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### Canada's Neutron Source, the NRU reactor, closes

anada has been a leader in neu-Itron scattering for 70 years, starting with the National Research Experimental (NRX) reactor completed by the National Research Council (NRC) in 1947. Early neutron scattering experiments were conducted at NRX and then continued at the 10 times more powerful National Research Universal (NRU) reactor, with a flux of  $3 \times 10^{14}$  n/cm<sup>2</sup>/s. The NRU reactor was completed in 1957 by Atomic Energy of Canada Ltd. (AECL), which was split off from the NRC in 1952 to promote peaceful use of nuclear energy. The NRU reactor was the primary facility for in-reactor testing of nuclear components during the development of Canada's fleet of nuclear power stations. The NRU reactor also produced radioisotopes such as molybdenum-99, which have been used to diagnose an estimated

500 million patients around the world over its lifetime.

When the NRU reactor at AE-CL's Chalk River Laboratories closed on March 31, 2018, it was the world's oldest major research reactor (>5 MW) in the world. Since February 2015, when the final shutdown of the NRU reactor was announced, the team at the neutron beam laboratory at NRU, known as the Canadian Neutron Beam Centre (CNBC), strived to extract as much value and impact from the reactor as possible in its final years of operation. In other words, the goal was to 'cross the finish line running', and that is what they achieved: all beamlines were collecting data until the end, except one that had completed its final measurements just hours before.

During the last minutes of the reactor's operation, a memorial neu-

tron radiograph was taken that captured the last neutrons exiting the reactor as it shut down (Figure 1). The image was taken of a specially made plaque, composed of layers of nickel alloy plates and gadolinium lettering to create contrast. The neutron image shows a stylized layout of the six neutron beamlines around the core of the NRU reactor, the biological shield that protects personnel, and the graphite column (a further explanation of the image and how this was done is provided at http://cins. ca/2018/05/30/the-final-neutrons/).

Most of these beamlines still performed among the best in the world, in terms of the quantity and quality of output in science and engineering. Among these high performers were a powder diffractometer, a polarized triple-axis spectrometer, a neutron reflectometer and a stress mapping



Figure 1. A neutron image of the plaque depicting the final neutrons captured in the NRU reactor, overlaid with labels of each neutron beamline's designation. (Image credit: CNBC).

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Figure 2. Bert Brockhouse with the first version of his triple-axis spectrometer for inelastic scattering at the NRU reactor (circa 1958–1959). (Image credit: AECL).

diffractometer. These beamlines supported a strong community: over the last 5 years, about 800 research participants from Canada and around the world, including students and researchers from universities, government labs, and industry.

Over its lifetime, the neutron scattering program at NRU made major contributions to materials science and to neutron beam instrumentation. Innovative neutron instruments and methods developed in Canada have been replicated at every major neutron beam centre worldwide. These include Brockhouse's tripleaxis spectrometer from the 1950s (some shielding from the original instrument from the 1950s was still in use on the E3 beamline at NRU) and advances in neutron stress scanning in the 1980s.

The neutron beam lab grew out of the pioneering efforts of scientists from NRC, and subsequently from AECL, from the late 1940s through the 1950s. Donald 'Don' G. Hurst was Head of the Neutron Spectrometers Section of the General Physics Branch of NRC's laboratories in Chalk River, known in the late '40s as the Atomic Energy Project. Hurst was the inspiration behind the neutron scattering program, working with experimentalists Gertrude 'Trudi' H. Goldschmidt (post-doc), Andrew 'Andy' J. Pressesky, Philip R. Tunnicliffe, and Norman Zinkan Alcock, and theorist John Ashley Spiers, to develop early neutron spectrometers, take measurements on gases, and solve the structure of deuterated ammonium chloride.

These scientists each left Chalk River between 1949 and 1951, leaving Hurst and Bertram 'Bert' Neville Brockhouse (1950–62)<sup>1</sup> as experimentalists to carry forward the development of neutron scattering,

supported by Walter 'Walt' J. Woytowich (1949-53) as technical support and Noel K. Pope (1950-53) in the Theoretical Physics Branch. Soon, scientists Dave G. Henshaw (1951-59), Alec Thomson Stewart (1952-57), and John 'Warwick' Knowles (1954-56) were added to the Section. Together, the Section laid foundations for neutron scattering experiments in gases, liquids and solids. Brockhouse took the lead on examining solids and the development of inelastic neutron scattering, which led to his Nobel Prize in 1994, after over 30 years from these pioneering contributions.

