materials research and innovation, and many Canadian companies are experienced in supplying nuclear facilities." **– Dr. Helmut Schober, Director of the world's leading neutron source, the Institut Laue-Langevin in France**

In Europe, the Institut Laue-Langevin (ILL) in France, the ISIS Neutron and Muon Facility in the UK, and the European Spallation Source (ESS) under construction in Sweden have all reached out to Canada to discuss partnerships. These facilities offer capabilities and opportunities that would not be available through partnerships with the American facilities. The ILL, currently the world's leading neutron source, offers a wide array of beamlines and the ability to provide deuterated, biologically relevant materials on site. Access to the ILL can be obtained immediately by purchasing membership in its international consortium. The ISIS facility offers a combination of powerful capabilities for the study of engineering materials and has precedents for international partnerships to access its resources. The ESS is planned to be the world's brightest neutron source. Although the first beamlines at the ESS are not expected to open for users until at least 2023, a partnership now would offer opportunities for Canadians to participate in designing and building beam components, ancillary equipment, and computational tools to deliver world-leading science over the coming decades—activities that are especially valuable to Objective 3: "Explore and invest in developing new neutron sources for the long term."

Partnering with neutron sources outside the US is an opportunity to diversify Canada's collaborations. Canadian science as a whole is highly collaborative with the US. While we continue to value these collaborations, the federal science strategy has identified the need to diversify our collaborations, because "being connected to the world's many research intensive countries is critical for Canada to be a leader in science, technology and innovation."[16] Partnering with neutron sources in these countries will enable Canadian scientists to participate in that facility's scientific life, which will lead to new connections and collaborations.

4.6 Current activities towards partnerships

To restore some access to neutron beams for Canadian research, McMaster University led a 'national' proposal to the CFI 2020 Innovation Fund competition for a $47M infrastructure project (a proposal entitled "Building a Future for Canadian Neutron Scattering"). That project and resulting infrastructure would be governed and managed under the framework that emerges from Objective 4. The CNI gathered executive-level support for this project, and ultimately 17 Canadian universities contributed portions of their CFI grant request quotas to this proposal. The proposal contained both domestic and foreign components. (Figure 2 illustrates how these proposed investments fit into a coherent national strategy.)

As foreign partnerships are the only way to gain some access to neutron beams in the short term, the "Building a Future for Canadian Neutron Scattering" proposal included an $11M contribution toward neutron beam infrastructure at two American neutron facilities: the SNS and the NCNR. In return, Canadians would gain immediate access to the needed range of neutron beam capabilities for six years.

[16] Innovation, Science, and Economic Development Canada. Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation 2014. https://www.ic.gc.ca/eic/site/113.nsf/eng/h_07657.html. Accessed Oct. 20, 2020.

The total amount of beam time leveraged at these foreign facilities would not replace what has been lost due to the closure of the CNBC, but will be at least double the amount that Canadians had under the previous agreement with the SNS, and would be a valuable start toward restoring access to neutron beams. Still, about five times this level of investment is needed to meet the national need for beam time at foreign facilities over the next several years.

4.7 Objective 1 Discussion Questions

1. *How can Canada best support the full range of users, including expert and non-expert users from universities, government labs, and industry, to access foreign neutron beam facilities? How do their needs differ?*
2. *What activities to support access to foreign neutron sources should be conducted within a Canadian program, as opposed to outsourcing to a foreign partner?*
3. *How should Canada make decisions on foreign partnerships? What criteria should be used to select the partners? What should be the process for this selection and for decisions about the amount of investment in each?*
4. *What role should Neutrons Canada, which is to be established as a national organization with institutional members, play in such decisions and in negotiating the arrangements with the partners?*

5 Building on domestic capabilities

In this section, we briefly review the domestic capabilities on which we can build, and then explore their potential contributions to a coherent national strategy.

> ***Strategy Objective 2: Build on existing domestic capabilities, including full exploitation of the McMaster Nuclear Reactor (MNR), a medium-brightness neutron source.***

5.1 A domestic opportunity to contribute to the global neutron supply

While Canada can partner with other countries to meet its needs for neutron beams (discussed in section 4), it need not focus all its resources on foreign partnerships. The experience of other countries that have lost their own major neutron sources shows that it is extremely difficult to maintain capability in this field without at least one smaller source that can be responsive to the needs of domestic researchers and give experience that enables them to compete for beam time at the major international facilities. Expertise erodes as users relocate to other countries that have a neutron source, or as users change research fields entirely. As a result, many students will lose the experience of performing research at neutron facilities, both domestic and foreign—a factor that has been shown to profoundly impact students' educational achievement and pursuit of careers in innovative sectors (section A6).

While Canada must explore options for new neutron sources (section 8), a new source with enough capacity to meet most of Canada's needs would not be operational for at least a decade, if built completely new. However, the unused potential at the medium-brightness McMaster Nuclear Reactor (MNR) represents an immediate opportunity to rebuild some domestic capability for high-throughput, high-demand experiments. Additionally, it offers an opportunity to add to the shrinking global neutron supply (section 4.3) and align with international efforts to address neutron scarcity. This approach is also in line with international viewpoints. For instance, a key element of Europe's neutron strategy has been to better use medium-brightness neutron sources for high-throughput, high-demand methods (typically, diffraction) and thereby enable high-brightness facilities to focus on methods that most require the highest brightness and that push the boundaries of neutron science (typically, spectroscopy).

The modernization of the MNR has enabled the initial rebuilding of its neutron beam laboratory (section 3.2). McMaster is also a suitable location for a neutron beam user facility, given its range of complementary capabilities: It has the largest group of materials researchers at any university in Canada, as well as one of the most comprehensive sets of materials research infrastructure at any university in the world. McMaster is also well located to support training and outreach, as many universities are located in the region and it is situated less than an hour from the Toronto and Hamilton international airports.

5.2 Full exploitation of the McMaster Nuclear Reactor

The multipurpose MNR is the only financially self-sustaining research reactor in the world, leveraging revenues from medical isotope production, analytical services, and the irradiation of materials—revenues that can subsequently be leveraged for some research and education services. As an example, the MNR supports the aviation industry by providing two neutron beamlines to NRay Services Inc., a company that offers non-destructive imaging of the aircraft turbine blades used in jet engines. Fees from NRay Services help to operate the reactor and provide access to researchers using the reactor's other services. Currently, the reactor's operating hours (16/5) and power are limited by the user fees it generates. Hence, there remains untapped capacity at the MNR facility. While the reactor is operating, it accommodates as many research activities as possible; however, it cannot support further research activities within the limits of its current fiscal model.

The MNR's limitations can be addressed with the investment of both capital and operating funds for the reactor itself as well as for the neutron beam lab. The most needed and most cost-effective capital investment is to add three diffraction beamlines, with associated sample environments and ancillary equipment, to fill out the MNR's diffraction suite (Table 2). This upgrade will enable the MNR to provide about 700 instrument days per year from a set of 5 instruments (Table 3)—a major contribution to Canada's needs. In comparison, the former CNBC provided 1,300 instrument days per year delivered by 6 instruments. The full cost of the capital investment is estimated at $25M, with the beamlines coming into operation over a period of seven years. The cost and timeline of such capital projects might be reduced by acquiring and adapting used equipment from the former CNBC. As these instruments become available at the MNR, operating funds ($2–3M/year) will be essential to maintain the neutron beam lab in a state of readiness for access by visiting researchers, supported by up to 18 full-time professional and technical staff.

Table 2. The MNR instrument suite needed for research on various categories of materials.

Instruments	Status	Energy	Structural	Bio	Quantum
Powder diffractometer	Proposed	✓	✓		✓
Reflectometer	Proposed		✓	✓	✓
Stress scanner	Proposed		✓		
Small-angle diffractometer	Under construction	✓	✓	✓	✓
Single-crystal diffractometer	Operational	✓			✓

Table 3. Comparison of key capacity indicators for experiments using neutron beams at MNR vs. the now-closed NRU reactor.

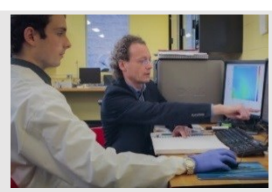
	NRU reactor	*MNR (2021)****	*MNR (Potential)*
*Neutron flux (n/cm²/s)**	30×10^{13}	1×10^{13}	2×10^{13}
*Neutron flux (n/cm²/s)***	48×10^{8}	5×10^{8}	10×10^{8}
Weekly operating cycle	24/7	16/5	24/7
Yearly operating capacity factor	60%	40%	80%
Instruments	6	2	5
Beam days	1300	280	1500

* Estimated thermal neutron flux in the moderator upstream of the beam tubes.
** Thermal neutron fluxes at the monochromator position on the beam lines.
***Assuming the opening of the small-angle diffractometer beamline as a user facility and upgraded beam filters.

A key difference between the MNR as compared to the now-shutdown NRU reactor is the MNR's lower neutron flux and lower operating capacity. This difference can be narrowed with additional operating funds ($7M/year) to double the available beam time (i.e. to boost the reactor's operating cycle from 16/5 to 24/7) and to maximize the quality of the beams (i.e. to double the neutron brightness by raising the reactor power from 2 MW to 5 MW). Continuous, high-power operation of the reactor could be achieved within a few years, for which the limiting factors are the time to attract and qualify sufficient operating staff and the time to procure additional nuclear fuel.

When fully upgraded and operated as described above, the MNR could support a user program on a scale approaching that reached by the CNBC, and could serve about half of the Canadian demand for

Prof. **Maikel Rheinstadter** (McMaster U.) teaches a graduate student to analyse how drug molecules interact with human-like tissues—research that could be advanced using the small-angle diffractometer at an upgraded MNR.



neutron beams and enable research in specific areas, While the MNR would be focused on high-demand 'workhorse' applications for which broad-band, continuous neutron intensities are appropriate, whole categories of experiments, particularly inelastic neutron scattering for the study of quantum materials, would still require access to a much brighter neutron source elsewhere.

5.3 Recent activities toward building domestic capacity

With the support of the CNI working group and 17 universities (described in section 4.6), McMaster University led a 'national' proposal to the CFI 2020 Innovation Fund competition for a $47M infrastructure project (a proposal entitled "Building a Future for Canadian Neutron Scattering"). The proposal requested $25M to complete the neutron beam lab at the MNR by acquiring the neutron beamlines and associated ancillary equipment proposed above (see Table 2). While this capital investment would be a major step forward, operational upgrades will still be needed to fully exploit the MNR and could be pursued as a parallel or subsequent step.

In addition, several Canadian universities are continuing to hire materials researchers who use neutron beams (section 3.1.1). Today, the Fedoruk Centre is inviting Saskatchewan universities to consider establishing a cluster of faculty that apply neutron beams for materials research, and is funding materials research projects that use nuclear tools, including neutron beams.

