Neutrons for Materials Research

An Enabler of Clean Energy Technology

A submission to Generation Energy

by the Canadian Neutron Beam Centre

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CANADIAN NEUTRON BEAM CENTRE
Probing Materials for Science and Industry

Canada's first Ministers have met to address the transition to a "low-carbon" economy

Canada and Clean Energy

Canada, along with the most other developed nations, has invested substantially to boost clean energy, a requisite step toward implementing the COP-21 Paris agreement in 2015. Although the new Trump administration seeks to remove the USA from the agreement formally, the momentum of the agreement continues as American states and cities conduct their own clean energy initiatives, and the Government of Canada is seizing the opportunity to be the North American leader.

In 2016, Canada's First Ministers committed to step up efforts to reduce greenhouse gas (GHG) emissions and promote clean economic growth, while recognizing that a transition to a low carbon economy is a long term project to be achieved by 2050. Canada's Energy Ministers met later that year to establish a way forward, and in August 2017, reaffirmed their commitment to implement the provincial and territorial-led Canadian Energy Strategy (CES) and the Pan-Canadian Framework on Clean Growth and Climate Change by collaborating on energy efficiency, clean electricity, and clean technology innovation.[1]

Meeting ambitious decarbonisation targets will require contributions from all of Canada's clean and low-carbon energy sources. We can begin to make progress in the short term because some clean technologies, such as nuclear and hydro, are deployable at scale today or can be ramped up in the near future.

In the long-term, it is recognized that technology development is also critical to meeting our goals. That's why Canada and the U.S.A. were among over 20 countries who committed to "Mission Innovation", a multinational COP21 commitment to double investments in clean energy research and development within five years.[2] Mission Innovation covers 11 focus areas

[1] http://www.scics.ca/en/product-produit/news-release-energy-and-mines-ministers-agree-to-collaborate-on-clean-growth-the-development-of-natural-resources-and-competitiveness/
[2] Mission Innovation. http://mission-innovation.net/.

for R&D, recognizing that there is much room for improvement in energy efficiency, and lots to gain from enhancing technology for nuclear and renewables or converting vehicles to other sources, in addition to developing new energy sources such as biofuels. Even basic energy research is included, because there are numerous scientific questions yet unanswered about materials that could have significant implications for energy applications.

Leading the way in technology will also enable Canada to assist the developing world to transition to clean economies.

Canada's development of clean energy technology, not only helps meet our GHG targets, it helps us build a clean growth economy propelled by science and innovation. Such an economy that is based on education and creativity, is stronger, and more resilient, resulting in high-paying, long-term jobs. Leading the way in technology will also enable Canada to assist the developing world to transition to clean economies.

The benefits of innovation in nuclear energy, such as generating more clean electricity with less waste, are explored separately elsewhere.[3] Nuclear tools and technologies are being used today to produce innovations for other clean technologies, or to solve other important challenges. Materials research using neutron beams in Canada is a primary example that is explored here in more detail. Both modes of nuclear innovation could be elements of a national long-term strategy to meet Canada's climate goals.

Canada is already a world leader in nuclear technologies, and a renewed commitment to nuclear innovation, with support from industry, academia, and government, would be an effective way for Canada to contribute to Mission Innovation.

What are Neutron Beams?

Just like beams of light are used in a microscope to learn about materials on a micrometre scale, beams of neutrons reveal nanometre-scale details about materials' molecular structures and motions that cannot be seen with other scientific tools – details that are critical to how materials perform.

A research reactor can provide neutron beams as tools for research, thereby extending the contribution of the nuclear sector well beyond power plants and medical isotopes.

[3] Canadian Nuclear Association. Nuclear Innovation: A Technology Roadmap to Clean, Low-Carbon Energy for Canada and the World. April 2016.

Materials Research Underpins Clean Energy Technology

Because everything is made of materials, knowledge of how materials behave underpins most developments in technology. Understanding how light and air interact with materials is critical for solar cells and wind turbines. Understanding how materials store energy is essential for developing electric vehicles or ways of saving energy from sunny and windy days for use later. Understanding how complex biological materials interact is needed to develop biofuels. These are just a few of the many materials research problems that underpin clean energy technology.

