A Compact Accelerator-Based Neutron Source for Canada?

A Discussion Paper for the Sylvia Fedoruk Canadian Centre For Nuclear Innovation

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February 2019

Executive Summary

Neutron beams are an essential part of the 21st century toolkit for the science and engineering of materials. Canada has, until now, relied on a major multi-purpose research reactor, the NRU reactor in Chalk River, as its neutron source. Its replacement is expected to cost $1-2B. Many other countries have recently invested in new, high-brightness neutron sources with capital costs of $0.5B to $3B. These price tags pose a challenge, and the re-investment rate is not keeping pace with actual and expected facility closures.

A less expensive, alternative technology, called a Compact Accelerator-Based Neutron Source (CANS), is being developed in Europe. A CANS has lower regulatory requirements and could easily be located at a university. A CANS can be tailored for the high demand "workhorse" neutron beam methods. Common applications of these methods include the study of new materials for clean energy technologies, of light-weighting technology for critical parts in cars and airplanes, or of biomolecules in our own bodies with implications for maintaining health or treating disease.

Because CANS technology has modular aspects, it would be possible to begin with an entry-level facility (e.g. $15-20M) and upgrade it over time into a national facility (e.g. $75-100M). Another possibility is to distribute a set of specialized facilities across the country. A single high-end CANS, or a set of smaller facilities, could replace most of the neutron beam capabilities of the NRU reactor.

CANS technology offers a new paradigm by which Canada can provide for most of its needs for neutron beam infrastructure domestically with a relatively modest investment. For the remaining research, Canada can partner with other countries to gain access to the brightest neutron sources. This new paradigm also simplifies the policy landscape by decoupling investment in neutron beams from decision-making about other infrastructure for nuclear innovation, such as a research reactor for nuclear power testing or for producing the medical isotope molybdenum-99. Further, a CANS could be upgraded to make certain isotopes, such as fluoride-18 for PET-CT scanning.

European proponents of CANS technology are close to demonstrating an entry-level CANS, which will use components that have already been demonstrated. For a high-end CANS, significant development and demonstration work remains, including a need to optimize all the components to work together most effectively.

Investment in a Canadian program to develop and demonstrate a CANS, in collaboration with European counterparts, is an attractive option to provide for the long-term future of Canadian research that relies on access to neutron beams.

Global Context

Neutron beams have been essential research tools for studying materials for 70 years. Because they continue to be part of the complete 21st century toolkit for science and engineering, other countries have re-invested $8B in capital at major neutron beam facilities since the year 2000.

But this re-investment is not keeping pace with actual and expected facility closures (including the March 2018 closure of Canada's primary neutron source, the NRU reactor). Facilities are closing due to age and to reduced popularity of the nuclear reactors that underlie them. Large reductions in supply of neutron beams are projected in Europe, even as the C$3 billion accelerator-powered European Spallation Source (ESS) is brought online in the 2020s.

Large, high-brightness facilities, like the ESS or the reactor-based Institut Laue-Langevin in France, are essential. Yet there is a lot of excellent research to be done at smaller, lower-brightness facilities, using "workhorse" neutron beam methods and developing new applications. These smaller facilities divert research demand away from the few large facilities, so that only the research that requires the brightest sources of neutrons will be done there. Smaller facilities also act as feeders, by training students and researchers who will go on to use the larger facilities.

To fill the role played by Europe's fleet of aging small and medium-brightness reactors, several research institutes throughout Europe are exploring an alternative technology, known as a Compact Accelerator-Based Neutron Source (CANS). CANS technology uses an accelerator to shine an intense particle beam on a target, causing it to release neutrons, which enter a suite of neutron beamlines for the experiments. Technical issues limit a CANS's neutron generation rate well below that of nuclear reactors or spallation sources. However, CANS technology is based on a smaller target station (hence the word "Compact"), which delivers a much higher fraction of the neutrons to the beams. This advantage partially offsets the lower neutron generation rate.