5.4 Objective 2 Discussion Questions

5. *If the McMaster Nuclear Reactor were fully exploited for neutron beams, what benefits could arise that would be more difficult or impossible to acquire if Canada relied exclusively on foreign neutron sources instead?*
6. *How can Canada best retain, leverage, and plan for succession of its scientific and technical expertise in neutron beam instrumentation and methods?*
7. *In what other ways can Canada build on its domestic capabilities for materials research with neutron beams?*
8. *What role should Neutrons Canada play in fully exploiting the McMaster Nuclear Reactor, in fostering domestic expertise, and in otherwise building Canada's domestic capabilities?*

6 Exploring new neutron sources for the long term

In this section, we briefly review the potential for investment in new neutron sources for the long term, and then consider activities to explore such options as part of a coherent national strategy.

Strategy Objective 3: Explore and invest in developing new neutron sources for the long term.

6.1 Global context

As described in section 4, countries around the world are reinvesting heavily in neutron sources—but the supply of neutron beams is shrinking as older sources retire faster than new ones come online. In an environment in which access to neutrons is increasingly difficult, Canada cannot expect to get a "free ride" on others' investments. To continue as a participant in this field in the coming decades, Canada must prepare to invest in new facilities for the long term, whether domestic, foreign, or both.

Canada's long-term strategy can be informed by, and complement, efforts in the US and Europe to plan for the future: The US is planning for the Second Target Station at the Spallation Neutron Source (SNS), while also examining conceptual designs for major refurbishment or new construction of reactor sources. Europe is focused on completing the European Spallation Source (ESS) and has gathered its existing facilities together in the League of advanced European Neutron Sources (LENS) to make the most effective use of existing facilities and address strategic planning for future neutron sources. One element of Europe's strategy is to better use medium-brightness neutron sources for high-throughput, high-demand methods (typically, diffraction), and thereby to enable high-brightness facilities to focus on methods that most require the highest brightness and that push the boundaries of neutron science (typically, spectroscopy). Further, since building new reactors is politically difficult in Europe, and since high-brightness reactors and spallation sources have huge price tags, the European strategy includes exploring the feasibility of innovative accelerator-based technologies for lower-cost, low- and medium-brightness sources.[17] Thus, Compact Accelerator-based Neutron Sources (CANS) are being developed to determine their feasibility as an alternative to building new reactors, and LENS is developing a position paper on how such technology could fit into a European roadmap for the future of neutron sources.

6.2 Canada's options

Options for the long term that will advance Canada's capabilities and complement global efforts to reinvest in neutron facilities include the following:

- Build a new domestic reactor source of neutrons, which could range from a $500M dedicated neutron beam reactor to a $1–2B multipurpose research reactor. Historically, consideration of a multipurpose reactor in Canada has been tied to the needs of the nuclear power and medical isotope sectors. The Canadian neutron beam user community could prepare to participate in such considerations as a coherent constituency alongside representatives from these sectors.
- Develop a Compact Accelerator-based Neutron Source in order to provide a new medium-brightness source to serve much of Canada's needs, which may be achievable for $100–200M.
- Make major contributions to new multinational sources and participate in their development. The ESS and the Second Target Station at the SNS are the known options for participating in world-leading capital projects that will offer Canadians access to high-brightness neutrons for decades into the future. Given the smaller size of Canada's scientific community, building its

[17] Neutron scattering facilities in Europe—Present status and future perspectives. 2016. ESFRI Scripta Volume I. esfri.eu/esfri-scripta-series. See also: France: Frédéric Ott. Compact Neutron Sources for Neutron Scattering. [Technical Report] CEA. Paris Saclay. 2018. <cea-01873010>; Germany: Rücker et al. The Jülich high brilliance neutron source project. doi.org/10.1140/epjp/i2016-16019-5.

own $2–3B spallation source to compete with these facilities is not an attractive option, especially since it would be for neutron beams only, rather than a multipurpose facility.

Scientific and business case development for these options should be a significant activity in the next few years. While reactor technologies are already established, there is still substantial research, development, and demonstration of technologies needed for new accelerator-based sources. Canada could learn a lot from international collaborations developing technology for the European Spallation Source or for a CANS. Regardless of the neutron source selected, technology development for the neutron beam instruments will be needed. Thus, Canada's strategy must include a program that encourages continuous renewal of Canadian expertise in these areas, so Canadian scientists can still contribute to the development of world-leading capabilities and can design equipment that Canadian researchers need. This strategy will enable Canada to participate in world-leading international science projects while developing its own CANS or reactor-based sources. Outcomes of such scientific and business case development activities will inform whether a new domestic reactor for neutron beams is needed, and how much access to foreign facilities will be required for the long term.

6.3 Current activities toward the long term

The University of Windsor is leading a feasibility study for a CANS funded by the New Frontiers Research Fund Exploration Stream. The study is collaborating with global experts in CANS technology to determine how to design a prototype CANS for Canada. Development of the prototype and associated demonstration activities could be a $20M project over several years. These activities would help Canada to determine how CANS technology can best contribute to the long-term strategy for materials research using neutron beams in Canada.

6.4 Objective 3 Discussion Questions

9. *What are the benefits of participating in multinational consortia to plan and build new neutron sources, in addition to gaining access to beam time in the future?*
10. *What are the benefits of developing a new domestic neutron source that are not achievable through such participation in multinational consortia?*
11. *How can the Canadian neutron beam community prepare to participate in national decision-making processes about new neutron sources, as a coherent constituency alongside the nuclear power and isotope production communities?*
12. *What role should Neutrons Canada play in planning for new neutron sources for the long term? Or in research, development, and demonstration projects for such sources?*

7 Creating a new framework

This section briefly describes the historic framework for stewardship of neutron beams in Canada; lessons to be learned from the past and present context; and the potential for a new university-led framework centred on a new entity, Neutrons Canada.

Strategy Objective 4: Create a new, national governance and management framework for the activities under Objectives 1–3.

7.1 Historic framework for neutron beams

In the early 1990s, the neutron beam facilities (later known as the CNBC) at the NRU reactor formally opened for user access through peer-reviewed competitions. This was made possible through $4M of joint funding from NSERC (through McMaster) and AECL to build two new beamlines. A further beamline, costing $2.4M, was completed in 2007 via CFI funding through Western University. Academic users of these facilities were organized into a not-for-profit corporation, the Canadian Institute for Neutron Scattering (CINS). Among other roles, CINS oversaw the peer review system for access and the management of NSERC operating grants from 1992 to 2013 (cumulative value of $14M) via the Major Facilities Access program and, later, the Major Resource Support (MRS) program. These grants were awarded to the then-presidents of CINS, who represented applicant teams from 10 or more universities. The grants partially offset the cost of maintaining the CNBC in a competitive state of readiness for users.

NSERC funds covered less than 10% of the full cost of operating the former CNBC (including attributed costs of the NRU reactor), while academic users became its primary beneficiaries from the 1990s onward. The balance of cost was covered by federal agencies. AECL, a crown corporation under Natural Resources Canada (NRCan), produced the neutrons at its NRU reactor as an in-kind contribution valued at about 65% of the total operating cost; the National Research Council (NRC) took over the direct operation of the neutron beam facilities in 1997 and covered most of the remaining 25% of the operating cost, which until then had been covered by AECL as well.

From 1998 until 2012, this framework was highly effective at enabling the research community to access neutron beams. This was reflected in peer reviews for NSERC and the NRC,[18] as well as reviews for the Canadian Council of Academies and the Treasury Board. But this framework did not give an effective voice to university stakeholders, nor was it transparent to universities the extent to which their research programs were being supported by neutron beams. In 2012, when university administrations did not appear engaged in the federal government's consultation about the restructuring of AECL, the government perceived no strong constituency for materials research with neutron beams in Canada.

The framework broke down when the federal funders underwent restructuring or the redirection of mandates. In 2012, NSERC withdrew from supporting operations of major science infrastructure in general, placing a moratorium on its MRS program. The NRC, shifting its focus to industry-driven research, divested responsibility for the CNBC. NRCan, while considering a possible nuclear innovation agenda, authorized AECL to take responsibility for the CNBC's operation, beginning in 2013, to ensure that Canada retained expertise that might be needed to support a potential nuclear innovation agenda in the future. Canadian Nuclear Laboratories (CNL), created through the restructuring of AECL in 2015, was contracted to continue operating the CNBC until the NRU reactor permanently shut down in 2018.

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[18] For example, the CNBC's percentage of beam time delivered to users was "an extraordinarily high number" and, in the case of industry clients, was "matched by no other neutron scattering facility [in the world]." Peer Review of the Steacie Institute for Molecular Sciences. Final Report of the Institute Review Committee (October 2004).

After the decision to permanently shut down the NRU reactor was made in 2015, none of these agencies— NRCan, AECL, CNL, the NRC, or NSERC—retained any mandate to provide neutron beam infrastructure for the national user community beyond the reactor's closure. At this time, Canada's neutron beam users, organized via CINS, appealed to university executives for help, leading to the formation of the Canadian Neutron Initiative in 2016.

7.2 Evolving framework for Major Research Facilities

The scale and the complexity of the infrastructure needed for Strategic Objectives 1–3 would qualify that set of infrastructure as a Major Research Facility (MRF), as defined in Canada's Fundamental Science Review;[19] it would be comparable to TRIUMF, Compute Canada, Ocean Networks Canada, the Canadian Light Source, and others. Canada's model for the stewardship of MRFs has been evolving, and it is often *ad hoc*. MRFs in Canada have been increasingly operated by entities outside government, and there is a trend toward operation by not-for-profit corporations owned by multiple member institutions.

An example of this *ad hoc* approach was "Canadian Participation at the Spallation Neutron Source" (SNS), an agreement between McMaster University and the SNS in the US that resulted from an award from the only competition of the CFI's International Access Fund in 2003. The funds were awarded as a capital contribution that the SNS used to develop neutron beam instruments. In return, the SNS granted Canadians access to beam time for a limited period. While this project was successful in accomplishing its aims, this approach to governance is not ideal, as it raises questions about sustainability (Are competitions for capital funds appropriate to sustain long-term operational needs?), credibility of national representation (On what basis can one university represent Canada?), and the appropriate distribution of administrative burden (Should one university be solely responsible for administering a program, when the intended benefit is for a national community?).