When Hurst left the Physics Division in 1955, Brockhouse took over as Section Head, and Knowles moved on to do neutron nuclear physics soon after. In 1960, Neutron Physics became a separate branch of AECL headed by Brockhouse. In addition to neutron scattering, the Branch included neutron nuclear physicists, who used the NRX or NRU reactors as a neutron or gamma-ray source for other methods including neutron-capture gamma-ray spectroscopy and positron annihilation. When Brockhouse left Chalk River in September 1962 to become a professor at McMaster University, Dave Woods took over the leadership of the Neutron Spectrometers Section. The Neutron Physics Branch was headed by Gilbert 'Gil' Alfred Bartholomew until 1971 (this was the only time the Section Head responsible for neutron scattering was not also the Branch Head).

Throughout the 1960s, '70s, and '80s external researchers obtained access to neutron beams primarily by collaborating with Neutron Physics Branch scientists: A.D.B. 'Dave'

<sup>&</sup>lt;sup>1</sup>Years indicate time associated with the neutron scattering lab unless otherwise noted.

Woods (1958–79, Section Head 1962-71, Branch Head 1971-79), Gerald Dolling (1961-85, Branch Head 1979-85), Roger A. Cowley (1961-62, and 1964-70), Brian M. Powell (1964-98, Branch Head 1991-98), William 'Bill' J. L. Buyers (1965-2007, Branch Head 1985-91), C. Peter Martel (1965-93), Eric C. Svensson (1966-2002), Thomas 'Tom' M. Holden (1966-98), and Soo M. Kim (1970–97). There was high turnover in the few technical staff positions that supported the experiments in these years. Yet a few served for significant periods, including: Ed A. Glaser (1956-70), Harold F. Nieman (1964-94), Remick 'Rem' S. Campbell (1967-78), Melvin 'Mel' M. Potter (1968-10), Alan H. Hewitt (1968-88), Don C. Tennant (1971-97), and Jim C. Evans (1979 - 86).

By the late '70s, the Branch operated several beamlines: triple-axis neutron spectrometers at the C4, C5, L3, and N5 beam ports, a gamma-ray monochromator for Compton scattering at C1, a fast neutron chopper at C2, and an external thermal-neutron beam for neutron-capture gammaray experiments at N4. In addition, university researchers also partnered with AECL to establish two additional beamlines at NRU: the McMaster University double-monochromator triple-axis spectrometer at E3, used by Professor Brockhouse's students, and the GWELFNEUD II diffractometer at D3, built by Professor Peter Egelstaff (Guelph University) for neutron scattering of liquids and gases. There was also an ultracold neutron experiment at T3 for McGill University.

The Neutron and Solid State Physics Branch, as it was renamed in 1971, enjoyed a strong international scientific reputation. Notable accom-

plishments include an extensive series of measurements on the inelastic neutron scattering from <sup>4</sup>He by Dave Woods and Eric Svensson. Woods and Svensson demonstrated the existence of a Bose-Einstein condensate in the superfluid phase of liquid <sup>4</sup>He and measured precisely the associated condensate fraction as a function of temperature. Many of their measurements stood as the world standard for many years, and their measurements of the static structure factor of liquid <sup>4</sup>He remain the most accurate to date. With Robin Armstrong from the University of Toronto, Bill Buyers experimentally confirmed the existence of the Haldane Gap in 1985. This confirmation overturned the wisdom of the day and led to the acceptance of topological theory, for which Duncan Haldane shared the Nobel Prize in physics in 2016, thereby opening the field of topological materials. The Branch also benefited from collaborations with members of the Theoretical Physics Branch, such as K. Bruce Winterbon (1964-89), Varley F. Sears (1965-97), and Henry R. Glyde (1969-75), on the theories of neutron scattering needed to understand experimental results. In particular, Sears published many foundational papers and his tables of neutron scattering lengths and cross sections are still in use today [1].

The Branch included prominent neutron nuclear physicists. Eric 'Davis' Earle, M. Aslam Lone, and Warwick Knowles collaborated with Arthur 'Art' B. McDonald, then a member of the Nuclear Physics Branch, on over 30 papers in the '70s and early '80s. These were primarily parity violation studies using accelerator-produced gamma rays that formed a basis for the Sudbury Neutrino Observatory (SNO) experiment. Davis Earle and many other AECL scientists and technical staff contributed to the technical development of SNO into the '90s, and the discoveries arising from it led to Mc-Donald's 2015 Nobel Prize in Physics as the leader of the SNO project.