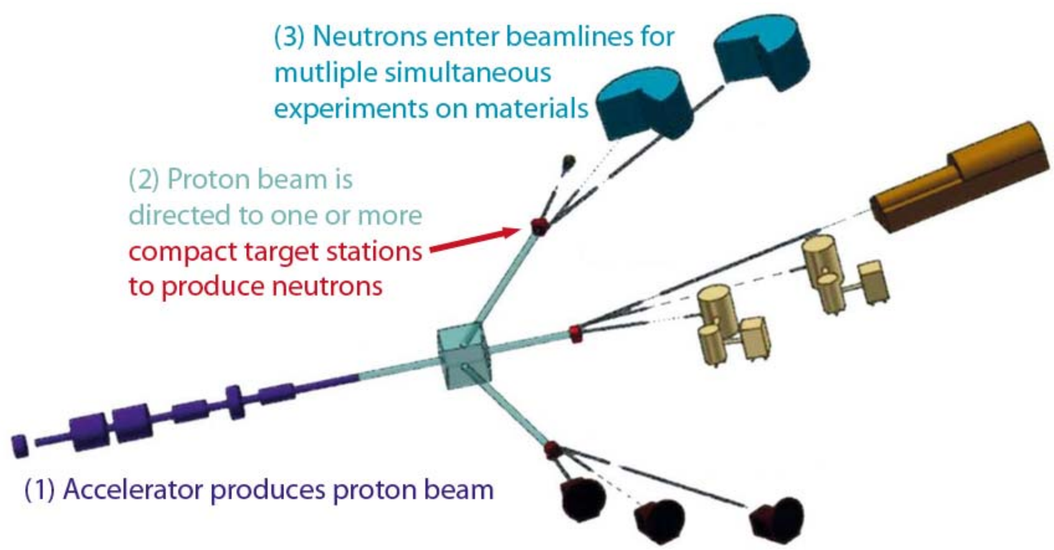

Figure 1. Conceptual illustration of a Compact Accelerator-Based Neutron Source (CANS). In this case, protons are used to produce neutrons. This CANS has three target stations, each optimized to feed neutrons to a set of three neutron beamlines, enabling a total of 9 experiments to be conducted simultaneously. (image: modified from reference [1]).

Notably, the Jülich Centre for Neutron Science, Germany, is in advanced planning stage to build an entry-level CANS at around C$15 million, excluding any building costs [2]. The design will accommodate six beamlines that do not require a high neutron flux, but its proponents claim the performance per beamline will rival the beamlines of the same type at much larger facilities.[1] Scientists in France's Atomic Energy Commission (the CEA) are proposing a brighter (i.e. high-end or sometimes called "high-brilliance") C$75 million CANS with 10 beamlines that could replace 40% of France's present capacity [3]. More discussion on cost and how a CANS works is found in the Appendix.

Accessible options for Canada

Assuming the performance predictions for a high-end CANS are correct, such a facility could meet most of Canada's needs for neutron beams and become the primary, long-term replacement for the neutron beam lab at the NRU reactor. The capital cost of a high-end CANS suitable for Canada is expected to be up to $100M, compared to $500M for a neutron beam reactor, or $1-2B for a multipurpose facility. One report projects annual operating costs of the neutron source in the range of 10-15% of the capital investment [4], while the cost to operate the associated neutron beam lab should be the same as at a reactor or spallation source. Thus, overall operating costs should be lower as well.

Because CANS technology is more scalable than spallation or reactor sources, it allows the option of multiple, smaller facilities, located at different parts of the country, strategically designed to match the regional research interests. It also allows the possibility to begin with an entry-level facility (e.g. $15-20M), which could be upgraded over time to suit evolving needs of the research community. Over time, it could become a national facility (e.g. $75-100M).

Finally, accelerators have much lower regulatory barriers than a nuclear reactor, making it easy to locate a CANS on a university campus.

Trade-offs for the above advantages include limitations in scope: Canadian research will still require access to the brightest neutron sources for research projects that the CANS cannot accommodate. A CANS will not meet the nuclear power industry's needs for materials irradiations that are now done inside nuclear reactors. With further investment in a CANS, it may be possible to divert a portion of the accelerator's beam to make certain isotopes, such as Fluoride-18 for PET-CT scanning, but not the isotopes best produced in a reactor, such as molybdenum-99 or cobalt-60. These limitations simplify the policy landscape by decoupling investment in neutron beams from decision-making about other infrastructure for nuclear innovation.

Overall, investment in a Canadian program to develop and demonstrate a CANS, in collaboration with European counterparts, is an attractive option to provide for the long-term future of Canadian research that relies on access to neutron beams.

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[1] Numerous statements in the NOVA proposal make this claim. For example, on page 39, "It [Flux at the sample] is of same order of magnitude as the flux for reflectometry at BER-II (instrument V6)."