More recently, the CFI has encouraged improvements in the governance of large projects that serve national communities. Often, a national entity, such as an MRF, will support an application by a team of institutions for a large award and then implement the project on behalf of its scientific user community. Further, the CFI's Innovation Fund has evolved in recent years, which has enabled the neutron beam user community to compete for an award similar to "Canadian Participation at the SNS"—but even the CFI acknowledges that the Innovation Fund is not designed for supporting national science facilities, let alone access to such facilities abroad, and it is examining better ways to support such facilities.[20]

Today, there remain serious challenges in the stewardship of MRFs in Canada—notably, the need for road-mapping Canada's needs for MRFs so as to inform orderly decision making about lifecycles as well as choices between options for new MRFs. Canada's Fundamental Science Review made recommendations to address these challenges, which were reviewed by Dr. Mona Nemer, Chief Science Advisor for Canada, who advised the federal government to take a portfolio approach by designating a central steward to handle oversight and long-range planning of MRFs.[21]

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[19] Canada's Fundamental Science Review. "Investing in Canada's Future: Strengthening the Foundations of Canadian Research." April 10, 2017. http://www.sciencereview.ca/eic/site/059.nsf/eng/home

[20] The Canada Foundation for Innovation, 2018. *The Canada Foundation for Innovation's Major Science Initiatives Fund: A report on the advancement of research facilities funded between 2012 and 2017*. Ottawa, Ont. https://www.innovation.ca/about/news/report-highlights-impact-program-fund-canadas-nationally-significant-research-facilities

[21] Office of the Chief Science Advisor of Canada. Annual Report of the Chief Science Advisor 2019-2020. http://science.gc.ca/eic/site/063.nsf/eng/h_98146.html

7.3 Lessons for the future

Key lessons from these past experiences include:

- The new framework for materials research using neutron beams should adopt the best current practices for MRFs and should be prepared to harmonize with the changing policy landscape for the governance, operations, and funding of MRFs in Canada.
- The funding for the framework must flow from an agency whose mandate includes the provision of research infrastructure.
- The new framework must be led by the academic sector, as it comprises the majority of users of neutron beams.
- The engagement of university administrations is required, in addition to that of researchers.
- Major funding applications for infrastructure should be coordinated within the national framework.
- The infrastructure should be operated by a national entity with a mission that includes enabling access by the user community.
- A national entity is needed to represent Canada in the negotiation of agreements with foreign neutron beam facilities.
- An organized user community can make valuable contributions by overseeing, and cooperating with, such a national entity.

7.4 Neutrons Canada

Building on these lessons, the Canadian Neutron Initiative has envisioned a new national entity, "Neutrons Canada"—a key part of Objective 4—that can manage the framework's strategic activities (Objectives 1, 2, and 3) as a coherent program, play a unifying role for the neutron beam community in Canada, and be a credible and trusted institutional voice. The Roundtable Meeting towards the establishment of "Neutrons Canada" was attended by Vice-Presidents of Research (VPRs) or their designates from 16 universities. The participants formed a consensus around three propositions:[22]

1. Canada should maintain its leadership role in materials research with neutron beams;
2. Canadian universities need to establish a pan-Canadian, university-led framework to govern, manage, and represent Canada's program for materials research with neutron beams; and
3. Canadian university VPRs should devote their own time and attention to help shape this new framework and to ensure ongoing engagement of their universities as Institutional Members.

The CNI working group will act as a steering committee for the establishment of Neutrons Canada.

7.4.1 Roles

Potential roles and responsibilities for Neutrons Canada identified at the Roundtable Meeting include:

- To serve as a body that coordinates the neutron beam community in planning, communicating, and shepherding major neutron initiatives through the decision-making process.
- To serve as a body that delivers the major neutron initiatives of Member Institutions.
- To provide stewardship, including the governance and management of resources, for a national program for user access to neutron beam facilities, both domestic and foreign.

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[22] Canadian Neutron Initiative. Canadian Leadership in Materials Research with Neutron Beams: Report on a Roundtable Meeting towards the establishment of "Neutrons Canada". Available from: https://fedorukcentre.ca/resources/canadian-neutron-initiative-cni.php

- To act as an umbrella organization for the highly qualified staff required by a national neutron program, channeling Canadian talents and leadership in national and international activities.
- To operate neutron beam facilities, particularly domestic ones.
- To negotiate and provide oversight for international partnerships.
- To serve as a credible institutional voice regarding neutron beam infrastructure (i.e. a voice that is distinct from advocacy groups).
- To network with other MRFs towards a coherent national framework for all Canadian MRFs.

7.4.2 Operations

Within the field of materials research using neutron beams, the most comparable organization to Neutrons Canada is the Jülich Centre for Neutron Science (JCNS) in Germany. The JCNS is the *only example in the world* of a neutron user program that has operated successfully beyond the closure of its neutron source. Its mode of operation as a 'virtual lab' that relies on accessing neutrons elsewhere (i.e. at 'outstations') is particularly instructive to Canada.[23] The JCNS offers access to 18 beamlines at three outstations in Germany, France, and the US, and is developing beamlines for a fourth outstation in Sweden at the soon-to-be opened European Spallation Source. The JCNS supports users at its outstations, develops neutron beamlines and methods (including the design and construction of instruments), and provides scientific IT services, in addition to conducting its own in-house research programs. The JCNS is also now being emulated by the French Alternative Energies and Atomic Energy Commission (CEA) in France in order to preserve its core of expertise at the Laboratoire Léon Brillouin, which was centred on its recently shut down Orphée reactor.

Within Canada, there are a number of research organizations for other scientific fields that operate or participate in MRFs that are similarly remote from their users, and often remote from their central administration as well. These organizations (sampled in Table 4) all foster their corresponding scientific communities, providing much more than just bare access to equipment.

Table 4. Examples of Canadian research organizations that operate or participate in MRFs that are remote from their users (and, with the exception of POLAR and the former CNBC, remote from their central administrations as well).

Organization	**Role in providing access to outstations and fostering scientific capabilities**
National Research Council (NRC) Herzberg	Facilitates Canadian participation in international astronomy facilities as "Canada's gateway to the stars."
Polar Knowledge Canada (POLAR)	Responsible for strengthening Canadian leadership in polar science and technology, in addition to providing access to the Canadian High Arctic Research Station.
TRIUMF	Acts as Canada's gateway for involvement in CERN, the world's largest particle physics project, located in Switzerland, in addition to providing its own facilities for access.
Canadian Light Source	Locates some Canadian staff at foreign light sources to facilitate Canadian research.
Canadian Neutron Beam Centre (now closed)	Fostered Canada's capabilities for materials research with neutron beams by providing access for expert and non-expert users, by training new users, and by developing beam equipment and methods.
ArcticNet	Built around the *CCGS Amundsen* research icebreaker, ArcticNet fosters the scientific capability needed to study, model, and manage the changing Canadian arctic.
Compute Canada	Operates a federation of high-performance computing systems distributed at universities.
CMC Microsystems	Fosters the capabilities of Canadian universities to design and fabricate micro and nanodevices for R&D purposes by facilitating access to specialized, expensive fabrication equipment and capabilities that are available at cleanroom facilities elsewhere in the country, in addition to providing its own such services.

[23] Discussion on a Virtual Institute for Neutron Scattering – A concept paper (November 2015). http://cins.ca/docs/vins.pdf

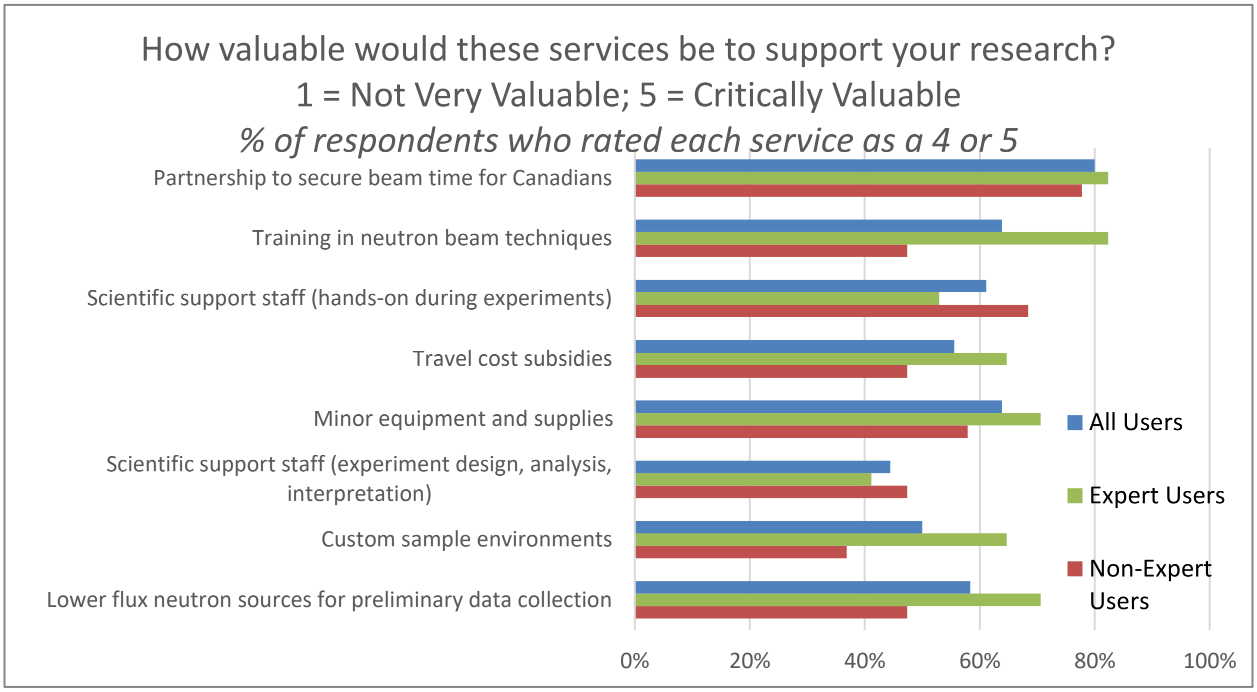

Figure 11. Percentage (%) of respondents who rated each service as highly or critically valuable (i.e. 4 or 5 on a scale of 1–5). Source: CINS-CNI 2020 survey.

To understand how a coordinated, national program for the stewardship of Canada's capability for materials research using neutron beams could foster the Canadian neutron beam community going forward, some key findings of the 2020 survey of neutron users are instructive (Figure 11 and Figure 12):

1. The most valued service would be to establish partnerships that secure access to beam time for Canadians (Figure 11) and thereby reduce the biggest barrier to access. Notably, the difficulties of accessing beam time are not only deterring new experiments (discussed in section 4.4), but are also hindering users from seeing a neutron beam experiment through to publication, because follow-up measurements are often needed to complete the project and satisfy reviewers (Figure 12). Provision of "Canadian beam time" at a foreign facility would enable new experiments as well as follow-up measurements.
2. Provision of training in neutron beam techniques would be the second most valued service (Figure 11). Training can help users compete for neutron beam time successfully, and also help them to address some challenges in data analysis and other identified barriers such as "time required to invest in the experiment" (Figure 12). In fact, over 80% of expert users (see section 3.1.3 for the distinction between expert and non-expert users) would highly value training in neutron beam techniques—demonstrating that training would be just as valuable among expert users as partnerships to secure beam time for Canadians (Figure 11).
3. Provision of scientific support staff to assist in various steps of a research project (e.g. in preparation for an experiment or later analysis of results) would also be highly valued (Figure 11). Nearly 70% of non-expert users would highly value hands-on scientific support. They also highly rated off-site scientific support more frequently than did expert users. Lack of scientific support for data analysis was the challenge most frequently mentioned by all respondents in completing a neutron beam experiment (Figure 12). Furthermore, provision of scientific staff is key to providing the training valued by all respondents.