Scientists and engineers rely on a full suite of tools to unlock the secrets of materials. The tools for material research range from simple microscopes to regional or national facilities that are shared as major scientific infrastructure. Three shared national facilities include the Canadian Light Source in Saskatoon, SK, TRIUMF in Vancouver, BC, and the Canadian Neutron Beam Centre (CNBC) in Chalk River, ON, which provide x-rays, muons, and neutrons respectively to materials researchers across Canada.

Neutron beams are versatile and irreplaceable tools and have a strong record of being used both to make scientific discoveries and to develop technology. Several examples of materials research using neutron beams for developing clean energy technology are provided below.

Better storage of clean electricity

Developing better, safer batteries, helps extend the use of clean electricity as a power source, whether in cars or mobile devices, or to store the energy produced by wind and solar. In one example, energy researchers from Hydro-Québec applied neutron beams to understand the chemical processes in battery materials that produce electricity. Other researchers are examining better materials for production or storage of energy from wind turbines and solar panels or in electric vehicles.[4]

Enhancing renewables

Developing more efficient biofuels, wind turbines and solar panels involves enhancing materials' performance. Research using neutron beams has demystifyed how pre-treatment affects the efficiency of biofuel production, and helped solar panel makers get data to refine their panels with cheaper and more energy-efficient organic materials, and is helping scientist design materials to make wind turbines more efficient.[5]

[4] Energy storage for wind turbines and solar panels: http://cins.ca/2016/11/15/energy-3/, http://cins.ca/2017/06/08/energy-storage/, http://cins.ca/2017/07/06/energy-storage-2/; For devices: http://cins.ca/2016/07/01/energy/.

[5] Biofuels: Green Chemistry. 2014 DOI: 10.1039/C3GC41962B. Solar: Advanced Energy Materials. 2011 DOI: 10.1002/aenm.201100128. Wind: http://cins.ca/2017/01/20/wind/

Light-weighting cars, ships and airplanes

Light-weighting cars and airplanes not only reduces fuel usage, but also makes using alternate energy sources like hydrogen more feasible. Materials researchers from GM, Ford, and Nemak Canada as well as universities have applied neutron beams to study manufacturing processes, using light metals like aluminum and magnesium, to ensure that new light-weight parts will be reliable. GKN Powder Metallurgy is using neutron beams to open the market to its light-weight aluminum technology. Rolls Royce recently patented a new light-weight alloy for its jet engines following research using neutron beams to help meet its emissions-reduction targets.[6]

Converting vehicles from fossil fuels

Powering cars with electricity or hydrogen requires developing better materials to store the hydrogen or electricity. Materials researchers use neutron beams to study and develop materials that store hydrogen safely and efficiently for use in cars and to develop better fuel cells that generate power from hydrogen. They are also using neutron beams to develop less expensive, longer-lasting, or safer batteries for electric vehicles.[7]

Extending the use of low-carbon baseload electricity sources

Materials research supporting the development of non-carbon-emitting electricity sources can eliminate the dependence on diesel in Indigenous, remote, and Northern communities, or support the conversion of industrial processes and building heat from fossil fuels to other sources. Small nuclear power units can be developed for off-grid applications to complement more baseload capacity using hydro or nuclear power, both of which rely on materials research to enhance reliability of critical components in their plants and avoid unexpected downtime. Large nuclear plants are the most S&T-intensive power plants operate, relying on materials

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[6] Rolls Royce: http://cins.ca/2017/01/10/aero-3/; GKN: http://cins.ca/2016/12/01/auto-4/; GM, Ford, and Nemak: Applying nuclear expertise to solve the auto industry's challenges. Automotive Parts Manufacturer's Association. Lead Reach and Connect. Winter/Spring 2015.
http://neutronsources.org/news/scientific-highlights/applying-nuclear-expertise-to-solve-the-auto-industrys-challenges.html

[7] Energy storage for electric vehicles: http://cins.ca/2017/08/02/energy-storage-3/; http://cins.ca/2017/06/08/energy-storage/, http://cins.ca/2016/11/15/energy-3/; Hydrogen Storage for Clean Cars: http://cins.ca/2012/03/01/energy-2/; Water Uptake and Swelling in Fuel Cell Membranes: http://cins.ca/2015/11/01/fuel-cells/; Neutron Imaging and Applications. Anderson *et al.* (Eds.) Springer 2009. ISBN 978-0-387-78693-3.