Canadian research that could be conducted using a CANS

The range of techniques and applications that could be conducted at a neutron beam lab powered by a CANS can be illustrated with the following Canadian examples:

- Neutron powder diffraction is a technique that is heavily in demand for solving the atomic and magnetic molecular-scale structures of many new materials, some of which could underpin innovation in clean energy technologies such as fuel cells, or better batteries for large-scale energy storage.
- Neutron stress measurements are essential for light-weighting cars and airplanes, and ensuring reliability of critical parts in electricity generation, oil & gas pipelines, railroad tracks, and navy ships.
- Neutron imaging is routinely used for commercial quality assurance of jet turbine blades (e.g. Nray Services). It is used to test nuclear reactor fuel, investigate reliability of military aircraft components (e.g. CF-18 wings), and is beginning to be used by the University of Saskatchewan's Global Institute of Food Security to select breed drought-resistant crops.
- Small-angle neutron scattering is especially useful in health and life sciences: developing cancer-killing magnetic nanoparticles, learning about movements of proteins in cell-like environments, or understanding the roles of key molecules in Alzheimer's disease. It is also used in metallurgy, for example, to characterize precipitates in prototype steel products to enhance strength and toughness for ensuring the long term reliability of pipelines and other structures.
- Neutron reflectometry is needed for studying interfaces (e.g. to minimize corrosion of metals, or solve biofouling limitations affecting medical devices) and thin films (e.g. storage materials for a hydrogen economy).

Optimizing a Canadian CANS

As mentioned earlier, an intrinsic advantage of CANS over a reactor is the ability to conserve a greater fraction of the neutrons for experiments through optimal design of key components, including the target station. In addition, the accelerator can deliver a particle beam to multiple target stations, each optimized as a neutron source for a specific technique or a set of techniques.

For example, one CANS could be designed with two target stations, one optimised for thermal neutrons, and the other for cold neutrons. The thermal neutron target could provide neutrons to multiple powder diffractometers, which are heavily in demand, while simultaneously providing them to beamlines for stress measurements and neutron imaging. The cold neutron target could host multiple small-angle neutron beamlines, also heavily in demand, while simultaneously hosting a neutron reflectometry beamline. Alternatively, two separate facilities could be built in two locations, each with a different specialization.

Appendix: Compact Accelerator-Based Neutron Source (CANS) technology and costs

Technology overview

Neutrons are sub-atomic particles that can be released from atoms during nuclear reactions. The neutrons are emitted more or less randomly in all directions. Since these electrically neutral particles cannot be steered or focused using electric or magnetic fields, most of the neutrons from a neutron source are lost. Only the small fraction that enters a neutron beamline is used.

In a CANS, the neutron production process begins by creating a particle beam using an accelerator (see figure 1 in the main text). The accelerated particles can be either protons or deuterons, but most concepts for CANS are based on protons. The proton beam then impinges on a target made of either lithium (chemical symbol Li) or Beryllium (Be), which releases neutrons as a by-product of the reaction with the protons. These neutron producing reactions are symbolized Li(p,n) or Be(p,n) where p and n represent proton and neutron respectively. As in a reactor or spallation source, once the neutrons are produced, their energies must be lowered (a process called "moderation") to make them suitable for use in a set of beamlines for simultaneous experiments. Moderation works by passing the neutrons through a lower temperature material.

In summary, a CANS consists of four major components: (1) a proton accelerator, (2) a proton-to-neutron conversion target, (3) a neutron moderator, and (4) neutron beamlines for research or industrial use. The first three are for producing the neutrons and getting them into a suitable energy state. The target and moderator are both located within the compact assembly called the "target station," which is the neutron source.

The idea of CANS technology is not new. In the early 1980's, a group of scientists at the Chalk River Laboratories wrote a report envisioning a Li(p,n) source, named CANUTRON [5]. Based on computer simulations, they expected CANUTRON's performance for neutron imaging to be comparable to imaging at a medium-sized research reactor. The CANUTRON idea did not get much attention because it was not needed then, with neutrons being well in supply from existing facilities, not only in Canada but also in the USA and Europe. Now with a shrinking neutron supply and rising cost of reactors, there has been much more interest in exploring the feasibility of such neutron sources.

Technology and cost comparison with reactors and spallation sources

The Li(p,n) or Be(p,n) reactions in a CANS produces much fewer neutrons than fission reactions used in a conventional nuclear reactor or spallation reactions (spallation is another accelerator based method, in which "spallation" refers to fragmentation of a target nucleus to release neutrons by using a spalling hammer, i.e. high-energy protons).

