MATERIALS RESEARCH WITH NEUTRON BEAMS FROM A RESEARCH REACTOR

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Abstract

Because of the unique ways that neutrons interact with matter, neutron beams from a research reactor can reveal knowledge about materials that cannot be obtained as easily with other scientific methods. Neutron beams are suitable for imaging methods (radiography or tomography), for scattering methods (diffraction, spectroscopy, and reflectometry) and for other possibilities. Neutron-beam methods are applied by students and researchers from academia, industry and government to support their materials research programs in several disciplines: physics, chemistry, materials science and life science. The arising knowledge about materials has been applied to advance technologies that appear in everyday life: transportation, communication, energy, environment and health. This paper illustrates the broad spectrum of materials research with neutron beams, by presenting examples from the Canadian Neutron Beam Centre at the NRU research reactor in Chalk River.

1. RESEARCH REACTORS PRODUCE NEUTRON BEAMS

Nuclear research reactors enable continuous fission of uranium-235, each atomic nucleus breaking into smaller atomic nuclei of various sizes and a few free neutrons. Neutrons are neutral subatomic particles that persist outside the usual confines of an atomic nucleus, eventually decaying into a proton, electron and neutrino with a half-life of about 15 minutes. A steady flux of neutrons diffuses throughout the core volume of a research reactor. Neutrons scatter from the atomic nuclei of other materials in the core of the reactor, including fuel, structural components and especially from materials with low atomic mass, such as hydrogen, deuterium, water, heavy water, graphite, or methane. These light materials efficiently moderate neutron speeds from the initial high energies of fission to ‘thermalized’ energies. The temperature of the moderator material determines the equilibrium spectrum of neutron energies. If the moderator is room-temperature water or heavy water, most of the neutrons settle into a ‘thermal spectrum’ with speeds in the range of 1000 m/s to 4000 m/s. If the moderator is very cold, for example liquid hydrogen with a temperature of about -250 oC, the neutron speeds would be slower, most of them in the range of 200 m/s to 1000 m/s, and labelled as “cold neutrons”. Neutrons are small enough that they exhibit both particle-like and wave-like behaviours. Cold neutrons in a liquid hydrogen moderator have longer wavelengths, most of them in the range of 0.4 to 2.0 nm, whereas thermal neutron wavelengths in a water moderator mostly fall in the range of 0.1 to 0.4 nm.

The core of a research reactor is typically surrounded by a thick wall – the biological shield that protects personnel in the working area around the reactor from the radiation emitted by fission and decay processes inside the reactor core. By simply opening a beam tube through the biological shield, neutrons and other radiation can escape from the core into the working area. Additional external shielding and other components can be placed in line with the beam tube to separate a stream of neutrons of a chosen wavelength and direct that 'monochromatic' neutron beam towards a specimen of material. The way the neutron beam is scattered from the specimen reveals crystalline structures or nanostructures as well as intermolecular vibrations, magnetic structures and magnetic excitations.

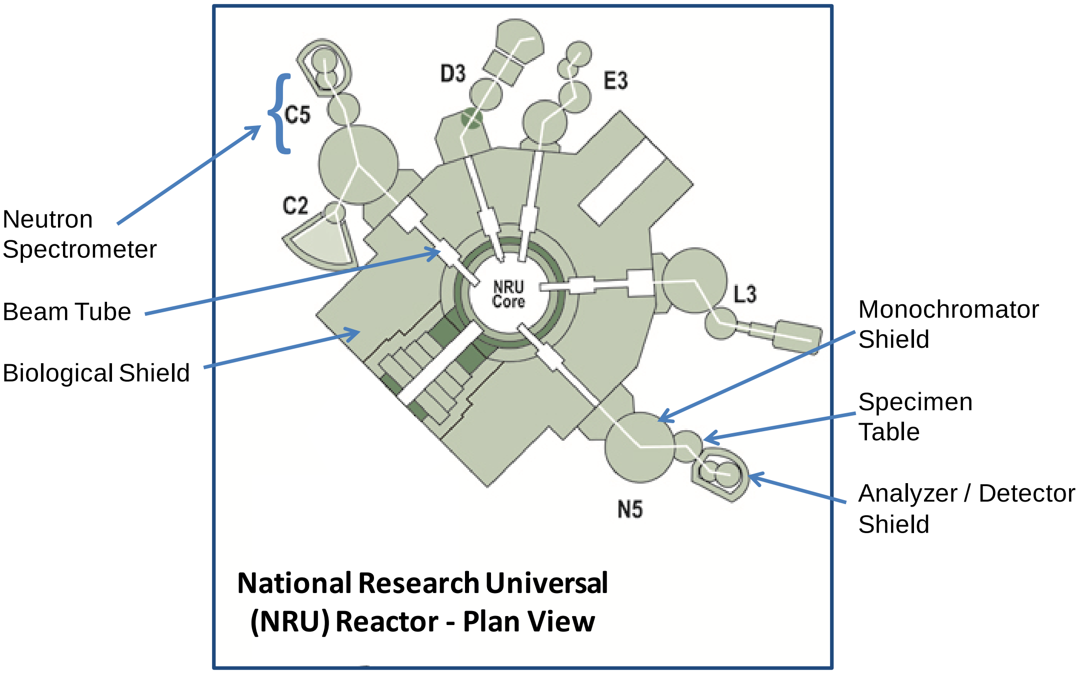

Figure 1 - Plan view of the NRU research reactor, showing the core, biological shield, beam tubes and external components that comprise six neutron spectrometers, labelled C2, C5, D3, E3, L3 and N5

2. NEUTRON BEAMS PROBE MATERIALS

The reason why materials researchers are interested to probe specimens with neutron beams, is the unique way that neutrons interact with matter. Neutrons are neutral particles, and mainly interact with the nuclei of atoms via the strong, short-ranged, nuclear force, not through any long-ranged Coulomb forces with the charged electron cloud that occupies the vast majority of an atom's volume. From the viewpoint of a neutron, matter is mostly empty space, the nucleus at the centre of each atom being a pin-point compared to the wavelength of the neutron, which is similar to the distances between atoms and molecules. The interaction of the neutron with atomic nuclei varies erratically with atomic size, and isotope. Also, while neutrons are electrically neutral, they carry a magnetic moment, and therefore interact with any magnetic structures or excitations that appear at the molecular level of materials. The way neutrons interact with matter frequently reveals features of materials that are challenging to study with other scientific probes of materials, such as light, X-rays, or electrons, all of which interact strongly with atomic electrons, rather than the nucleus.