research to ensure safe, reliable and economic operations, including research concerning critical components, fuel, maintenance methods, waste, understanding the effects of radiation and developing the next generation of more efficient plants. A highly impactful example is described in the inset.[8,9]

Following two forced outages of NB Power's nuclear plant, which together cost over $50M, nuclear power utilities sponsored research over 10 years to manage cracking in feeder tubes at the stations. Stress analyses using neutron beams made key contributions to several outcomes, including: (1) informed decisions about $5M/yr activities to manage the cracking thereby avoiding further unplanned down-time; (2) the $4B export of two reactors to China continued without design changes; (3) the nuclear power industry assured safe operations at all stations, saved substantial time and resources during maintenance outages, and developed materials and maintenance methods to solve the cracking over the long term.

Better Carbon Capture

Capturing carbon dioxide (CO_2) before it enters the atmosphere reduces the GHG emissions of other industrial processes in addition to energy production. Neutron beams have been used to investigate materials that can capture CO_2 more efficiently than the ones in use today, to show how it can be stored in natural rock formations, and to predict carbon storage capacity of mineral deposits.[10]

Energy Efficiency in Manufacturing

Developing more energy-efficient ways of making products can save money as well as protect the environment. Following research using neutron beams, Nemak Canada expects to save millions by simplifying the heat treatment process for car engine blocks, and Hydro-Québec spun off a company to commercialize energy-saving technology for the production of paper.[11]

Efficient Energy Grid

Developing power lines using high-temperature superconductors that conserve all the electricity during transmission would make remote sources of hydro power more feasible to develop as well as help us make better use of existing capacity. University researchers frequently use neutron beams to aid discovery in superconductivity that could one day enable this technology.[12] Other researchers are using them to study materials already in use, in transformers for example, in order to improve the energy efficiency of the electricity grid.[13]

A further way in which materials research using neutron beams supports clean electricity is by **sharing infrastructure**: the same source of neutrons for materials research can be used for

[8] A Decade of Feeder Studies for Canada's Nuclear Power Technology. http://cins.ca/2015/02/01/a-decade-of-feeder-studies-summary/ .

[9] Canadian capabilities are also leveraged by the international nuclear community to support the management of their aging nuclear stations: e.g. Japan (CNBC http://cins.ca/2014/03/01/nuclear-3/) and the UK (http://cins.ca/2016/03/01/nuclear/).

[10] CO_2 capture: NIST. http://www.nist.gov/ncnr/zeolite-020712.cfm. CO_2 storage: Jülich Centre for Neutron Science. http://neutronsources.org/news/scientific-highlights/underground-storage-of-carbon-dioxide-safer-than-expected.html; Carbon storage prediction: http://cins.ca/2017/08/18/oil-gas/

[11] Engine blocks: see footnote 6; Paper: CNBC http://cins.ca/2014/01/01/paper/.

[12] For example, see CNBC http://cins.ca/2012/09/01/discovery-4/ and http://cins.ca/2012/01/01/discovery-5/.

[13] See Paul Scherrer Institute: http://neutronsources.org/news/scientific-highlights/en-route-to-better-transformers.html.

testing of nuclear fuels and materials for nuclear power, and building expertise in reactor operations. Advanced nuclear energy could generate much more clean electricity while producing less waste. Unique and innovative Canadian nuclear power stations can be exported to other countries, helping our economy while helping to reduce global GHG emissions.

Materials Research Underpins Other Canadian Priorities

Knowledge of how materials behave underpins developments in technology in other priority areas, such as health, security, and economic growth. The tools for materials research can be tuned for Canada's interests in these areas.