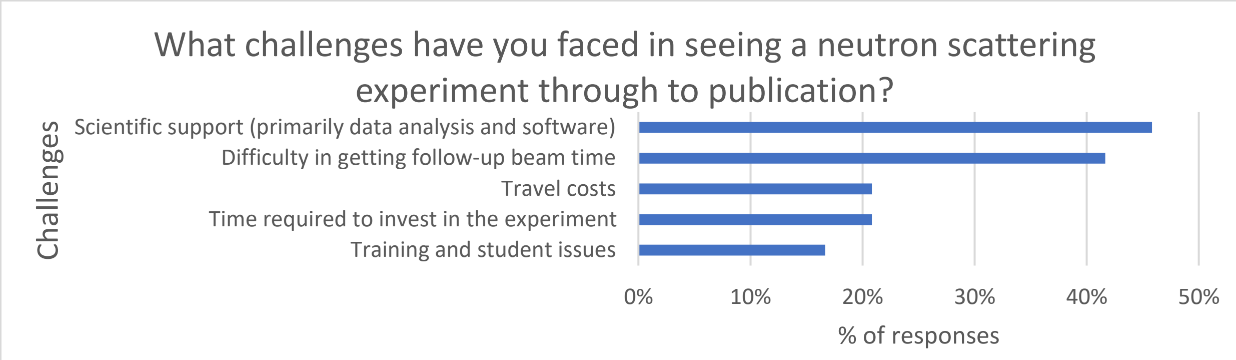

Figure 12. In the above open-ended question, respondents described barriers they face to completing publications after they conduct a neutron beam experiment. Identified barriers were grouped into the categories shown. Source: CINS-CNI 2020 survey.

4. All of the services identified in the survey (Figure 11) would be valued by Canadian researchers (the lowest average rating was 3.4 out of 5).
5. Expert and non-expert users have different needs and would value the services offered by such a program differently (Figure 11). In addition to the above-mentioned differences, the survey revealed that more expert users than non-expert users would highly value the provision of (1) travel cost subsidies, (2) minor equipment and supplies, (3) custom sample environments, and (4) opportunities for preliminary data collection using low-flux instruments.

Considering the experience of the JCNS, the Canadian Neutron Beam Centre, and other Canadian MRFs, and taking into account the insights gained from such stakeholders, the following may be proposed as ways for a national entity to provide direct support to maintain and rejuvenate the research community:

- Negotiating partnership agreements for access to neutron sources on behalf of Canada, and securing funding for those partnerships.
- Supporting individual experiments, including by providing assistance in designing experiments and competing for beam time; hands-on assistance during the experiments themselves; support for data analysis and publication of results; providing minor equipment and supplies for experiments; and offsetting travel costs to the outstations to perform experiments.
- Developing, designing, and fabricating beamline equipment to respond to the emerging scientific requirements of Canadian researchers, and commissioning these tools for use at the outstations.
- Providing specialized computing systems for data management and analysis.
- Reaching out to attract new users and train non-experts; sponsoring students and post-docs; and organizing neutron scattering workshops.
- Partnering with universities across Canada to establish research and education programs, which may include creating faculty positions in neutron scattering.
- Developing commercial activities, including marketing to industry, contracting for neutron beam services, facilitating the supply of services to neutron beam facilities, and spinning-off technologies to Canadian businesses.
- Delivering science communications and outreach to stakeholders, students, and the public
- Promote equity, diversity and inclusion in the neutron beam community (see section 8).

For all of these operational services, dedicated scientific and technical personnel are critical. Leading neutron user facilities around the world operate with six to ten staff per beamline,[24] while the CNBC, with only three or four staff per beamline, was described by one international peer review as "a world-class program run on a shoestring."[25] Provision of adequate personnel is a function of all successful MRFs. The severe limitations of relying on the 'volunteerism' of graduate students and professors, instead of on dedicated staff, to operate shared university-based resources was a major reason why high-performance computing facilities federated to become Compute Canada, now a unified MRF.[26]

A national entity could also be the body that ties the program together to ensure that all activities at the various outstations are prioritized, supported, and managed in alignment with Canadian strategic directions. Centralization of various administrative functions can avoid duplication and raise the quality of delivery through dedicated staff to provide various functions, such as:

- Administering research funds, enabling procurements, analyzing program performance, and reporting for accountability.
- Allocating resources, such as beam time through a user proposal review system or capital investments through competitive proposals for upgrades of neutron instruments.
- Providing secretarial support for governing bodies, including a Board of Directors and scientific advisory committees.
- Providing other overhead functions, including human resources, legal services, IT, and safety and regulatory compliance.

7.4.3 Governance

Neutrons Canada should be positioned as managing an MRF-scale program within the funding jurisdiction of Innovation, Science and Economic Development Canada (ISED) and its portfolio of agencies (e.g. the CFI). As such, it should adopt emerging best practices for the governance and management of MRFs. The CNI working group envisions Neutrons Canada to be a university-led entity whose Members are organizations (primarily universities) with an interest in neutron beams. Members would elect an independent Board of Directors on the basis of governance competencies, technical knowledge, and the principles of equity, diversity, and inclusion (Figure 13). Members of the Board would not represent interests of neutron sources or host institutions. The Board would appoint an Executive Director ("Director") to lead the organization.

The Director's highly qualified staff would operate the national program, including implementing development projects and facilitating user access to neutron sources in Canada and abroad. This program could include the direct operation of domestic facilities (e.g. a neutron beam lab at the McMaster Nuclear Reactor). Neutrons Canada would act as a paying customer of the neutron sources and would negotiate terms of engagement with each source, which could include deployment of employees to those facilities to support user access. CINS would represent the user community, providing advice to the Director, and could coordinate with Neutrons Canada on strategic planning and funding applications. Other advisory committees could extend the expertise of Neutrons Canada as

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[24] Analysis by Ken Andersen, Head of Neutron Instruments Division, European Spallation Source. Oct. 2016.
[25] According to the review, the CNBC's percentage of beam time delivered to users was "extraordinarily high" and, in the case of industry clients, the CNBC was "matched by no other neutron scattering facility [in the world]" (see footnote 13).
[26] "The current 'volunteerism' model is an enormous burden at all levels." Compute Canada: MSI Fund Full Proposal (2011).

needed, and could include experts from industry, from other MRFs, and from the international neutron community.

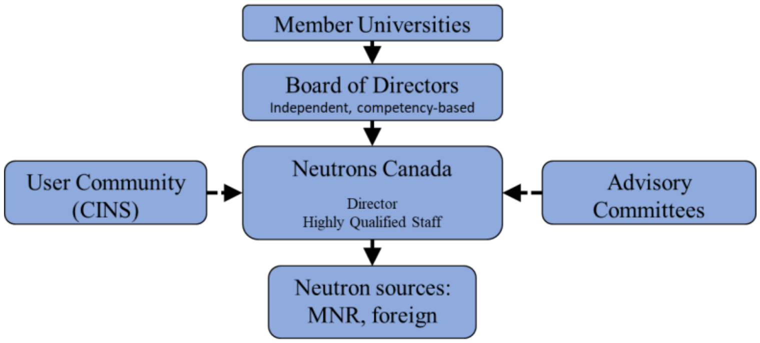

Figure 13. The proposed governance structure for Neutrons Canada.

7.5 Objective 4 Discussion Questions

13. *What benefits arise from having a national organization, Neutrons Canada, to perform functions such as:*
    a. *Planning and shepherding major neutron initiatives through decision-making processes and implementing major neutron initiatives?*
    b. *Governing and managing a national program for user access to neutron beam facilities, both domestic and foreign?*
    c. *Negotiating with foreign facilities?*
    d. *Maintaining the continuity of expertise needed to support both (i) the operations of neutron facilities, and (ii) the implementation of capital projects?*

14. *What is the potential value of centralized efforts to engage industry in (i) applying neutron beams, (ii) supplying services to develop neutron beam facilities, and (iii) spinning-off technologies?*

15. *What value can a neutron beam program contribute to science outreach to youth and the general public?*

8 Equity, Diversity, and Inclusion

Increased equity, diversity, and inclusion (EDI) in the Canadian research enterprise is a goal of federal science policy, in order to advance knowledge and innovation to respond to local, national, and even global challenges. Many scientific fields in Canada are not reflective of the composition of the general population, and the materials research community is no different. In 2017, the CNBC conducted an analysis of 105 Canadian professors who were known to have used neutron beams in recent years, whether in Canada or at foreign neutron sources; results revealed this group to be 11% female, and 14% were visible minorities. Canadian professor respondents to a 2020 survey of neutron beam users identified as 20% female, and 19% were visible minorities; no respondents declared themselves to be Indigenous or a person with a disability.[27] The population of students and post-docs who access neutron beams is known to be much more diverse. In the last five years of the CNBC's operations, students and post-docs who conducted experiments there were 32% female, and 42% were visible minorities.

Now, lack of access to neutron beams may further frustrate efforts to promote EDI within the materials research community. EDI literature has often identified the challenges of relocation to pursue scientific careers as a barrier to gender equity.[28] Women are more likely than men to face dilemmas of sacrificing family obligations or interests by relocating, or sacrificing career prospects by not relocating. Men are more likely than women to move to another country to be able to access a neutron source, or another Major Research Facility, if it is central to advancing their careers. Women will be more likely than men to redirect their research interests to avoid such a move, even if new lines of query may be less promising. Women often have larger caregiving responsibilities, which also makes it difficult to travel to neutron sources, even for short visits to conduct experiments. The COVID-19 pandemic has amplified this disparity, with more women being responsible for children being schooled from home.

A national program that facilitates user access to neutron beam facilities can offer various means to address such disparities. The program could ensure that Canadians in materials research fields are not faced with the prospect of having to move their families abroad in order to be competitive. It could also create opportunities for remote experiments, or offer support for childcare as needed to ensure they can travel for experiments.