In addition, AECL nuclear fuel researchers operated a neutron imaging beamline at the N1 beam port of the NRU reactor, as neutron imaging is uniquely powerful for non-destructive examination of hydriding, a common cause of fuel failures. Under the direction of Alan Ross and then Glen MacGillivray. N1 developed into a world-leading radiography facility in the '80s. In 1994, AECL spun off this capability as a private business, Nray Services, which was headed by MacGillivray and served the aerospace industry for inspection of turbine blades. Nray immediately moved its operations to the McMaster Nuclear Reactor, where it still operates today.

experienced reduced AECL funding in the mid-'80s, and in response, it began cutting deeply its fundamental research programs. AECL chose to focus remaining resources for fundamental research efforts on just a few large facilities that it described as "unique in Canada, at the forefront of all such facilities worldwide and available to all qualified Canadian scientists." [2] Thus, losses in personnel in the Neutron and Solid State Physics Branch were mainly limited to the sections for neutron nuclear physics and detector development, leaving the section for neutron scattering experiments intact.

The construction of the DUAL-SPEC facility (1985–92), which included two beamlines, at a capital cost of \$4M, marked a turning point for general user access to neu-

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tron beams at Chalk River. DUAL-SPEC's construction and operations were funded jointly by AECL and NSERC (a federal funding agency for university research). The NSERC grant was awarded to Malcolm Collins of McMaster University, which represented applicants from 10 universities, to ensure that it would be operated as a national user facility. The Canadian Institute for Neutron Scattering was formed to represent users' collective interests in the facility. A national user model was soon adopted for the other neutron spectrometers that remained, following a restructuring of the beam facilities in preparation for the installation of DUALSPEC: three triple-axis spectrometers at E3, L3, and N5, and a prototype low-angle scattering instrument at T3.

In parallel to the development of partnerships with university users, commercial services to industry emerged. In 1983, Tom Holden with Brian Powell and Gerald Dolling demonstrated stress mapping of intact components of nuclear power reactors on the C5 and L3 beamlines, which led to the Applied Neutron Diffraction for Industry (ANDI) service. After the Space Shuttle Challenger disaster in January 1986, ANDI was selected to examine an as-manufactured section of a booster rocket casing provided by the accident investigation. Neutron diffraction showed that the stress distribution in question was acceptable, pointing the failure investigation to look elsewhere. ANDI became the go-to service for failure analyses for high-profile incidents, such as the Point Lepreau Nuclear Generating Station shutdowns in 1997 and 2001, the Space Shuttle Columbia accident in 2003 and the 2005 train derailment at Lake Wabamun in Alberta, which spilled 800,000 liters of oil. ANDI ran successfully for over 20 years, providing proprietary data to enhance safety and reliability or optimize processes in energy and manufacturing sectors such as air, automotive, rail, and marine transportation, metal production, oil and gas, and defence.

In the early 1990s, the future was bright at AECL's newly renamed Neutron and Condensed-Matter Sciences Branch, with the success of ANDI and the growing user-access program through DUALSPEC. The user community was rallying behind a reactor concept for NRU's successor, the Irradiation Research Facility. New neutron scattering experimentalists had joined the expanding branch, including John H. Root (1986-present), Zin Tun (1989-present), Ian P. Swainson (1992-2010), Ron B. Rogge (1993-present), and John Katsaras (1994-2010). Frank J. Marsiglio (1990-97) joined the Theoretical Physics Branch to provide theoretical support for understanding superconductivity, the subject of many neutron experiments. In fact, when the Theoretical Physics Branch was disbanded in 1993, four theorists, whose work was relevant to materials research, transferred to the Neutron and Condensed-Matter Sciences Branch: Varley Sears, Frank Marsiglio, Michel Couture (1986-96), and Hoong-Chien 'Paul' Lee (1968–93). At the same time, Ted Hsu (1992-94) joined as a research associate in theory (Hsu was later the science critic as a Member of Parliament, 2011–15).

The neutron scattering experiments were also well supported with additional technical staff who had recently joined the Branch. Those who provided dedicated supported for a decade or more include: Mike W. Montaigne (1985–99), Gerry A. Sims (1986–95), J.J.-P. 'Jimmy' Bolduc (1986–2016), Larry E. MacEwan (1988–2015), and John Fox (1993–2014). In particular, Ron L. Donaberger (1986–2015), gained sufficient neutron diffraction expertise to serve as a local expert for many user experiments.