The “Big Three” strengths of neutron beam methods are listed here:

(1) Neutrons penetrate deeply into most materials (millimetres, centimetres) even though the energies of thermal neutrons are a million times lower than X-rays of similar wavelength – i.e. thermal neutrons are completely non-destructive probes of materials in bulk or at depth.

(2) Neutrons reveal magnetic structures that appear in many innovative materials that have high technological impact or potential to revolutionize technologies, including colossal magneto-resistors for information storage, high-temperature superconductors to maximize energy efficiency, high-field permanent magnets for miniaturization of electric motors, and advanced quantum materials.

(3) Neutrons distinguish among isotopes of a given atom, which enables researchers to adjust the contrast and visibility of molecular features through isotope substitution in complex biological structures, as well as to detect light atoms in the presence of heavy atoms, for example lithium ions in battery materials, or hydrogen in a metal matrix.

3. NEUTRON IMAGING

The easy penetration of neutrons through most materials, along with their high sensitivity to hydrogen, opens up possibilities for imaging the interior structures of many objects, and revealing complementary details that might be comparatively difficult to see with X-rays. Neutron radiography is directly analogous to X-ray radiography, which is familiar in the form of dental X-rays – images of bone with darker features where softer tissue or regions of decay provide contrast with the general background. X-ray absorption increases uniformly with atomic size, with heavy-metal fillings absorbing more than calcium-loaded bone, which in turn absorbs more than the metal-free tissue of the gums. An image made with neutrons would reveal different light and dark regions, the hydrogen-rich proteins in the gums absorbing and scattering far more neutrons away from the transmitted beam than the heavy metal fillings. Neutron and X-ray radiography images are not necessarily ‘negatives’ of each other, but if there are structural features inside an object that contain a lot of hydrogen, such as water, oil, plastic or biological materials, neutrons may reveal them more readily than X-rays against a background of heavier materials, such as metals or ceramics. At neutron beam laboratories around the world, the technology for neutron radiography is continuously advancing with respect to spatial resolution and speed of image capture. The first stroboscopic neutron radiography demonstration was made in 2002 as a collaboration of FRM II (Munich), the ILL (Grenoble), the University of Heidelberg and the Paul Scherrer Institute (Switzerland), in which a four-piston BMW engine was probed to reveal the distribution of lubricant at various points in the operating cycle, with the high flux neutron beam line H9 at the Institut Laue Langevin (ILL), delivering exposure times of the order ~ 100ms.

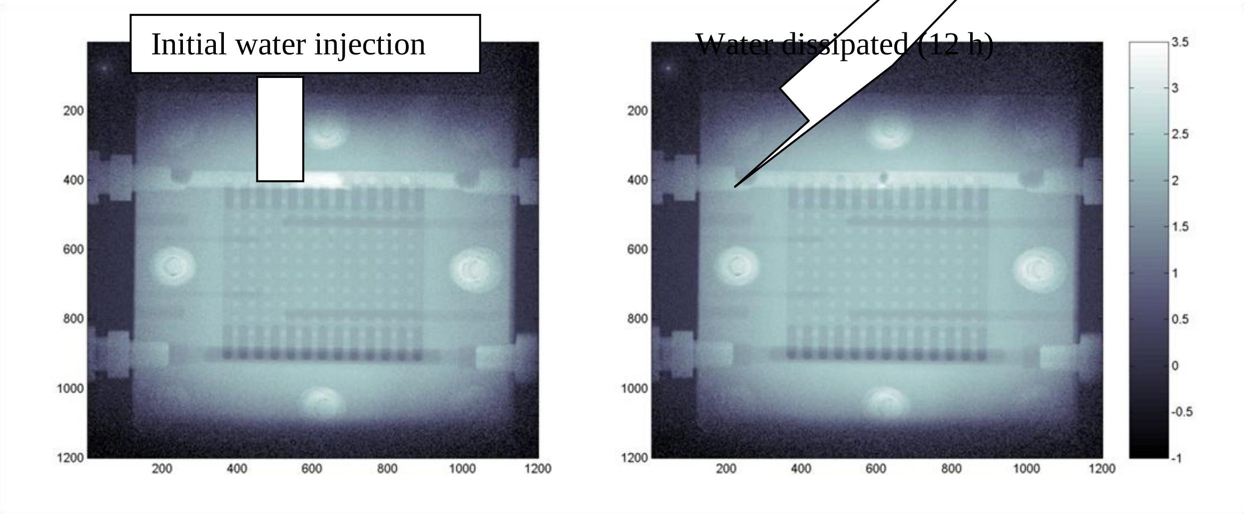

Figure 2 - Neutron radiographs of a prototype hydrogen fuel cell, showing dissipation of injected water (light patch in upper horizontal channel) after 12 hours. The images were taken at the NRU reactor.