Clean Growth Economy

Any of these innovations, whether in energy or life sciences, will advance Canada's objective of a 'clean growth economy', which is a stronger, more resilient economy with high-paying, long term jobs based on science and technology skills and innovation. Materials research also contributes to business innovation in advanced manufacturing and other major industrial sectors, helping them manage environmental impacts, reduce waste, add value to products, and develop leading technologies.[14]

Health and Well-Being

Health and other life sciences are undergoing a revolution. Knowledge is being generated and new applications are emerging on a daily basis, with materials research contributing to Canada's leadership in biotechnology and pharmaceuticals. Neutron beams at one time were mainly applied to hard materials, but are now emerging as powerful and irreplaceable tools for soft materials of living things:

For **global food security**, research has boosted crop yields of Canola and wheat in Canada, and we are still making breakthroughs. Advanced materials imaging techniques, including neutron imaging, are currently being developed to accelerate development of crops by

[14] Aerospace: Helping to improve the lifetime of critical parts, reduce scrap waste and advance methods to make or repair engines (CNBC http://cins.ca/2016/05/01/aero-2/ and http://cins.ca/2015/09/01/aero/). Oil & Gas: Helping to decide when to replace pipeline section to prevent leaks (CNBC http://cins.ca/2014/09/01/pipelines/), to develop more reliable components for harsh conditions (CNBC http://cins.ca/2013/11/01/natural-gas-2/) and ways of reducing toxic additives in gasoline (NIST http://science.energy.gov/bes/highlights/2013/bes-2013-07-a/). Automotive: Examples in footnote 6, and CNBC http://cins.ca/2016/04/01/auto-2/. Metal Production: One steel product manufacturer expanded its plant, partly because of research that enabled it to add value to its products (CNBC http://cins.ca/2013/09/01/metal/).

matching genetic variation to observable traits that enhance drought resistance, for example.[15]

To **unravel the mysteries of our bodies,** research on the building blocks of living systems to determine their functions and how they interact is foundational. Neutron beams are distinctly powerful for studying cell membranes and biomolecules that interact with cell membranes, including cholesterol and vitamin E as well as proteins that play roles in cancer treatment or cardiac and neuronal disorders, yielding recent discoveries to better understand Parkinson's disease, human immunodeficiency virus (HIV), antibiotics, and anesthetics. Other recent neutron-beam projects have examined biomolecules that play roles in genetics, in the shelf life of drugs, and in factors that affect our bodies' ability to receive drugs. Recently, they have also been applied to **cancer-fighting technology**, and materials with potential to reduce surgery recovery times.[16]

Security in a Modern World

Countering modern threats such as terrorism at home or abroad requires us to adapt, but science and technology, including materials research, gives us an edge. We can make our military more agile and less dependent on oil, using new light-weight armour materials and alternate energy sources. We can reduce threats with technologies to help prevent the spread of nuclear weapons and to detect illicit nuclear materials. Materials research is making contributions to all these areas today.[17]

[15] University of Saskatchewan. July 29, 2015. http://words.usask.ca/news/2015/07/29/u-of-s-awarded-37-2-million-to-design-crops-for-global-food-security/

[16] Cholesterol: http://cins.ca/2017/03/03/bio-5/; Cholesterol and Aspirin: http://cins.ca/2016/01/01/cholesterol/. Vitamin E: http://cins.ca/2016/09/27/bio-3/. Cancer treatment: In press at http://cins.ca/discover/ and *Biophysical Journal.* April 16, 2014 doi:10.1016/j.bpj.2014.02.036. Cancer diagnosis: http://cins.ca/2016/10/26/bio-4/. Treatment of cardiac and neuronal disorders: NIST Center for Neutron Research. Annual Report 2015. https://www.ncnr.nist.gov/AnnualReport/. p10. Parkinson's disease: *J. Biological Chemistry*. Jan. 9, 2015. doi: 10.1074/jbc.M114.610584. HIV (human immunodeficiency virus): *Biophysical Journal*. Oct. 20, 2010. doi:10.1016/j.bpj.2010.07.062 Antibiotics: NIST Center for Neutron Research. Annual Report 2015. https://www.ncnr.nist.gov/AnnualReport. p8. Anesthetics: *Langmuir*, Feb. 21, 2012. doi:10.1021/la204317k. Genetics: *Science* 08 May 2015: doi:10.1126/science.1259308. Medical coatings: http://cins.ca/2016/10/26/bio-4/. Shelf life of drugs: *J. Phys. Chem. B*, 2013 doi:10.1021/jp408710r. and *J. Pharmaceutical Sciences.* 2015 June. doi:10.1002/jps.24429. Ability to receive drugs: *Pharmaceutics, Drug Delivery and Pharmaceutical Technology*, 2015 doi:10.1002/jps.24470. Minimally invasive surgery: http://cins.ca/2017/10/03/iot/

[17] Developing fuel for civil research reactors that are less susceptible to diversion for military uses (CNBC http://cins.ca/2016/06/01/nuclear-2/); investigating nuclear materials in containers that may not be safe to open (CNBC http://cins.ca/2015/10/01/mystery-flask/); advancing understandings of materials to safely extend the useful lives of our fleets of ships (CNBC http://cins.ca/2014/11/01/defence/ and http://cins.ca/2014/05/01/defence-2/); examples of materials research that required neutron beams to help develop light materials or alternate energy sources were provided earlier.