The hopeful outlook in the Branch was validated when Brockhouse shared the 1994 Nobel Prize in Physics with Clifford Shull of Oak Ridge National Lab (USA) for their pioneering contributions to neutron scattering in the 1950s. Their selection for the prize reflected the versatility and irreplaceability of neutron beams as scientific tools, providing insights about materials that cannot be obtained by other scientific techniques. Over the 30 years since Brockhouse's pioneering work, his methods had been replicated and further advanced at major neutron sources around the world, enabling many areas of research in solid state physics.

But in spring 1996 when many other government agencies were facing cutbacks, AECL's budget was cut 40%, and decisions were made to eliminate all of its remaining fundamental research activities. The Physics Division was disbanded, then composed of primarily accelerator physics at the Tandem Accelerator Superconducting Cyclotron, neutron scattering at NRU, and support for development of SNO. There was a strong outcry from the neutron user community, and Bill Buyers leveraged contacts in federal departments to advocate for retention of neutron scattering. Senior officials at Natural Resources Canada (responsible for nuclear matters) and Industry Canada (responsible for science and economic development)

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agreed and struck a deal to transfer the neutron beam lab to the National Research Council (NRC) as the Neutron Program for Materials Research (NPMR) on April 1, 1997. The deal provided a smaller budget that could accommodate the neutron scattering experimentalists and technicians, but not the theorists or neutron nuclear physicists. The science staff were transferred to NRC immediately, while the technical staff were seconded to NRC for 3 years ending in March 2001, after which some were transferred to NRC and others were redeployed within AECL.

Rebuilding the Program began under NRC with the strong support of the neutron scattering community, which attracted funds from government granting agencies to boost operations and construct a reflectometer at the D3 beamline. Many of the prominent scientists whose work characterized the earlier decades had retired or would retire in the early years under NRC. When Brian Powell retired in 1998. John Root became Program Leader, and remains so today. New scientists were attracted, in addition to post-docs and research associates, to support the user program: Mu-Ping Nieh (2002-10), Helmut

Fritzsche (2003–present), Lachlan M.D. Cranswick (2004–10), Zahra Yamani (2004–present), Michael A. Gharghouri (2004–present), Dimitry G. Sediako (2006–17), and Norbert Kučerka (2006–14). New technical staff were added during these years as well, including Tim Whan (2001–15), Raymond Sammon (2003–present), Shutao Li (2007–17), and Dave Dean (2007–present), each of whom provided valuable support for over a decade.

The NPMR emerged strongly from the crisis of the mid-'90s. An international peer review in 2004 reported that only three facilities in the world had more users per beamline, and that the CNBC provided an extraordinarily high fraction of the beam time to users (90%), compared to 50-66% elsewhere, and to industry as a commercial service (13%). They concluded that NPMR was a world-class program run on a shoestring budget. Renamed the Canadian Neutron Beam Centre (CNBC) in 2005, the Centre reached a peak around 2008, running at full capacity with six beamlines highly subscribed by a community of over 700 frequent and occasional research participants, over 5 years, of all types: scientists,

engineers, and students, from universities, industry, and government labs, from Canada and around the world. The ANDI service had generated about \$6M of fee-for-service revenue for over 200 projects. The CNBC's \$4M/year operations had achieved a funding balance of 60% from NRC for baseline operations, 30% from NSERC to maintain facilities in a state of readiness for user access, and 10% from commercial services and other R&D income. Numerous beamline upgrades were put in place, distinguishing the CNBC in stress scanning, powder diffraction, and polarized triple-axis spectroscopy.

The final decade of CNBC operation was characterized by persistence through challenges. Federal austerity measures following the global 2008 recession first led to hiring freezes at NRC, and then significant cuts at NRC and NSERC. These cuts, in parallel to the restructuring of NRC led to a decision by NRC in 2012 to eliminate CNBC's funding. However, AECL, which was then undergoing its own restructuring, agreed to take responsibility for funding, governance and operation of the CNBC, effective April 1, 2013. In addition, a

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Figure 3. DUALSPEC at the time of NRU's closure in March 2018, comprised of the C2 Powder Diffractometer and the C5 Polarized Beam Triple-Axis Spectrometer. Parts of the D3 Reflectometer and E3 Triple-Axis Spectrometer are visible in the background. (Image credit: CNBC).

heavy water leak led to an unplanned shutdown of the NRU reactor beginning in May 2009 and required a challenging repair, thereby creating uncertainty over whether the reactor would be restarted at all. The repair job was completed in August 2010 at a cost of well over \$100M. Discussions of replacing the NRU reactor were put on hold as government attention was dominated by questions of Chalk River's role as a national nuclear lab, the structure of AECL, a national nuclear policy, global shortages of Mo-99 caused by unplanned shutdowns of NRU reactor, and a \$1.6B lawsuit from Nordion over cancelling the MAPLE reactors intended for Mo-99 production.