By rotating the specimen to acquire a series of neutron radiographs, the internal structures of the object can be reconstructed in a three-dimensional model. This method, called neutron tomography, is completely analogous to computer-assisted tomographic scanning (CAT-scanning) familiar in clinical imaging, where gamma rays are transmitted through a patient in several directions to form a three-dimensional picture of internal organs and disease structures. However, again, the easy penetration of neutrons into most materials and special sensitivity of neutrons to light atoms, especially hydrogen, provides opportunities for image contrast that might reveal internal structure details not so easily distinguished by X-rays or gamma rays.

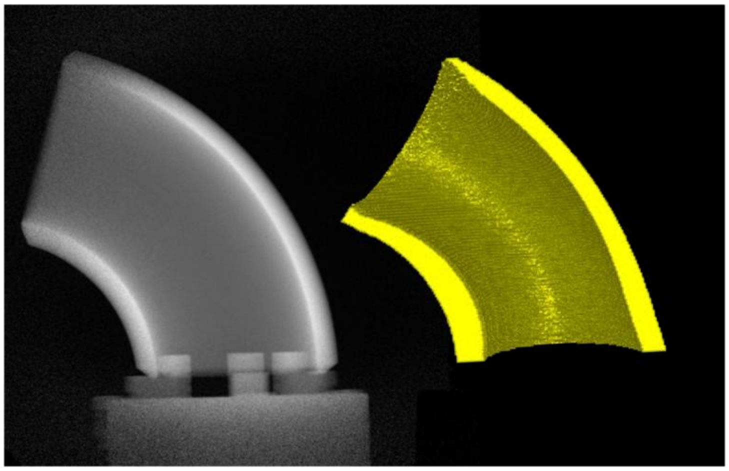

Figure 3 - A single neutron radiograph of a bent steel pipe (~ 70mm diameter) is compared to a tomographic reconstruction from several neutron radiographs, revealing the thickening of the pipe wall on the intrados of the bend. Images were collected with a Mar345 image-plate detector on the N5 neutron beam at the NRU reactor in Chalk River.

4. NEUTRON SCATTERING

While neutron imaging reveals structural information on a large scale, neutron scattering exploits the abilities of neutrons to probe structures and dynamics of materials at the level of inter-atomic distances or nanostructures. Whether a sample is composed of a hard material (metals, alloys, ceramics) or a soft material (polymers, biological membranes, vesicles) or a complex mixture (metal-matrix composites, colloids, emulsions), neutrons can extract information about distances, molecular-interaction energies and magnetism, often while the sample is simultaneously held in scientifically or technologically relevant conditions (temperature, pressure, stress, chemical environment). A neutron beam, prepared with initial direction, cross-section, magnetic polarization and energy (ie wavelength or velocity), directed into a sample, will produce scattered neutrons over a range of scattering angles and a range of scattered-neutron energies, and possible change of polarization, all of which can be characterized with suitable detection equipment. The changes in scattered neutron direction and energy can be analyzed to reveal the underlying crystalline or nanostructures of the material as well as the available excitations in the material, such as phonons or magnons.

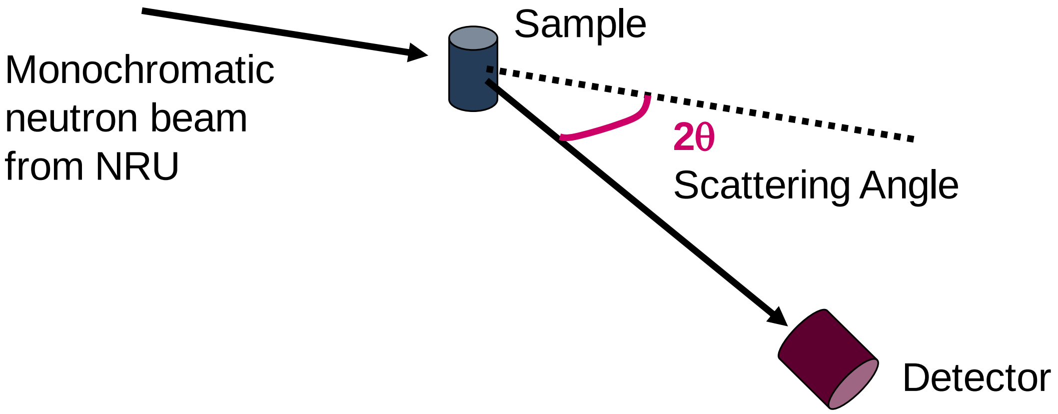

Figure 4 - A beam of neutrons, with initial direction, shape and wavelength, enters a sample of material. The neutrons are scattered into various directions and their energies (wavelengths) are shifted by interaction with atomic nuclei or magnetism in the sample at the length scale of intermolecular distances (nanometres).

A familiar manifestation of neutron scattering is neutron diffraction. As with X-ray diffraction, neutrons can diffract from single crystals, powders and polycrystalline solid materials. The easy penetration of neutrons into most materials ensures that neutron diffraction probes the entire volume of a specimen, yielding bulk-average information, and enabling the possibility of non-destructive mapping of the interior of a specimen. Neutrons can penetrate through the walls of a furnace or other specimen environment, to probe a sample that is held within, at conditions of interest. The structural information extracted by neutron diffraction reveals distances between the atomic planes that comprise crystals, the occupancy of crystal sites by various atoms or isotopes, distortions of the crystal lattice due to applied or residual stresses, crystal-lattice damage, statistical distributions of crystal orientations in a poly-crystal, and average microstructural grain sizes.