More generally, such a program would also be best positioned to promote EDI and reduce systemic barriers across the community. It could promote a positive environment where the values that support EDI are upheld in the activities that it oversees. For instance, a national program could:

(1) Ensure that any competitive peer-review processes to allocate beam time at domestic facilities, or "Canadian" beam time at foreign facilities, are conducted according to best practices of EDI;

(2) Conduct national training programs (e.g. summer schools at neutron sources) and offer other opportunities (e.g. scholarships, fellowships, hiring) to ensure that access is equitable across the Canadian community;

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[27] Summary of Results from the CINS-CNI 2020 Survey. Oct 5, 2020. Available from: https://fedorukcentre.ca/documents/resources/cni/cins-cni-survey-2020-report.pdf

[28] For example: Louise Ackers. (2004) Managing relationships in peripatetic careers: Scientific mobility in the European Union. Women's Studies International Forum. 27(3): 189-201

(3) Ensure that early career researchers are included in the development teams for major neutron infrastructure, and that they are integrated in a meaningful way that supports their leadership development throughout the project; and

(4) Ensure that such projects are conducted with a culture of belonging for everyone, which is created by a collaborative, supportive, and respectful environment.

In contrast, foreign neutron facilities cannot be expected (on their own) to promote Canadian EDI objectives. The unique challenges of including Indigenous Canadians, for example, may not result in action without Canadian leadership. While other countries share some of our EDI objectives, such as removing gender barriers in science, their approaches may or may not reflect Canadian practice.

As a result of promoting EDI in science, the Canadian neutron beam user community will be more diverse and inclusive of gender, career stage, culture, discipline, and many other attributes, leading to more innovative ideas and outcomes, enriching everyone.

8.1 EDI Discussion Questions

16. *What role can a national neutron strategy play in promoting equity, diversity, and inclusion, recognizing that groups such as women, racial and ethnic minorities, Indigenous communities, and persons with disabilities are presently underrepresented in the neutron beam community?*

17. *What role can a national neutron strategy play in fostering expertise among atypical users, such as researchers from less research-intensive institutions, including smaller, rural, and Northern universities, colleges, and polytechnics? How can we ensure that the needs of these users are considered?*

18. *How can Canada ensure equity, diversity, and inclusion in the neutron beam user community while relying on access to foreign facilities?*

19. *When new neutron beam infrastructure is to be constructed in Canada, how can local and Indigenous communities be engaged to ensure a meaningful partnership?*

9 Fiscal model of a national program

This section discusses a financial model for a full-scale national program that includes all the strategic activities discussed in previous sections. The financial model focuses on the program's first seven years of operation.

Such a program is expected to cost about $20–25M per year to operate. For comparison, Europe's approximately €500M in annual expenditures for its 9 neutron facilities used by about 5,000 researchers scales to about $50M per year for Canada. If the annualized capital cost of a major investment in a new domestic neutron source were added to the Canadian program, the cost could approach this 'European scale' of investment. The anticipated $20–25M per year for the program is much less than the $100M per year or more that Canada had invested in the NRU reactor, which was operated not just for neutron beams, but also for isotope production and for the irradiation of fuels and materials for nuclear power.

Furthermore, Canadian university research labs that access neutron beams—whether frequently or occasionally—represent investments of about $90M per year from all sources. Continuing to provide researchers with access to neutron beams is important to ensure a maximum return on these other investments.

9.1 Cost model

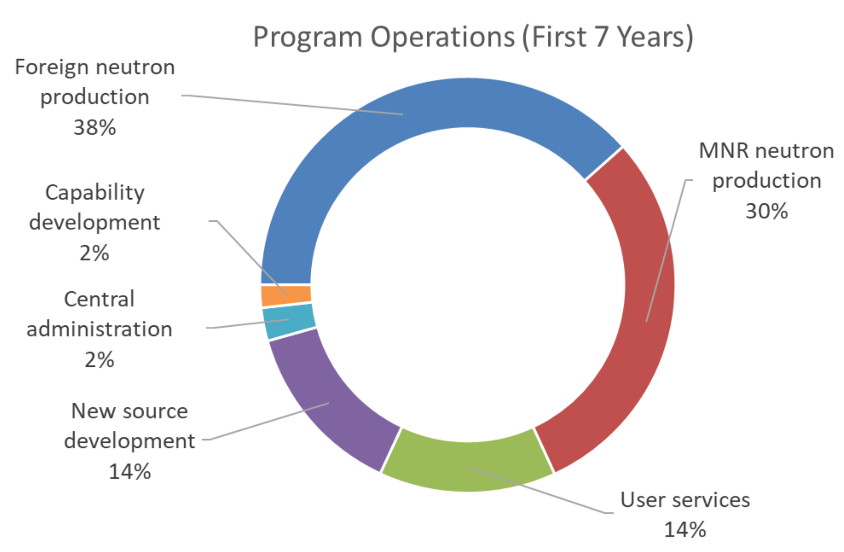
The scale of the proposed program is grounded in the number of users of, and demand for, neutron beam time during the 15 years leading up to the closure of the CNBC and in the decade when Canada had an agreement with the SNS. The total beam time used by Canadian researchers has historically been about 1,300–1,400 CNBC-equivalent beam days per year. The measurement unit 'CNBC-equivalent beam days' reflects adjustments for higher or lower brightness elsewhere (e.g. a beam day at the SNS could be considered equivalent to three beam days at the CNBC).

The following cost model assumes that the strategic activities identified in this discussion document will be implemented over the next several years. This scenario also assumes:

1. Sufficient contributions to foreign partnerships to meet the full Canadian demand for access to neutrons in the short-term (Objective 1);
2. Achieving full exploitation of the McMaster Nuclear Reactor by the end of year 7 (Objective 2);
3. Research, development, and demonstration of technology for a new neutron source (Objective 3); and
4. A new entity, Neutrons Canada, that manages the national program, providing all the potential functions outlined in section 7.4 (Objective 4).

The costs for the program are grounded in the known costs of: (1) operating a domestic neutron beam laboratory (i.e. the CNBC); (2) operating the McMaster Nuclear Reactor; (3) beam time at foreign facilities; and (4) recent projects to develop neutron beam infrastructure. The breakdown of the distribution of the costs between activities and over time are presented here (Figure 14) as a likely scenario for illustrative purposes, as these details are subject to the emerging needs of Canadian neutron beam users and negotiations with the neutron sources. The costs are presented as full costs of the activities, except for certain costs that must be provided by program hosts (e.g. the provision of buildings).

The total costs over the first seven years of operations in this scenario average $20M per year, in addition to a $25M capital project to complete the neutron beam lab at the McMaster Nuclear Reactor.



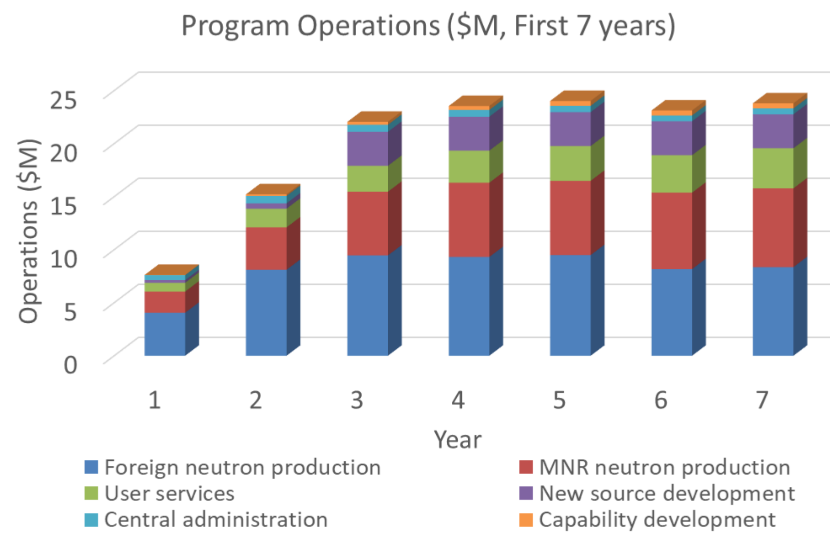


Figure 14. Illustrative breakdown of the first seven years of operations of a full-scale Canadian national program for materials research with neutron beams, with a distribution of costs by various functions. "Operations" excludes a $25M capital project to complete the neutron beam lab at the McMaster Nuclear Reactor. Key: Foreign neutron production = Cash to foreign partners; MNR neutron production = Cash to the MNR as the neutron source; User services = Operations of neutron beam instruments at the neutron sources (including staff), as well as travel and a beam time allocation system; New source development = Research, development, and demonstration of technology for a new neutron source; Capability development = Outreach and training to foster capability to use neutron beams; and Central administration = Governance, management, and common services.

9.2 Funding model

The full-scale national program would best be funded and managed as a unit, similar to other programs based on MRFs. However, $20–25M per year is more than can be sustained through existing science funding competitions, although efforts are underway to obtain some pieces of the program attainable via such competitions (see section 10). In the absence of a comprehensive framework for funding MRFs, the program's funding must be *ad hoc* for now and specially considered by the Government of Canada. The Canadian Neutron Initiative (CNI) has recommended that the Government of Canada commit $124M for the first seven years of the program's operation, with five-year renewable funding terms. A commitment to the first seven years will enable orderly planning and implementation of activities that require substantial lead time, such as upgrading the capacity of the McMaster Nuclear Reactor.[29]

The CFI is emerging as the leader in funding the operations of shared, university-based research facilities. Therefore, the CNI has proposed that the CFI is best positioned to act as the funder and overseer of the program, at least until a new framework for MRFs—such as was proposed by Canada's Fundamental Science Review—emerges. The proposed five-year renewable term is consistent with the CFI's Major Science Initiatives Fund.

When fully established, the new framework should include cost-sharing with the provinces; however, support for materials research using neutron beams has been a matter of federal jurisdiction. Continued federal leadership in funding is essential, especially for the program's international-facing activities. For components of the program hosted in Canada, a 60% contribution from the CFI is consistent with Canada's Fundamental Science Review's recommendation for MRFs.[30] For the partnerships with foreign facilities, the federal government may need to provide nearly all (if not all) of the Canadian contribution. Revenue from industry fee-for-service work may reach 2–3% as the program matures and should be reinvested in improvements to capabilities and services offered to industry and other users.

[29] Canadian Neutron Initiative. Submission for the Pre-Budget Consultations in Advance of the 2019 Budget. August 2018. http://cins.ca/docs/FINA_2018.pdf

[30] Canada's Fundamental Science Review. "Investing in Canada's Future: Strengthening the Foundations of Canadian Research." April 10, 2017. http://www.sciencereview.ca/eic/site/059.nsf/eng/home

10 Conclusion: A roadmap to restoring access to neutron beams

Canada's challenges to protect the health and safety of our communities, to ensure a clean and sustainable environment, and to provide high-quality meaningful employment requires a complete twenty-first century scientific toolkit—including neutron beams—for developing materials that underpin technology solutions.