Canada on the World Stage

Leadership in innovation for global good is an excellent role on the world stage for Canada. Once known for 'blue helmet' peacekeeping, Canadians could be known as the 'blue lab coats' because we help solve the science and technology challenges underlying clean energy, security, public health and food supply in the developing world and at home.

Looking to the Future

The transition to a clean growth economy will present on-going technological challenges in the production and use of energy for decades. Throughout this period, increasingly stringent environmental targets will demand material advancements in manufacturing of cars, ships, airplanes, and much more. There is no end yet in sight to the appearance of new materials and new ways of making them that can boost economic prosperity. Terrorism may pass, but new security threats will emerge. The revolution in health sciences and biotechnologies will last for many decades, if not centuries.

A Looming Gap in Canada's Materials Research Capability

Rising to these challenges requires a strong science and technology foundation, including the full suite of tools for materials research. Canada has made major investments to renew many of its capabilities over the past 15 years, including two of the three national science facilities that support materials research: TRIUMF (Vancouver, BC) and the Canadian Light Source (Saskatoon, BC).

The fate of the Canadian Neutron Beam Centre (CNBC), however, is tied to the pending closure of its source of neutrons, the National Research Universal (NRU) reactor, in March 2018. Canada built the NRU reactor at Chalk River in the 1950s to support every known, foreseeable and even unforeseen application of neutrons to science, technology and industry. Bertram Brockhouse developed neutron beams at Chalk River as tools for materials research and was awarded the Nobel Prize in physics because they have become irreplaceable, providing insights about materials that cannot be obtained by other scientific techniques. The value of neutron beams is clear from $9B in capital that has been invested by other innovative countries so far in this century, so that their people can acquire critical knowledge they can't get any other way.

Researchers in over 30 Canadian universities, and in government and industry will be affected by the closure. Inaction risks crippling our ability to apply this tool to our innovation agenda. Once lost, this capability will be hard to regain.

A National Solution

Today, the CNBC is operated by Canadian Nuclear Laboratories in a partnership with the National Research Council, and is funded through Natural Resources Canada (NRCan) via Atomic Energy of Canada Ltd. None of these four agencies have a mandate to operate a Canadian neutron beam program following the CNBC's closure. In the absence of such a mandate, the academic community is taking the lead, charting a path forward.

The Canadian Neutron Initiative (CNI) is a response to the urgent challenge, aiming to sustain access for Canadians to this critical scientific tool, today and tomorrow. The executive leadership of the CNI working group is provided by the University of Saskatchewan, McMaster University, the Canadian Nuclear Association, and the Canadian Institute for Neutron Scattering.

The CNI seeks to establish a new university-led framework for leadership, management and funding of Canada's capacity for materials research with neutron beams, building on existing national and international resources. The new framework will ensure Canadians can access neutron beams for world-class research and innovation in materials as well as training students for highly-skilled careers.

For the next decade, the Canada must focus on coordinating access to leading neutron-beam facilities abroad. Canada will also need to fully exploit domestic, university-based capabilities, including the McMaster Nuclear Reactor, which will be Canada's most powerful research reactor by far at that time. Both aspects will be needed to maintain and rejuvenate a capable community of researchers in this field.

For the longer term beyond 2030, a national decision-making process focused on large-scale research infrastructure is needed. A neutron-based research community, which is rejuvenated through the CNI, can inform deliberations about a potential new research reactor, alongside other nuclear stakeholders, including the nuclear medicine community, and the nuclear power industry. The neutron community can help to maximize return on future investments, by designing in leading-edge scientific capabilities that will attract international collaboration and place Canada at the forefront of materials research and innovation for decades.