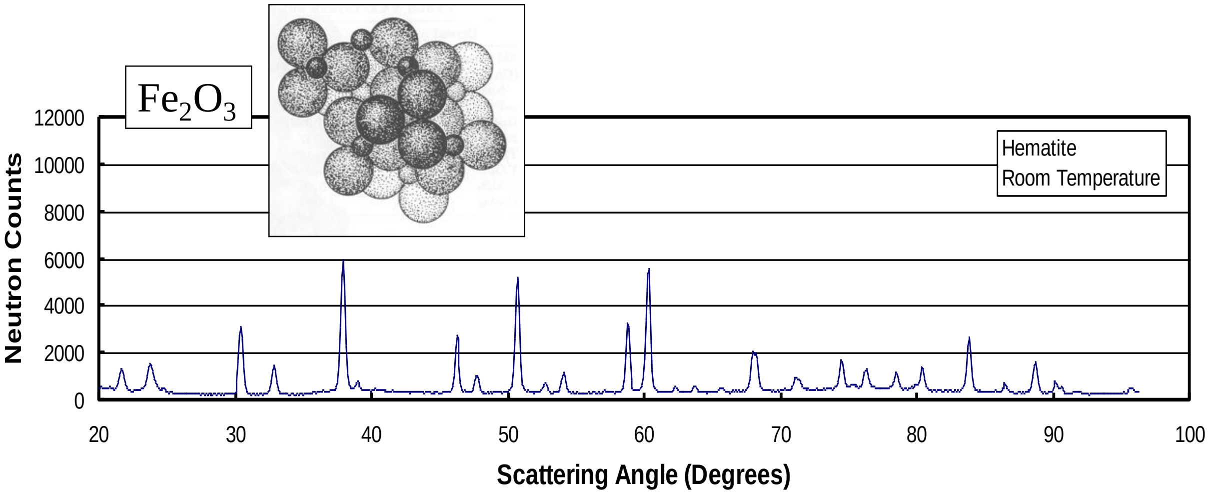

Figure 5 - A neutron powder diffraction pattern from iron oxide (hematite) was collected on the C2 diffractometer at the NRU reactor. The pattern of peak intensities and scattering angles is a fingerprint of the underlying crystal structure. The C2 instrument has a single, curved, 800-channel position-sensitive detector that acquires the full diffraction pattern in a single setting, providing resolution and throughput that is highly competitive among neutron beam laboratories in North America.

A second category of structural analysis by neutron scattering is provided by a method called reflectometry. Similar to the way fibre optics transmit light over long distances with minimal loss of intensity through ‘total internal reflection’ at the surfaces of each fibre, neutrons are also totally reflected at surfaces or interfaces, when scattering angles are very low. As the neutron scattering angle increases, there comes a point where neutrons partially penetrate the interface and enter the material in the next layer. Reflection may then occur at the next interface, as well, and the two neutron waves, reflected from each surface, interfere with each other to create a pattern of intensity oscillations as a function of scattering angle. When this reflectivity pattern is analyzed, the thickness of each interface, its roughness and the atomic or isotopic composition can be extracted, averaging over a comparatively large surface area (~cm 2) with a depth resolution and range in the scale of nanometres. Neutron reflectometry measurements can be performed on specimens while they are exposed to electrochemical conditions, hydrogen at selected pressures and temperatures, or magnetic fields to reveal new knowledge about corrosion, absorption of gases, polymeric coatings for medical implants, structures in biological membranes, superconductivity, spintronic materials and much more.

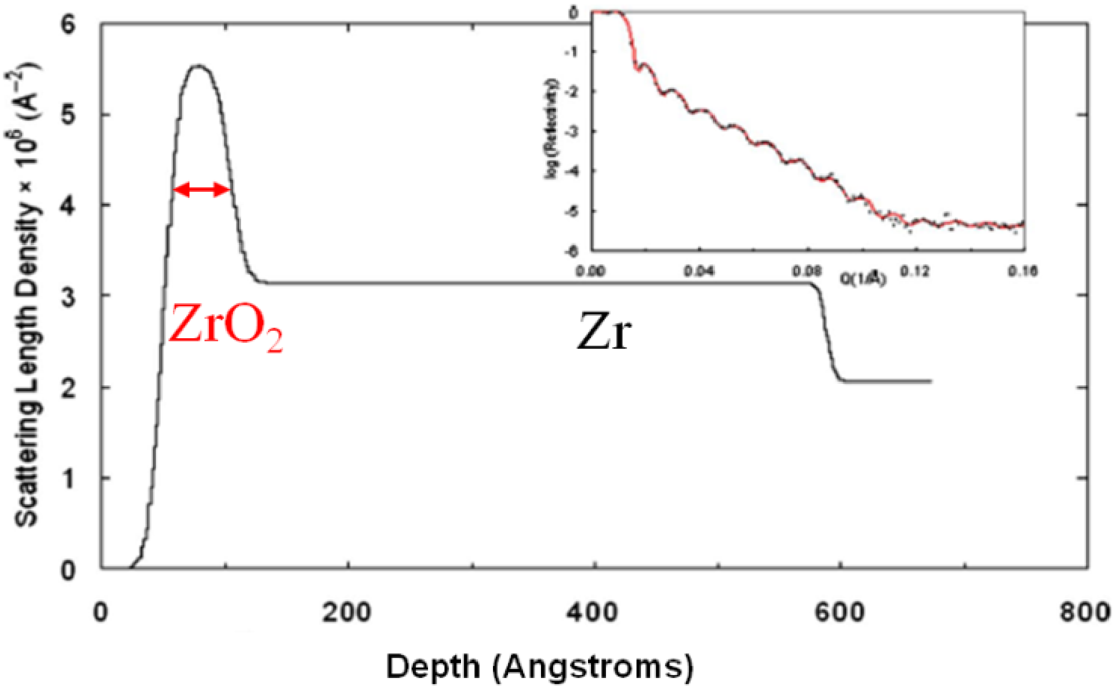

Figure 6 - A neutron interference pattern (inset), collected with the D3 neutron reflectometer at the NRU reactor is modelled to extract a profile of composition versus depth, here revealing that the native oxide on a zirconium metal surface is about 50 Angstroms (5 nm) thick.