All these factors created further uncertainty about the continued lifetime of the Canadian Neutron Beam Centre. The CNBC did not recover

from staff losses in soft materials expertise or in the ANDI service's momentum following the 15-month shutdown. Yet in other areas, the CNBC bounced back. Research participants grew to over 800 over the last 5 years, compared with over 700 for the 5 years ending in 2008. Although proprietary research for industry dropped off, the total proportion of beam time for industry remained the same. Mark Vigder (2009-present) led a small team in a successful renewal of the data acquisition and instrument control systems for the beamlines. New scientists joined, replenishing the professional ranks: Roxana Flacau (2010-14), Julien Lang (2015-present), Hung 'Harry' Ha (2015-present), and Levente Balogh (2016-18). Chad D. Boyer (2009–present), originally a technical officer, was promoted to a

scientist role, having begun serving as a local expert for user experiments in 2014.

The Canadian Nuclear Safety Commission required a plan from AECL concerning whether and how it would continue or cease operations of the NRU reactor beyond 2016. After reviewing the business case for extending NRU's license to 2021, the Government of Canada announced in February 2015 that it would support an application for license extension until March 31, 2018, citing heavy financial costs and changes in the medical isotope market that had reduced reliance on NRU. Canadian Nuclear Laboratories (CNL, the successor agency of AECL that has operated the Chalk River Laboratories since 2014) immediately confirmed that the government intended this to be the final closure date for the reactor, and planning began for how to retain staff needed to operate and maximize value from NRU's remaining life. Thus, CNL offered positions to all CNBC personnel. Most of the science staff accepted the offers and were assigned to a Neutron Scattering Branch, created for that purpose. As a result, the CNBC has been operated since August 2015 as a team of individuals drawn from both NRC and CNL.

Today, the CNBC is in a winddown mode, wrapping up the scientific outcomes of the final neutron beam experiments, and working towards dispositioning the neutron beam equipment. Zin Tun and Derrick West (2012-present, designer) are also completing a project for McMaster University to design and build a small-angle neutron scattering (SANS) beamline for the Mc-Master Nuclear Reactor. CNL's neutron scattering scientists now form a Section led by Ron Rogge within the Materials Sciences Branch of CNL. This section can continue using neutron scattering, to the extent that the neutron capabilities needed to support CNL research projects may be accessible elsewhere.

Will Canada replace the NRU reactor? The federal government's clearest policy statement about a new research reactor was made in 2010, in which it signaled to indus-

try and the Ontario government, which owns most of Canada's nuclear power stations, that it was not interested in funding a new research reactor by itself. It stated that an investment decision would need to be based on appropriate sharing of costs among the many users and beneficiaries. Apart from this requirement, the federal government is officially neutral. Thus, a prerequisite to such a decision is alignment of both levels of government and of stakeholders on a compelling scientific and business case. As each of the three traditional stakeholder communities. nuclear power, medical isotopes, and neutron beams, are presently in a state of reorganization or rebuilding following the restructuring of AECL and the loss of the NRU reactor, only time will tell if such an alignment will occur.

Since 2015 when the coming closure of NRU was announced, the Canadian Institute for Neutron Scattering (CINS), which represents the neutron beam community, has been looking to secure funds for a new mode of operation using other neutron sources: CINS aims to secure sufficient beam time at leading foreign facilities to meet Canadian demand for experiments that require the brightest sources of neutrons. CINS also aims to fully exploit the McMaster Nuclear Reactor as Canada's best remaining source of neutrons. CINS sees potential to upgrade the McMaster Nuclear Reactor's neutron flux and operating cycle and to add further beamlines, such as a powder diffractometer and reflectometer, thereby making it more suitable for a range of highdemand capabilities.

Whatever the future may hold for Canadian neutron beam users, an enduring truth is that neutrons interact with materials in unique ways to reveal knowledge that is often difficult or impossible to acquire otherwise. Neutrons will continue to be needed.

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