A national neutron strategy will provide a roadmap for Canada to put into place the required infrastructure and framework to enable Canadians to use neutron beams to meet such challenges. Specifically, **Canada must (1) restore access to neutron beams for its researchers immediately through foreign partnerships with high-brightness neutron sources in other countries. Canada must (2) complete the neutron beam lab at the McMaster Nuclear Reactor to provide some domestic capacity in the medium term. Canada must (3) explore long-term options for new neutron sources. Finally, Canada must (4) create an excellent framework for the governance and management of the above activities to ensure responsible stewardship and optimal performance of the major public investments required.**

Accomplishing these objectives will ensure that whenever any of the thousands of Canadian scientists and engineers who conduct research on materials encounter questions that require neutron beams, they will be able to get the answers they need using these versatile and irreplaceable tools for materials research.

As a result of having a complete scientific toolkit, Canadians will accelerate the pace of innovation to make impacts on Canada's social, environmental, and economic challenges. New insights into the relationships between the structure and properties of a material and its manufacturing methods will drive technological innovations that will range from enabling the advanced manufacturing of clean and energy-efficient vehicles, to ensuring safe and reliable clean energy production through high-performing materials in power stations, to fighting diseases such as Alzheimer's and COVID-19 through better understandings of their molecular mechanisms. Canadians will also lay foundations for breakthroughs in new materials with greatly enhanced performance that will have a transformative influence on many technologies—**and with such innovations come the promise of enhanced quality of life for all Canadians.**

Appendix A: Impact of materials research using neutron beams

Canada's challenge is to build an economy that is clean and sustainable, offers high-quality, meaningful work, and provides safe and secure communities. Such an economy is propelled by research and innovation.

We can innovate to protect the environment and drive growth. We can develop clean energy technology for the electricity grid. We can push the limits of materials for our cars, planes, and ships to use less energy. We can exploit alternative power sources to reduce production costs and reduce or eliminate greenhouse gas emissions. We can develop new materials and nanotechnologies to create the next generation of electronic and medical devices. We can develop new ways of making materials, like 3D printing, to enhance productivity.

We can innovate to improve life in Canada and around the globe, including for the vulnerable. We can make our military more agile and less dependent on oil through the application of new, lightweight armour materials. We can reduce threats with technologies that help prevent the spread of nuclear materials.

As we see that our work contributes to this better future, we find satisfaction.

Rising to this challenge requires a strong foundation of science and technology, including a full suite of twenty-first century tools for materials research, upon which many advancements depend. Everything is made of materials, after all.

Neutron beams have become irreplaceable scientific tools, providing insights about materials that cannot be obtained by other investigative techniques—which is the reason why Bertram Brockhouse, Canadian pioneer of neutron scattering for materials research, was honoured with the Nobel Prize in Physics. The continuing value of neutron beams is recognized by innovative nations that have already committed over $8B in capital investment in the twenty-first century for neutron facilities around the world. Neutron beam methods are complementary to, but cannot be replaced by, other tools to probe materials, like beams of light, electrons, and muons, all of which are available at major Canadian science facilities.[31]

Materials researchers in Canada and around the world are using neutron beams to deliver impacts in priority areas for innovation. Some Canadian examples are described in the following sections, and further examples can be found at: cins.ca/discover.

A1. A clean environment

About 85% of greenhouse gas emissions in Canada result from energy production and related activities.[32] Materials research using neutron beams enables more reliable emissions-free baseload electricity generation. A few examples:

- With 15% of Canada's electricity generated by nuclear power, innovations to maintain the safety and reliability of this emissions-free baseload source are essential. Neutron stress-scanning was

[31] For example, the Canadian Light Source, TRIUMF, the Brockhouse Institute for Materials Research, and CanmetMATERIALS.

[32] CAIT Climate Data Explorer. 2015. Washington, DC: World Resources Institute. Accessed from Environment Canada. The Science of Climate Change. Annex 2. Nov. 23, 2015. http://www.ec.gc.ca/sc-cs/Default.asp?lang=En&n=A5F83C26-1#_s09.

applied to examine cracking in key components that caused the 1997 and 2001 Point Lepreau Nuclear Generating Station shutdowns, which together cost over $50M. The results provided assurance to the regulator that the station could be restarted, thus avoiding further losses. Subsequent neutron beam research aided Canada's fleet of reactors to reduce downtime associated with the cracking issue over the next 20 years. The value of the avoided losses in electricity production from this research was in the hundreds of millions of dollars—a figure exceeding all of Canada's direct investments in neutron beam capabilities since the 1940s (http://bit.ly/34su3Gx). Research with neutron beams continues to make valuable contributions to the safe, reliable, and economic operation of Canada's nuclear power plants by determining the fitness-for-service of critical reactor components. The reliability of this clean energy source helped Ontario to replace its baseload electricity from coal plants, thereby eliminating "smog days" in Toronto since 2014.

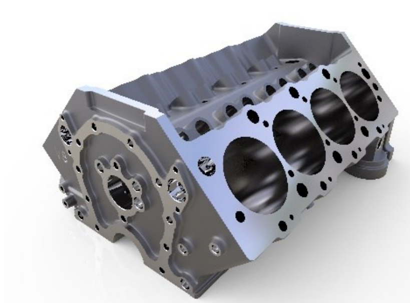
Neutron beams were critical to explain and prevent downtime from leaks at Canada's fleet of nuclear power reactors.

- Hydro-Québec has used neutron stress-scanning data in research to improve the reliability of turbine runners, which are key components in hydroelectric dams. Turbine runners can cost up to $10M each, and losses in electricity production if one fails can be very costly. Hydro-Québec has used the stress-scanning results to show that optimization of manufacturing processes like welding and heat treatment can improve the lifetime of turbines, often without any increase in the manufacturing cost (http://cins.ca/2015/07/01/hydro/).

A2. Economic competitiveness and clean growth

Materials research with neutron beams enables innovation in the advanced manufacturing of energy-efficient, lightweight planes, ships, and cars. It does so by generating understanding of the effects of manufacturing processes on materials for more efficient engines, reducing waste and production costs, and increasing lifetimes of critical parts. Neutron beams provide new knowledge of metal alloys for researchers looking for ways to make reliable, lightweight parts for cars that will boost fuel efficiency. They generate insights to create new materials for batteries, fuel cells, and hydrogen storage technologies. Both light-weighting and energy storage are critical enablers for powering cars with electricity, hydrogen, or other clean fuels. Neutron beams are also applied to evaluate 3D printing and nanotechnologies for advanced manufacturing, in the search for new materials and methods to produce next-generation computers, electronics, and medical devices. A few examples:

- Nemak Canada evaluated the effectiveness of less resource-intensive heat treatment processes on aluminum alloy engine blocks to ensure that these processes would not compromise reliability. The results are saving the Nemak plant in Windsor, Ontario, $2–3M every year.
- Canadian aerospace leaders Bombardier and StandardAero gained knowledge needed to reduce scrap waste and advance methods to make and repair engines (http://cins.ca/tag/aero+impact/), while Rolls-Royce recently patented a new alloy that it aims to use in higher-efficiency jet engines (http://cins.ca/2017/01/10/aero-3/).
- In 2014, Ivaco Rolling Mills invested $80M to expand its plant in Eastern Ontario. The company attributed part of



Neutron beams were critical to ensuring reliability of car engine parts manufactured with innovative methods.

its recent success to neutron stress-scanning research that enabled the company to add value to its steel rod products (http://cins.ca/2013/09/01/metal/).

A3. Safety and security

Materials research with neutron beams enhances the safety of pipelines and rails, and helps to determine the fitness-for-service of naval ships, by examining the stresses deep inside rail tracks, line pipes, or ship hulls, which can lead to catastrophic failures. Neutron methods have supported advances in the manufacturing of lightweight naval ships for our allies, and have aided in extending operating lifetimes in Canada's existing fleet. A few examples:

- The Canadian pipeline industry has improved its practices to ensure acceptable stress levels, avoid cracking, and predict pipeline lifetimes, based on neutron beam analyses of stress (http://cins.ca/2017/09/27/pipeline/).
- Examination of railroad tracks associated with a 2005 train derailment, which spilled over 800,000 L of oil into Lake Wabamun in Alberta, produced data that informed the 2011 updates to Transport Canada's "Track Safety Rules" regarding the minimum frequency of ultrasonic rail testing (http://cins.ca/2014/07/01/rail).
- Defence Research and Development Canada (DRDC) qualified a new method for joining metals to repair Canadian naval vessels. Canada's allies are now advancing this method further to join aluminum components in the construction of high-speed, lightweight ships (http://cins.ca/2013/03/01/defence-5/). DRDC has also gained knowledge to safely extend the lifetimes of Canadian ships, thereby saving resources for other security needs. It has also leveraged these findings to gain close working relationships with Canada's allies on projects to manage corrosion and other aging concerns common to many Western navies (http://cins.ca/2014/11/01/defence/; http://cins.ca/2014/05/01/defence-2/).

Neutron beams were critical to explain cracking issues in Canada's aging pipelines and to develop industry-standard practices to ensure reliability.

A4. Health and food security

Neutron beams are emerging as powerful and irreplaceable tools for examining soft materials of living things, including biomolecules such as cholesterol and vitamin E, as well as molecules that play a role in cancer treatment, Alzheimer's disease, human immunodeficiency virus (HIV), and bacterial resistance to antibiotics, to name a few. Materials research with neutron beams assists with designing better medical devices and disease treatments, as well as in developing resilient crops for global food security. A few examples:

- Econous Systems Inc. is using new coating technology for medical devices to develop medical tests for the early detection of ovarian cancer, which is essential for surviving this disease (http://cins.ca/2016/10/26/bio-4/).
- Life scientists are applying knowledge from neutron beam tests to pre-clinical trials of cancer treatments based on cancer-killing nanoparticles (http://cins.ca/2017/10/26/cancer/).

Neutron beams have been applied by researchers at the University of Saskatchewan to advance global food security.

- The Global Institute for Food Security at the University of Saskatchewan has recently developed neutron imaging as a method to accelerate the development of crops, such as by matching genetic variation to observable traits that enhance drought resistance (http://cins.ca/2017/05/04/agriculture/).

A5. Fundamental research and scientific reputation

Neutron beams are an irreplaceable part of the complete twenty-first century scientific toolkit not only for the above priority areas, but also for laying scientific foundations for future breakthroughs by studying new materials and nanotechnologies. Access to neutron beams has enabled Canadians to contribute to quantum materials research that was honoured with a Nobel Prize in 2016, and to produce competitive research outputs (as described in sections 3.1 and in Appendix B). The remaining mysteries in quantum materials are fertile grounds for further Nobel Prize-winning discoveries because continued research will lay scientific groundwork that is essential for determining whether quantum materials' remarkable properties form the technological basis for future generations of faster and more powerful information technologies and devices—innovations that could be based on superconducting electronics, spintronics, and quantum computing, for example. Such technological benefits often come a decade or more after the foundational research. For instance, research in multiferroic quantum materials over the past 15 years using neutron spectroscopy at the CNBC and elsewhere has led to prototypes that are now being explored with Intel for a future generation of computer processors and memory chips (doi.org/10.1021/acs.nanolett.6b05152).