The final major category of neutron scattering methods is a form of spectroscopy, where both the new direction (momentum) of neutrons is determined after scattering, as in diffraction, as well as the new energy of the neutrons is determined after scattering. The change in energy from incident to scattered neutron arises by exciting lattice vibrations or waves of magnetism within the specimen. Measurements of neutron inelastic scattering, help to inform fundamental ideas about dynamic processes in condensed states of matter: solids, liquids, interacting spins and lattice vibrations. Although neutrons are neutral particles they have a magnetic moment and a beam of neutrons can be polarized, setting all neutrons in a 'spin-up' state before entering the specimen. A neutron-polarizing analyzer can then detect how many neutrons have changed polarization to the 'spin-down' state because of interaction with magnetic structures or dynamics in the specimen. Polarized-neutron inelastic scattering provides the most detailed insights about magnetic excitations in condensed matter, enabling researchers to be certain that features in the measured spectrum are due either to magnetic or to crystal-lattice 'nuclear' vibrations. An excellent introduction to neutron inelastic scattering and applications to characterize magnetic spin excitations is found in reference 1.

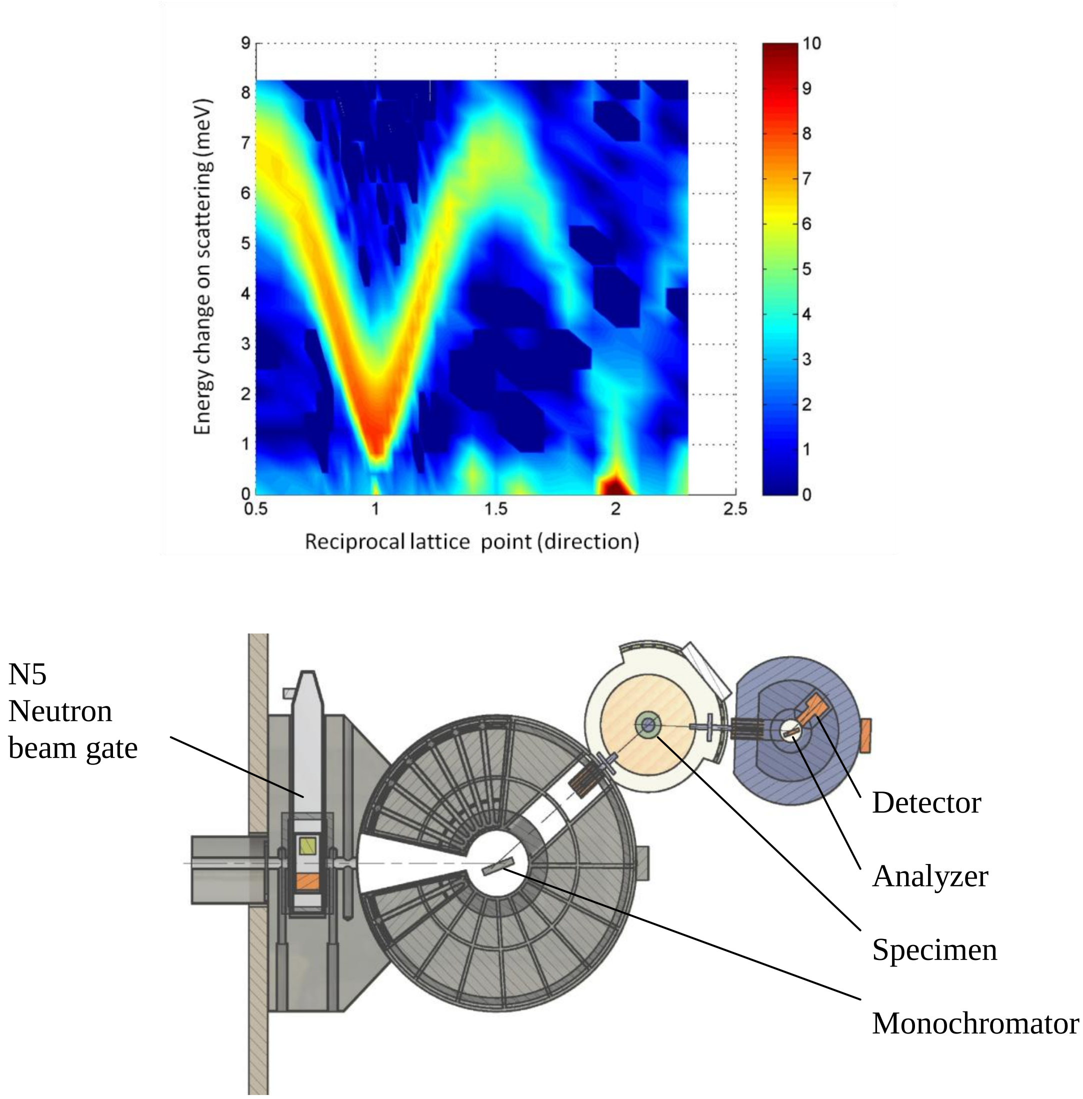

Figure 7 – A neutron inelastic scattering map (dispersion) from a specimen of manganese fluoride, shown above, was collected with the N5 triple-axis neutron spectrometer at the NRU reactor, shown below. Crystals diffract the neutron beam to select incident neutron energy (monochromator) and the scattered energy (analyzer) of neutrons that reach the detector.