However, two advantages of Li(p,n) or Be(p,n) reactions offset lower neutron production: (1) Much less unwanted radiation is produced, which reduces the volume of biological shielding, and (2) the neutrons have much lower energies to begin with (well below 1 MeV, compared to several MeV; hence a CANS is sometimes called a "low-energy neutron source"), which reduces the volume of the moderator. In a CANS, a moderator a few centimetres thick is enough to decrease the neutron energies to tens of meV, [2] suitable for industrial and scientific applications. Thus, the target station is much more compact than either a reactor or spallation source, which allows the beamlines to start much closer to neutron source. As a result, a much greater fraction of the neutrons are conserved for the neutron beamlines.

Further, because reactors and spallation sources have high capital costs, their operations are shared for many applications that have some competing requirements, and this is reflected in compromises in the design of key components such as the moderator. In a CANS, the designs of the accelerator and the target/moderator assembly can be optimized for a narrow set of applications to realize further efficiency gains. Thus, a fully optimized CANS may achieve a beamline performance that will rival a similar beamline at a medium-flux reactor or a spallation source.

The low capital cost advantage comes from the CANS accelerator. The proton beam to induce a Li(p,n) or Be(p,n) reaction is relatively simple to generate, as it only requires acceleration of protons to about 2.5 MeV energy. For comparison, the commercial cyclotron recently installed at the Fedoruk Centre on the campus of the University of Saskatchewan achieves a ten times higher energy proton beam (24 MeV). Acquisition of the cyclotron, including construction of the building and associated lab facilities to process radioisotopes, was a $25M project completed in 2016. This is the order of magnitude required to build a CANS including buildings and an associated neutron beam lab. Table 1 illustrates the range of capital costs, depending on desired capabilities.

There are significant uncertainties in these cost estimates, and there are risks associated with a first-of-a-kind facility. Although many of the components of a CANS have been demonstrated at other facilities, there is undoubtedly significant development work to be done to develop the design and optimize all the components to work together most effectively. A liquid lithium target would be the most effective for the neutron production, but such targets have only been demonstrated with lower power proton beams. Feasibility of liquid metal targets has been proven at the Spallation Neutron Source (USA), which uses liquid mercury. Designing, building, and demonstrating a liquid lithium target is a significant research project in itself. One can avoid this uncertainty by choosing to use an alternate target such as solid beryllium in exchange for a lower neutron flux, as is being done for the NOVA ERA facility in development in Germany [2]. One option is to build a CANS with an easier-to-develop solid beryllium target station to achieve a functional facility more quickly, and then develop a second target station based on liquid lithium.

[2] One milli-electron-volt is one-billionth of a mega-electro-volt. 1 meV = 10^{-9} MeV

Table 1 Recent capital cost estimates of CANS sources with a range of capabilities, in 2018 Canadian dollars. Note: Estimates contain large uncertainties, and are intended primarily to illustrate the range of costs and capabilities.

Class	**Source parameters**	**Capital Cost**	**Notes**	**Reference**
Fully maximized high-end CANS for a "national user facility" for France		\$300M	For example, maximum power accelerator, 5 target stations, feeding 30 state-of-the-art instruments; all-inclusive costs. This is more than what Canada needs.	CEA 2018
High-end CANS suitable for a Canadian national user facility; similar to a medium-flux reactor	Lithium target, 20-30MeV deuterons, 100kW beam; 10^{15} neutrons/sec	\$72M + instruments	Accelerator (\$42M); 2 target stations (\$18M); buildings and overheads for the source (20% = \$12M). Instruments and beam-halls could bring the total to up to \$100M.	CEA 2018; Cost calibrated from known ESS costs; reference design from 2004 IAEA report
Medium brightness facility, similar to Low Energy Neutron Source at Indiana Univ.	Beryllium target, 13MeV protons, 30kW beam; 10^{14} neutrons/sec	\$30M + building & instruments	Only includes the source.	2004 IAEA; order-of-magnitude estimate
Low-brightness, "university lab-scale" facility	Beryllium target, 10MeV protons, 0.4kW beam 2 x 10^{13} neutrons/sec	\$6M + building & instruments	Cost of the 6 proposed basic instruments for NOVA ERA is estimated at \$7M.	NOVA ERA (2017)

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