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THE NRU REACTOR: PAST,PRESENT AND FUTURE

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THE NRU REACTOR: PAST, PRESENT & FUTURE

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Abstract

The NRU (National Research Universal) Reactor has operated at Atomic Energy of Canada's (AECL's) Chalk River Laboratories since 1957. NRU is a 135 MWt multipurpose heavy water-cooled and moderated research reactor that provides a neutron source for a wide range of applications.

This paper reviews NRU reactor's current capabilities and highlights of past experience, from the perspectives of materials research with neutron beams, isotope production and irradiation of nuclear fuels, materials and components.

One of NRU's primary mandates in recent times has been the production of Molybenum-99, which is needed for the majority of imaging procedures in nuclear medicine worldwide. Per previously announced Government of Canada policy, it is expected that NRU will cease supplying Molybdenum-99 beyond 2016, constituting a major change in the mandate and operation of the reactor.

The operation of NRU beyond 2016 is being considered to support industry-led, cost-shared nuclear innovation in Canada. This marks a new era for NRU, where business-driven needs and partnerships shape the way this powerful and versatile resource for science and technology delivers benefits to Canada and the world.

Introduction

The National Research Universal (NRU) Reactor is a cornerstone of AECL's Chalk River Laboratories (CRL), located 190 kilometres northwest of Ottawa. On reaching first criticality on 1957 November 3, the NRU reactor was a significant achievement that established CRL as a world leader in nuclear science and technology. Some 57 years later, NRU remains one of the largest and most versatile research reactors in the world, continuing to operate safely and reliably for the purpose of (i) medical and industrial radioisotope production, (ii) materials research using neutron beams, and (iii) research and development of nuclear fuel and materials using in-core irradiation facilities.

AECL and NRU have been instrumental in the design of Canada's nuclear power reactor fleet, as well as its safe and efficient operation. As one of the world's most versatile research reactors, and a principal source of Canada's nuclear science innovation, NRU has produced the knowledge required to develop, maintain and evolve Canada's fleet of nuclear power stations. Although NRU does not produce electricity, it is Canada's only major fuel and materials test reactor, used to support and advance nuclear power reactor design and operation. Work performed in NRU is leading to advances in medical, industrial and scientific fields to the benefit of Canadians and the world. NRU is a key component of Canada's nuclear energy sector, as well as many other non-nuclear industries and businesses.

This paper reviews the NRU reactor's current capabilities and highlights of past experience, from the perspectives of materials research with neutron beams, isotope production and irradiation of nuclear fuels, materials and components. It also considers the future of NRU's mandate under the current AECL restructuring initiative led by the Government of Canada.

1. NRU Operations Summary

The NRU reactor is a thermal, heterogeneous, heavy-water cooled and moderated reactor. Originally a natural uranium reactor rated at 200 MWt (thermal power), it was converted to highly enriched uranium in 1964 and to low enriched uranium in 1993. It is presently licensed to 135 MWt. It was the first reactor in the world capable of refueling at full power operation. The reactor core is contained within a cylindrical aluminum vessel approximately 3.5 m in diameter and 3.7 m tall, consisting of 227 vertical lattice positions in a hexagonal array with a 19.7 cm lattice pitch (Figure 1). Approximately half of the lattice positions contain fuel rods and control rods, with the remainder available for isotope production, experimental loops for fuel and materials testing, and other experimental equipment.

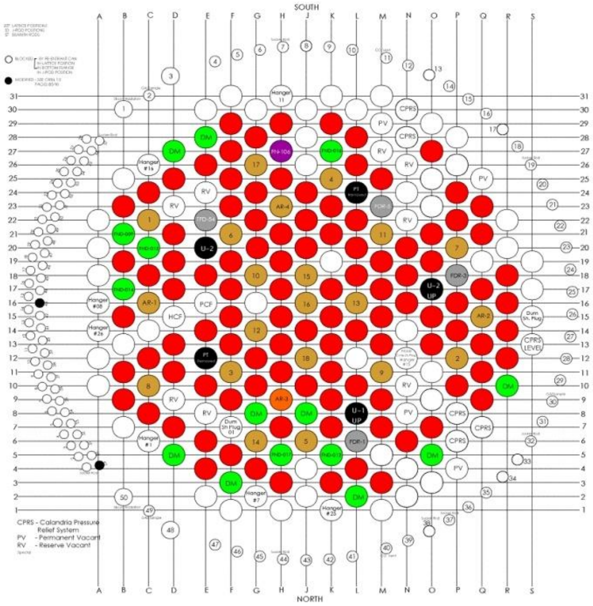

Figure 1 NRU Lattice Diagram [1] (sites are out of date; for reference to lattice structure only).