5. NEUTRON BEAM METHODS CONTRIBUTE TO SCIENCE AND TECHNOLOGY

The knowledge of structures and dynamics of materials at the molecular and nanoscale can be applied to any scientific discipline that involves materials: physics, chemistry, materials engineering, life science, or earth science. The knowledge arising from neutron beam measurements has been applied to many technologies important for daily life, and linked to several industry sectors: nuclear energy, oil & gas, aerospace, automotive, materials production and other manufacturing. Neutron scattering measurements provide insights into the condition of materials during exploration of fundamental properties, through development of new technologies to full scale material processing, to manufacturing, service performance and ultimate failure – spanning the full range of 'technology readiness levels' and beyond. The following examples are drawn from the Canadian Neutron Beam Centre (CNBC) at the NRU reactor at Chalk River Laboratories, and are explained more fully in an Annual Report to the Canadian scattering community [2].

5.1 Basic Research

Research at the leading edges of scientific knowledge is the foundation for game-changing technologies of the future, and the basis to revolutionize ideas about the nature of our world. Past examples of scientific breakthroughs of this calibre include the theories of relativity, and quantum mechanics, and the realizations of nuclear energy, neutron-scattering, lasers or transitors from these new ideas. Researchers leading in these breakthroughs were recognized with Nobel Prizes. Today, an important scientific frontier is attempting to understand the phenomenon of high-temperature superconductivity and related quantum materials. The scientific importance of this research domain is demonstrated through publication in the most highly cited scientific journals, and through awards bestowed by scientific societies. Examples of high-impact journals that recently published research enabled by neutron scattering at the CNBC include Nature Communications [3-4], Physical Review Letters [5-10], and Nature Materials [11]. CNBC collaborators Walter Hardy, Doug Bonn, and Ruixing Liang from the University of British Columbia were awarded the 2005 Brockhouse Canada Prize for Interdisciplinary Research in Science and Engineering. Bruce Gaulin (McMaster University) and Bill Buyers (CNBC), much of whose research has been enabled through the CNBC's neutron beam facilities and expertise, were both inducted as Fellows of the Neutron Scattering Society of America in 2014 for seminal and sustained contributions to fundamental research in solid-state physics, and leadership in the field of neutron-scattering in North America.

5.2 Application-driven research

On the next level forward, many scientists study materials because they are candidates for overcoming barriers to new technologies. For example, an environmentally-friendly alternative to fossil fuels may be hydrogen, because it only produces water and energy when it is combined with oxygen. One hurdle to cross on the way to a future 'hydrogen economy', where vehicles are powered by hydrogen, is to better store and release hydrogen safely, efficiently and cost-effectively. Pressurized storage tanks might be an option in the short-term, but the targets for capacity and efficiency set by the US Department of Energy will require the development of hydrogen-storage materials that concentrate hydrogen in the solid state, such as metal hydrides or more exotic metal-oxide framework materials. Neutron scattering methods are especially effective for characterizing candidate hydrogen-storage materials because neutrons are very sensitive to hydrogen within metals.

Magnesium has a very high storage capacity for hydrogen (7.6 wt.%), but it's practical application is limited by its slow response in accepting and releasing the hydrogen. The slow response is due in part to a build-up of magnesium hydride at the surface, which blocks further movement of the hydrogen in and out of the magnesium film. Recently, Prof. D. Mitlin (U of

Alberta) achieved much higher rates of hydrogen absorption and desorption in magnesium when a combination of other metals was added (chromium and vanadium). He needed neutron scattering to understand the cause of this improved performance to guide further development and accessed the CNBC to undertake neutron reflectometry measurements while the storage material was exposed to hydrogen and subjected to relevant temperatures. The measurements proved that the addition of chromium and vanadium was impeding the formation of the blocking layer of magnesium hydride, therefore enabling faster movement of hydrogen through the material.

The elucidation of the underlying mechanism led to an examination of the effect of adding other metals like chromium and iron together to the magnesium. This alloy turned out to be another promising hydrogen storage system, in which the blocking layer is prevented in a manner similar to the magnesium-chromium vanadium system. [2, 12]

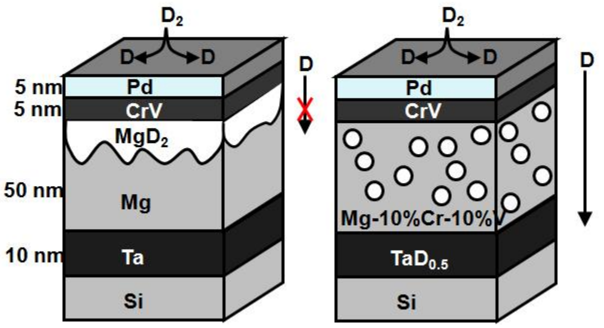

Figure 8 - Illustration of hydride formation (in the form of deuterium, D) in thin films of magnesium in which a blocking layer forms (left), and of magnesium-chromium-vanadium in which the hydrogen moves more freely (right).

A second example of application-driven science is in the domain of health-related molecular biophysics. The human body is a complex system, with thousands of molecules in every cell performing different functions. There is much to be learned yet in how these molecules provide their functions, because they reside in or interact with cell membranes, an environment which is problematic to study with many common scientific techniques. Neutron beams are used to study these molecules, because they are effective yet gentle probes of delicate samples that require carefully controlled environments. The ability of neutrons to penetrate inside equipment to hold membranes in biologically relevant conditions of temperature, pH and humidity, to probe these soft materials with absolutely no destructive effect, and, by isotopic substitution of hydrogen with deuterium enhance the contrast and visibility of selected portions of the molecules of interest is a powerful combination to reveal new knowledge about processes in health-related sciences.