A6. Training Highly Qualified People

While not all such fundamental science projects will lead to breakthroughs, conducting materials research at major neutron facilities has been shown to profoundly impact students' educational achievement and pursuit of careers in sectors that need their skills for innovation. Over 1,000 visiting Highly Qualified People received hands-on training in neutron beam techniques at the CNBC from 1984–2018. A recent study[33] identified 300 of these alumni and found that of the undergraduates, 60% went

Highest Degree Attained by Bachelor's and Master's Students Following Training at the CNBC

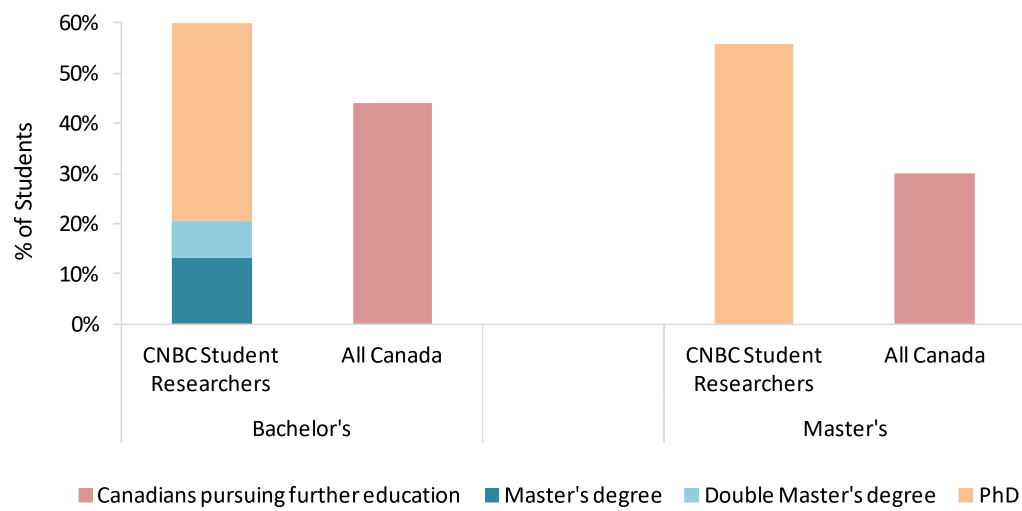


Figure 15. The highest degrees attained by students who were pursuing Bachelor's or Master's degrees when they received hands-on training at the CNBC, compared to all Canadian students who stated an intention to pursue further education of any kind when surveyed at graduation.

[33] Strategic Policy Economics. "Study of the CNBC performance and impacts." February 2019.

Training Students for High-Technology Careers

Engineering graduate students Stephanie Stafford and Paula Mosbrucker prepare to use a neutron beamline. Stafford is now a metallurgical engineer for **Evraz** in the **oil and gas industry**. Mosbrucker is now an engineering group leader for **Kinectrics** in the **nuclear power industry**.

on to earn a graduate degree, of which two-thirds earned a PhD. Of the Master's students, over half went on to earn a PhD—rates that are far above Canadian norms (Figure 15). In interviews, these alumni credited their neutron beam experience as contributing to their subsequent academic achievement and career success.

Common themes among CNBC alumni interviewed about the CNBC's impact on their careers are as follows:

- Through pressure to complete an experiment in limited time, they learned disciplined research skills, including attention to detail and planning.
- Through exposure to industry-oriented researchers, they gained an appreciation for applied sciences and were attracted to industry careers.
- Through exposure to a safety and security culture, they were more prepared for the cultures of the industries they entered.
- They valued learning directly from highly skilled researchers, who were respectful and helpful throughout their entire visit.
- They valued the opportunity to use state-of-the-art materials research tools and techniques that were only available at the CNBC.
- They valued learning to perform in a sophisticated national laboratory environment, which prepared them for working in complex industrial environments.

The study also found that these alumni have gravitated to where Canada needs their skills most: Almost 80% now work in the three R&D-intensive sectors that contribute most to Canadian innovation: Manufacturing, Higher Education, and Science and Engineering Services. About 13% work in Public Administration or Financial and Business Services.

Most Canadian research professors who access neutron beams to study materials rely on the expertise of staff at the neutron facility (e.g. at the former CNBC). For example, most research professors who are neutron beam users are experts in particular problems in engineering, physics, chemistry, or biology—and in several methods of studying materials that underlie these problems—but most do not use neutron beams frequently enough to fully specialize in applying them to study materials. With nearly every academic experiment to study materials at a neutron beam facility, one or more students are advancing their research skills through interacting with staff experts in terms of preparing the conceptual design and the samples, conducting the experiment, interpreting the data, and publishing the results.

Canadian students have also valued their time at foreign neutron beam facilities—when they have access to them. Notably, the previous partnership with the SNS leveraged research papers by 88 Canadian students and post-docs from 2008–2018. The quality of the training is indicated by the fact that Canadian PhD students received two of only four prestigious "Outstanding Student Research Prizes" that the Neutron Scattering Society of America has awarded to date.

Appendix B: Record of the Chalk River Laboratories (1947–2018)

Canada's strong reputation and leadership position in materials research using neutron beams was centred around the infrastructure and expertise at Chalk River Laboratories for 70 years. In recent years, this reputation was further enhanced by Canada's participation in the SNS, as described in section 4.2. Here, we briefly review this historic context.

The first experiments in neutron scattering at Chalk River Laboratories began in the late 1940s at the NRX reactor. Canada then built the National Research Universal (NRU) reactor in the 1950s to support every known, foreseeable, and even unforeseeable application of neutrons to science, technology, and industry. The multipurpose NRU reactor operated for over 60 years, until it was permanently shut down in 2018 due to increasing operating costs as it aged. It served as a science and technology platform for (1) medical isotope production, enabling about 1 billion medical procedures globally; (2) the development of nuclear power, the source of 60% of Ontario's electricity today; and (3) neutron beams. Through the 1950s and 1960s, Bertram Brockhouse and his contemporaries pioneered early methods to use neutron beams for materials research, and for this work Brockhouse was recognized with the 1994 Nobel Prize in Physics. By then, his methods had been replicated and further developed around the world.

The neutron beam laboratory at the NRU reactor, known later as the Canadian Neutron Beam Centre (CNBC), grew into an international research centre from the 1960s to the 1980s. Notably, W.J.L. Buyers used neutron beams there in 1985 to make the first observations of the Haldane gap, thereby confirming Duncan Haldane's theoretical predictions of a new class of quantum materials—topological materials—for which Haldane shared the 2016 Nobel Prize in Physics and Buyers was inducted as an Officer of the Order of Canada. This ground-breaking work opened up a new field of materials physics research, which has been explored vigorously for the last decade, leading to discoveries that one day could revolutionize computers and devices. Canadian scientists and their collaborators continued to make major advances in this domain using their access to neutron beam facilities up to 2018.

In the 1980s, Canadian scientists at Chalk River Laboratories pioneered a neutron beam method to identify and measure stresses deep inside metals to determine fitness-for-service or causes of failures. This method enabled Canadians to participate in NASA's investigation of the Challenger and Columbia space shuttle accidents, and to support the Transportation Safety Board's investigation of an environmental disaster when a train derailment spilled oil into Lake Wabamun in Alberta (see section A3). Being at Chalk River also provided complementary capabilities to handle radioactive materials and enabled services for nuclear and non-nuclear industries that were difficult to emulate elsewhere. Until its closure in 2018, the CNBC continued to be a world leader in applying neutron stress analysis to improve the reliability and cost-effectiveness of engineered components for nuclear power plants, pipelines, cars, ships, and airplanes—over 230 industry-funded projects, with a total revenue of at least $6M.

The CNBC was formalized into a national user program in the early 1990s, and the National Research Council took over its operations in 1997. Beginning about that time, foreign world-leading neutron beam facilities out-invested the CNBC (see section 4.1), developing new capabilities for high-brightness neutron sources. Yet most of the CNBC's beamlines still performed competitively for high-demand 'workhorse' applications until its closure. Among these high performers were a powder diffractometer, a polarized triple-axis spectrometer, a neutron reflectometer, and a stress-mapping diffractometer; these capabilities attracted many foreign collaborators and users (see section 3.1).

Figure 16.
% of international scientists who rated each facility as advantageous to Canada in 2006. Source: Strapolec (CCA 2006 data)

The quality and renown of Canadian scientific leadership in applying neutron beams can be seen in a Council of Canadian Academies (CCA) assessment that surveyed prominent international scientists. These scientists rated the CNBC as providing the most advantage to Canada, over every other national-scale laboratory in the country (Figure 16).[34] Further, a bibliometric study[35] found that papers arising from the CNBC published between 2000–2017 were cited 40% above the world average and represented 70% more than the average share of the world's 10% most Highly Cited Papers. This level of scientific impact was found to be very competitive both with other Canadian facilities for materials research and with neutron beam facilities abroad (Figure 17). A few of the key findings of a further study of the impacts from the CNBC included:[36]

> **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 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 investing sectors. The CNBC stood out as a highly industry-centric research institution.
>
> **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.

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[34] The CCA survey results were analyzed in: Strapolec. "Study of CNBC Performance and Impacts" (Feb. 2019) Available from: http://cins.ca/resources/cnbc/

[35] Science-Metrix. "Bibliometric study on CNBC's scientific publications 1980–2017" (Sept. 2018). Available from: http://cins.ca/resources/cnbc/

[36] Strapolec. "Study of CNBC Performance and Impacts" (Feb 2019). Available from: http://cins.ca/resources/cnbc/

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.

In February 2015, the Government of Canada announced that it would permanently shut down the NRU reactor, which was then the oldest major research reactor in the world, on March 31, 2018 for reasons unrelated to the reactor's neutron beam mission.[37] Prior to this decision, the federal government had expended significant resources to reduce the world's dependency on the NRU reactor for its supply of Mo-99, one of the most commonly used medical isotopes, thereby mitigating the impact of its closure. Natural Resources Canada also worked with Atomic Energy of Canada, Ltd. (and with its successor Canadian Nuclear Laboratories) to consider the business case for continued operation with contributions from industry for nuclear power research or the production of other isotopes for medicine and industry, but were unable to justify the cost of about $160M per year of fully overhead reactor costs. Furthermore, the restructuring of AECL and the National Research Council has left no government agency in a position to deliver a national program for user access to neutron beams going forward.