The molecule known as Vitamin E is the only essential nutrient for which no one knows how it delivers a benefit. A scientific understanding of the function of Vitamin E could be applied to optimize vitamin supplements. However, Vitamin E is difficult to study in clinical trials because the effects of vitamin E only become apparent over long time scales. Instead, using neutrons at the CNBC, a research team from Brock University has been able to pin-point the location of vitamin E's anti-oxidant activity at the interface of a model membrane with its aqueous environment. They have been able to show that a significant body of research on vitamin E, that is, its oxidation kinetics and its products, must revisited, taking into consideration the physical properties of the model membrane, and are now suggesting that vitamin E supplements may be ineffective, in fact. [2] The same research team has also applied neutron scattering methods at the CNBC to understand an anti-microbial agent, known as "chlorhexidine," which is commonly used in personal hygiene products, such as soaps, contact lens solutions, and mouthwashes. Chlorhexidine disrupts bacterial membranes to kill the bacteria. The further insights from neutron scattering measurements about the interaction of chlorhexidine with cell membranes may open a pathway towards a patentable, membrane-based drug delivery system. [2]

5.3 Technology development

Engineers perform research to solve specific industrial challenges along the way to improving technologies, from developing new alloys with more desirable properties to improving manufacturing processes. Such research is often done either directly for industry, or with university researchers who are collaborating with industry partners.

Pipeline owners need to prevent failures by using the best scientific methods available to interpret inspection data and inform decisions about, for example, whether to replace a small section of pipeline, which may cost over a hundred thousand dollars. To help solve challenging problems like this, the global pipeline industry pools resources through the Pipeline Research Council International.

Researchers from Queen's University are working with GdF Suez to help interpret pipeline inspection data from a technique called Magnetic flux leakage (MFL). Their research seeks to develop a library that maps MFL data to specific kinds of defects and conditions of stress around the defect—factors which influence the likelihood of failure. MFL is sensitive to the loss of metal from corrosion or mechanical damage, which could be caused by a backhoe digging in the wrong place, for example. Thus, GdF

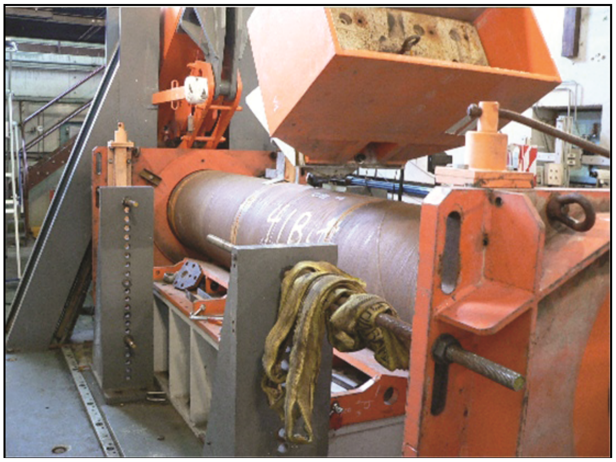

Figure 9 - GdF Suez lab simulates dents produced by a backhoe. Stress data obtained by neutron diffraction, will be useful to the industry in making hundred thousand-dollar decisions about how to manage pipelines that have sustained mechanical damage, for example, as a result of a backhoe digging in the wrong place.

Suez produced dents and gouges in full-sized, pressurised sections of pipe, mimicking the damage caused by a backhoe.

Prof. Clapham's research group mapped the stress around these gouges with neutron diffraction at the CNBC, and is comparing those actual, measured stresses to computer simulations and the (more indirect) experimental data provided through the MFL signal. The group aims to find correlations that can be used to determine if an MFL inspection signal in the field was produced by mechanical damage, and to estimate the level of risk represented by the damage. That data will serve industry as scientific input into decision-making about how to manage affected pipelines [2].

An example of improving manufacturing practices is a collaboration between Nemak (a Canadian automobile engine manufacturer), Ryerson University, and the CNBC, each of whom contributed their own tools and expertise in metallurgy, mechanical testing and computer modelling. Nemak's objective was to find the best way to make V-6 aluminum engine blocks. These engines have extremely low tolerance for distortion in the shape of the cylinder holes in the block. Stress relief methods are used after casting the block to increase dimensional stability, and yet each manufacturing step comes with its own costs and impacts on the materials properties. To improve the cost-effectiveness of manufacturing, the collaborative team needed to better understand the factors contributing to dimensional instability.

Figure 10 - Nemak prototype engine block installed on the L3 neutron stress scanner at the NRU reactor.

The CNBC applied neutron beams in several studies to map the stress distribution and microstructure in new aluminum alloys as well as engine blocks following the application of stress-relief such as a heat treatment. The CNBC also developed and implemented some new experimental technologies to observe microstructural evolution during solidification of the alloys as would occur during casting of an engine block. The new knowledge obtained by neutron diffraction may be suggesting a way to simplify the current heat treatment practice, without compromising reliability of the final product. Practical validation is needed; however, if proven, a simplification in manufacturing process could reduce production time, reduce energy usage, and save millions per year on the manufacturing processes [1].

5.4 Applied Research 'in the field'

Industry sometimes needs timely access to neutron beams to solve immediate problems and determine how to manage on-going issues. A primary example was a highly impactful line of research on pipe cracking over a 15 year period that began with an urgent failure analysis and grew to qualify better maintenance and prevention techniques.

In January 1997, the Pt. Lepreau Generating Station (PLGS) was shut down for repair of a heavy-water leak from a through-wall crack in a feeder outlet bend. A second such incident occurred in March 2001. These outages together cost about $10M in repairs, inspections, and related work, plus about $50M to replace the lost electricity. NB Power and Atomic Energy of Canada Ltd. (AECL) carried out urgent failure analyses, which included non-destructive stress measurement by neutron diffraction at the CNBC. In both cases, the residual stress from the manufacture of the bend was found to be nearly at the point of yielding. With a clear understanding of the cause of the failure, of which the neutron-beam stress-scans were a part, NB Power was able to assure the regulator in both instances that the PLGS could be restarted safely, thus avoiding further unplanned down time costs.