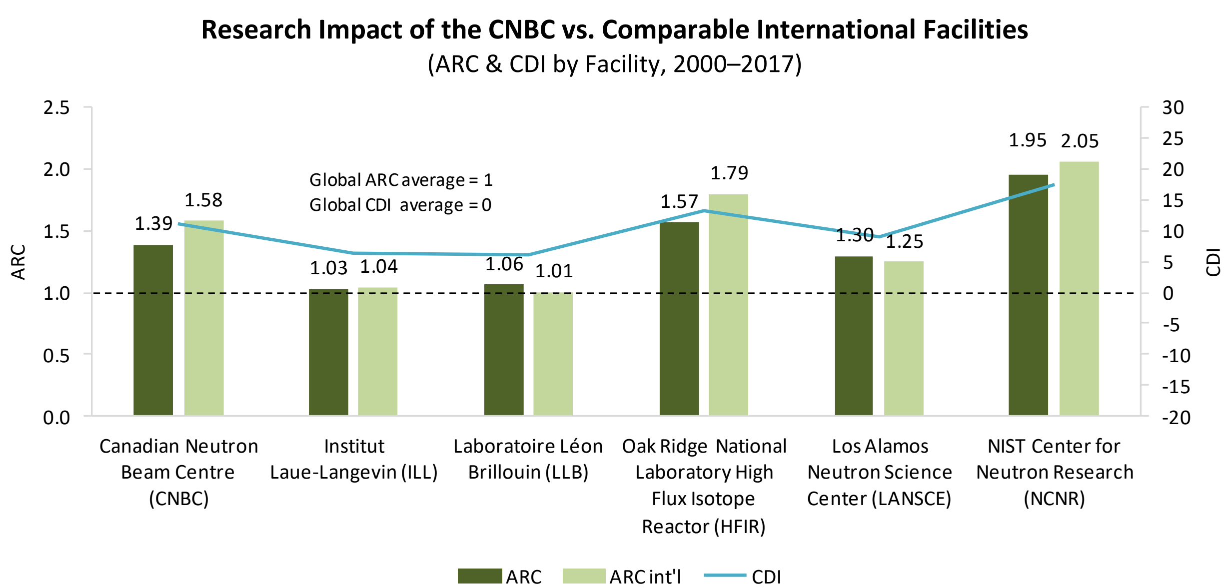
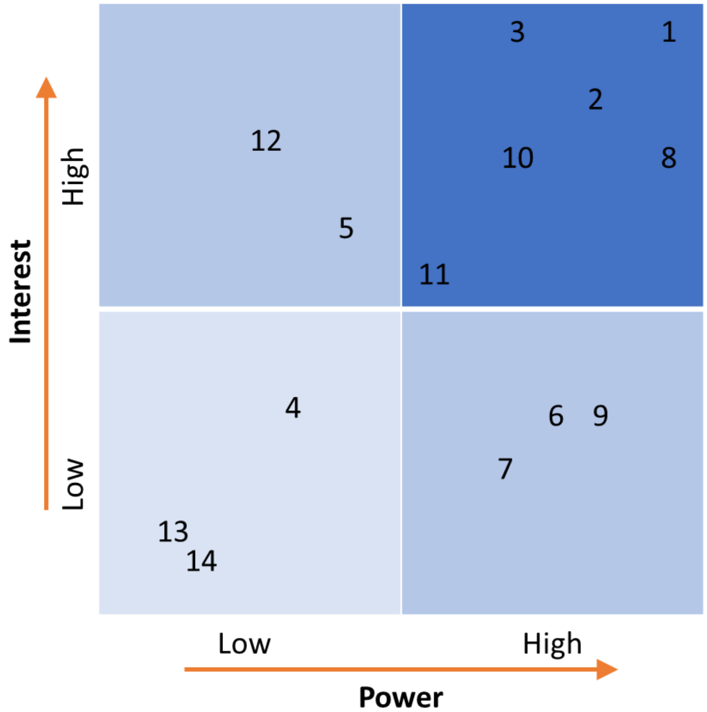


Figure 17. Average of Relative Citations (ARCs), the international ARCs (for papers with foreign co-authors), and the Citation Distribution Index (CDI) scores for the CNBC and comparable US and European facilities for the period 2000–2017. The CDI is a measure of the degree to which published papers consistently achieve high citation scores, and is an alternative metric to the ARC score. Source: Science-Metrix 2018, Strapolec Analysis (see footnote 36).

[37] The announcement focused on changes to the medical isotope market and increasing operating costs. http://news.gc.ca/web/article-en.do?nid=929189; and http://www.cnl.ca/en/home/news-and-publications/bulletins/2015/NRU_decision.aspx. Feb. 6, 2015.

Appendix C: National Neutron Strategy stakeholders analysis



1. CNI leaders
2. Supporting universities
3. Researchers (CINS)
4. Research societies (e.g. CAP)
5. Industry and gov't users
6. Nuclear power sector
7. Medical isotopes
8. Federal science policy
9. Federal energy policy
10. Provincial funding bodies
11. Major Research Facilities
12. Foreign neutron sources
13. SLOWPOKE reactors
14. TRIUMF Ultra-Cold Neutron facility

Figure 18 Stakeholder matrix illustrating varies levels of power and interest in a national neutron strategy.

Stakeholder Type	Description
Leaders of strategic activities:	
University of Saskatchewan	Chair of the Canadian Neutron Initiative (CNI) working group
McMaster University	Owner of the McMaster Nuclear Reactor; leader of the CFI-IF 'national' proposal for neutron beam infrastructure
University of Windsor	Leader of a feasibility study for a compact accelerator-based neutron source (CANS)
Primary users of neutron beams:	
Universities: 21 'supporters' of the CNI; Universities Canada and U15 University users: CINS, CAP, CIC, CIM	About 100 principal investigators from 30 Canadian universities access neutron beams for research over a 5-year period. Users' universities are represented by Universities Canada and U15. Users are represented by the Canadian Institute for Neutron Scattering (CINS) and by larger profession-based organizations such as the Canadian Association of Physicists, the Chemical Institute of Canada, and the Metallurgy & Materials Society
Industry and government researchers	Companies (e.g. Nemak Canada) and government labs (e.g. NRC, or AECL-owned Chalk River Laboratories, operated by Canadian Nuclear Laboratories) access neutron beams, often on a fee-for-service basis for proprietary research

International users and organizations	European neutron sources are organized under the League of advanced European Neutron Sources; users are organized in volunteer organizations such as the Neutron Scattering Society of America, the European Neutron Scattering Association, and the Asia-Oceania Neutron Scattering Association
Neutron producers and other users of neutrons:	
Nuclear power sector	Represented by the Canadian Nuclear Association, the nuclear power sector would use a new multipurpose research reactor for research on nuclear fuel and testing of reactor materials
Medical isotope producers	Represented by the Canadian Nuclear Isotope Council, medical isotope producers would use a new multipurpose research reactor for production of isotopes
McMaster Nuclear Reactor	Supplies irradiation services such as isotope production; now hosts two neutron beamlines for materials research
NRay Services Inc.	A commercial provider of neutron imaging services based at the McMaster Nuclear Reactor
Other university research reactors	Several SLOWPOKE reactors are operated by universities; these reactors are much too low-brightness for neutron diffraction
TRIUMF	TRIUMF operates an ultra-cold neutron facility for studying neutrons (i.e. particle research, not materials research)
Accelerator expertise:	
TRIUMF, Canadian Light Source	Substantial expertise in accelerator technology is available to explore alternatives to reactors as neutron sources
Government agencies:	
Science policy: ISED, Chief Science Advisor, CFI, the tri-councils	Stewardship of neutron beams for materials research and innovation is a matter of science policy for Major Research Facilities (MRFs), and hence should be under the jurisdiction of ISED and its portfolio of agencies. The CFI and the Chief Science Advisor are emerging leaders in MRF policy, assisting ISED
Federal economic development: FedDev Ontario, Western Diversification	These agencies are potential sources of supplemental investments in research infrastructure, including MRFs, within their regions
Energy and isotope policy: NRCan, AECL	Stewardship of neutron beams has historically been under Natural Resources Canada as a matter of energy policy due to its connection to nuclear research reactors. AECL is NRCan's agency for overseeing the contract with the operator of the Chalk River Laboratories. Discussion of a new multipurpose research reactor would need to involve these agencies
Provincial agencies: e.g. Ontario Research Fund, Innovation Saskatchewan, Ontario Ministry of Energy	These agencies are often sources of provincial funds to match federal investments in research infrastructure, including MRFs. The Ontario Ministry of Energy is a key stakeholder in discussions of nuclear innovation (e.g. a new research reactor)
Major Research Facilities:	
Canada: TRIUMF, SNOLAB, NRC Herzberg, Canadian Light Source, Ocean Networks Canada	These are comparable organizations within Canada whose collective experiences can inform the development of Neutrons Canada's governance, management, and funding

International: Jülich Centre for Neutron Science; 15 major neutron sources around the world	The Jülich Centre for Neutron Science in Germany is the most comparable foreign counterpart to Neutrons Canada; it is the sole example of a program that has continued beyond the closure of its neutron source by relying on access to distributed "outstations." About 15 major neutron sources are potential partners and sources of experience for managing neutron beam infrastructure: 9 in Europe (ILL, ESS, ISIS, etc.); 3 in the US (SNS, NCNR, HFIR); 1 in Australia (OPAL); and others in Asia
Science policy-related resources:	
CIFAR, Public Policy Forum, Council of Canadian Academies, Canadian Science Policy Centre	These are examples of Canadian organizations with experience in organizing and hosting strategy- and consensus-building meetings in a science policy context

Appendix D: CNI working group

As of November 2020, the Canadian Neutron Initiative working group included the following executive leaders:

- Karen Chad (Chair), University of Saskatchewan, Vice-President of Research
- Karen Mossman, McMaster University, Vice-President of Research
- Michael Siu, University of Windsor, Vice-President of Research & Innovation
- Alice Aiken, Dalhousie University, Vice-President of Research & Innovation
- Walter Dixon, University of Alberta, Vice-President of Research & Innovation
- Thad Harroun, Canadian Institute for Neutron Scattering, President

Supporting institutions included:

1. Brock University
2. Canadian Institute for Neutron Scattering
3. Canadian Light Source
4. Canadian Nuclear Association
5. Dalhousie University
6. McGill University
7. McMaster University
8. Memorial University of Newfoundland
9. Nemak Canada Corp.
10. Queen’s University
11. Simon Fraser University
12. Sylvia Fedoruk Canadian Centre for Nuclear Innovation Inc.
13. University of Alberta
14. University of British Columbia
15. University of Calgary
16. University of Guelph
17. Université de Montréal
18. Université du Québec à Trois-Rivières
19. University of Toronto
20. University of Saskatchewan
21. University of Windsor
22. University of Winnipeg
23. Western University