The industry needed to better understand the factors driving the degradation, which bends were most at risk, and how to manage the risk of cracking. The industry collectively funded, among other activities, significant efforts to measure the distribution and magnitude of residual stresses at feeder pipe bends using the CNBC frequently from 2001 to 2008, and most recently in 2011. Residual stress measurements by neutron diffraction constituted a valuable input into this research over this period that together had the following cumulative impacts [13]:

- increased assurance for nuclear regulators to relicense CANDU reactors
- timely assurance for continued construction of CANDU reactors at Qinshan, China,
- assistance in multi-million-dollar decisions about strategies to manage the cracking, avoiding tens of million-dollar costs due to unplanned down time,
- saving significant outage time and inspection resources during planned maintenance outages,
- enhanced safety requirements in regulatory documents for new reactors,
- high confidence that feeder cracking of the types seen at PLGS and Gentilly-2 will not be life-limiting factors for existing CANDU reactors once they are refurbished, and
- qualification of an innovative welding method that is now entering the marketplace.

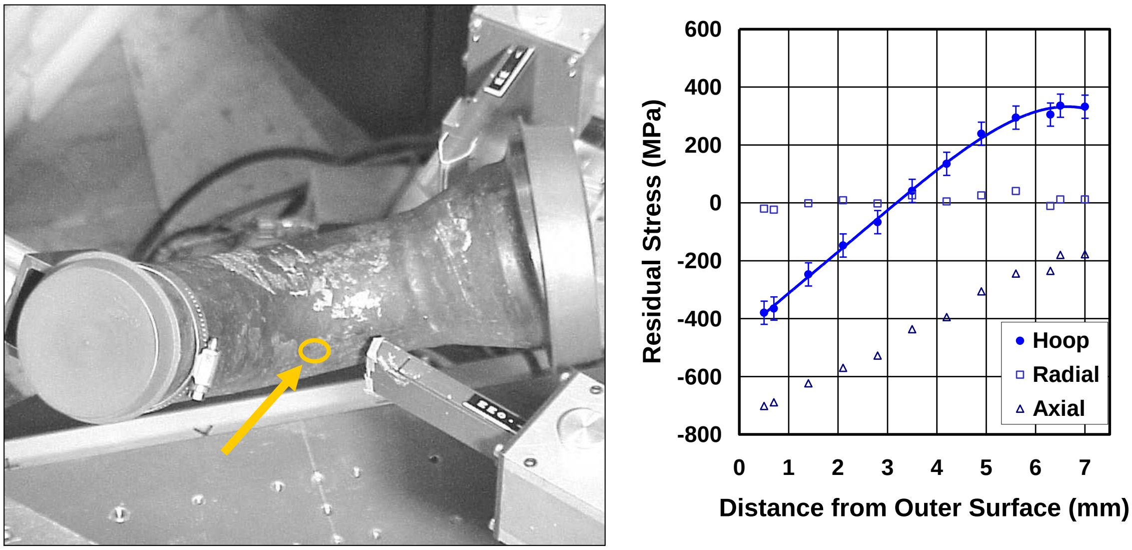

Figure 11 - Crossed neutron beams pinpoint locations inside the wall of a bent steel feeder, to scan residual stress versus depth below the outer surface, non-destructively. The measurements reveal increasing tensile stress towards the inner surface of the pipe, which could accelerate the growth of through-wall axial cracks.

6. ENABLING FRONTIER SCIENCE AND TECHNOLOGY

For industrial and government researchers, the ability to apply neutron beam methods to characterize hard materials, such as metals, alloys and composites will continue to be valuable in the foreseeable future, as reliability of hard-material components underlies safe, economic operations of our infrastructure, including power plants, pipelines, bridges, cars, airplanes, ships, and railroads. Industries with low tolerance for failure need to know, with certainty, the properties of the materials they use in critical components. Neutrons beams are unrivalled in their ability to directly and non-destructively determine stress, texture, and other properties deep inside metallic components, and the CNBC has led the way in this area. More examples of current impacts arising from industrial projects at the CNBC are found in its recent activity report. [2]

On the other hand, strong growth in the interdisciplinary areas of biochemistry and biophysics is driving the evolution of tools from physics and chemistry to understand the soft materials that appear in life sciences, polymers and the emerging nanotechnologies that promise major impacts in health, environment and energy sectors. Neutron beam facilities outside of Canada have been advancing their capabilities in recent decades to enable frontier contributions to science and technology of soft materials, including cold-neutron sources in their research reactors and building neutron-beam instruments that are optimized to reveal nanometre-scaled structures and lower-energy excitations. Lacking a cold neutron source, the NRU reactor can only support a limited subset of soft materials research in niche areas where contributions are competitive with those of the twenty or so other neutron beam facilities around the world. To reach a world-class level of enabling science and technology of soft materials, contributing across the full range of technology readiness in Canada, would require an investment to upgrade the NRU reactor substantially or to replace it with a modern neutron facility featuring a compact, high-flux core, a cold source, state-of-the-art beam optics and expanded instrument suite fed by cold-neutron guides. Examples of recent national investments of this type can be found in Germany (FRM-II, Munich, opened in 2002), Australia (OPAL, opened in 2007)), and the United States of America (NIST Center for Neutron Research, upgrades currently underway).

7. CONCLUSION

This paper has summarized how a research reactor generates neutron beams, and how neutron beams probe materials of all kinds, revealing knowledge that cannot be obtained easily by other scientific methods. Even with the limitations of the NRU reactor, a medium-flux source of thermal neutrons alone, Canadians have access there to facilities and expertise that support leading-edge science and technology over the full range of technology readiness levels and beyond – supporting innovation with nuclear methods for broad social and economic impacts, both in the short term and in years to come.

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