Prior to 2009, NRU consistently operated at a high annual capacity of 80%, with the exception of four major maintenance outages:

- 1972 June to 1974 August: The aluminum reactor vessel was replaced and design changes were implemented to eliminate leaks from the upper and lower vessel seals.
- 1985 April to November: A horizontal through-tube was removed from the core, necessitated by cracks that had developed in its welds.
- 1991 January to December: A leak from a stress-corrosion crack in a 304 stainless steel pipe connected to the bottom header was repaired.
- 2009 May to 2010 August: The reactor was shutdown to repair a leak in the aluminum reactor vessel side wall, to complete a comprehensive inspection of the condition and thickness of the vessel wall and to repair areas where significant wall thinning was detected.

In recent years (2011-2014), annual month-long outages have been implemented to undertake inspections and maintenance to ensure continued safe and reliable operation. During this period, the average annual capacity factor has been 66% (i.e. approximately 240 days per year).

The NRU reactor is home to the Canadian Neutron Beam Centre (CNBC), a user facility for world-class materials research using neutron beams. The CNBC is the only Canadian facility of its kind and only one of twenty such facilities worldwide (Section 3). NRU is also one of the world's leading producers of medical radioisotopes used to diagnose and treat cancer and other life-threatening diseases affecting millions of people worldwide each year (Section 4).

The NRU reactor contains two experimental test loops (the U1 and U2 loops) that operate at temperature and pressure conditions typical of commercial power reactors [1]. These loops provide a means for irradiating fuel and materials to support nuclear power generation (Sections 5 and 6). Presently out of service, work continues to upgrade both experimental loops to current codes and standards in order to resume irradiation tests of fuel and materials. Studying the effects of radiation on materials is also possible in various facilities in the NRU core (Section 5), including Fast Neutron (FN) rods, Hydraulic Capsule Facility (HCF), Multi-Capsule Rods (MCR) and Cobalt Carrier Rods (CCR).

Recently, AECL has implemented the Isotope Supply Reliability Project, Integrated Implementation Plan, and Equipment Reliability Program. With seven reactor safety upgrades having been declared in-service in 2010 May, these three programs focus on improving NRU operating reliability to support the isotope supply chain, while maintaining safety as the highest priority. These improvements will ensure continued safe and reliable operation of NRU to maintain the supply of Mo-99 through 2016 and to continue producing other medical and industrial isotopes and support experimental research programs in the years to follow.

2. NRU Reactor Physics

To maintain NRU's safe and reliable operation, reactor physics support is required to accurately model the reactor core and provide detailed neutronic calculations, such as neutron flux and power distributions, burnup of driver fuel rods, reactivity changes during on-line refueling, and reactivity worth of control rods. During the 1970s, physics calculations were performed using a 2-dimensional code. In the early 1980s, a more detailed calculation model was developed [2] and a three-dimensional neutron diffusion code in two energy groups was developed. Further modification and improvement ultimately produced the present TRIAD code, which simulates the neutronics of the NRU core.

The NRU reactor core consists of many different types of rods, such as driver fuel rods, Mo-99 production rods, absorber rods and control rods. The number of driver fuel rods in the core varies from 75 to 100, depending on the nature of experimental programs being undertaken and the demand for radioisotope production. In the TRIAD code, 301 reactor sites are modeled, and each of the hexagonal sites is modeled as six triangular prisms, with 18 axial segments of variable heights. There are a total of $6\times301\times18$ triangular prisms (or meshes) for the whole reactor. The detailed flux shapes and neutron spectra through each type of cell are determined using the WIMS-AECL neutron transport code [3]. The homogenized cell parameters, in two energy groups, are then calculated by flux- and volume-weighting the region's material properties. Examples of cell parameters are the diffusion coefficients and various absorption, removal and fission cross sections. After the cell parameters are calculated, the flux and power distributions for the cells in the NRU core can be determined using a modified neutron diffusion theory. During the 2000s, the TRIAD code was validated against power, flux and reactivity measurements [4].

The TRIAD code is also used to track the burnup of fuel rods and isotopic contents in rods for isotope production, as they move in and out of the reactor. Reactor snapshots are stored as core loadings, which contain the necessary data for all axial segments of each type of rod in the reactor. Fuel burnup is integrated from one snapshot to the next using a fixed power distribution. Both measured and simulated channel power distributions are used, together with the simulated axial power distributions (since there are no axial power distribution measurements). TRIAD fuel burnup calculations have been validated against fuel burnup measurements for isotopic ratios of uranium using thermal ionization mass spectrometry techniques [5].

In the past, older versions of WIMS, WIMS-AECL 2d, and associated ENDF/B-V data library were used for NRU physics modeling. At present, the latest version of WIMS-AECL 3.1.3.1, and ENDF/B-VI or -VII data libraries are used to generate cell parameters more accurately for new assemblies or loop fuel strings inserted in the core. The present version of TRIAD is equipped to predict flux and power distributions for future core changes, particularly as NRU's mandate continues to evolve.

In the longer term, apart from using neutron diffusion theory to model the NRU reactor, a more accurate Monte Carlo method using the MCNP code will be considered. Preliminary Monte Carlo calculations to track fuel burnup in NRU have been performed. However, the MCNP code using the Monte Carlo method requires long computing times (~ 10 hours) to perform a calculation, and is not considered to be a replacement of TRIAD's routine physics support for NRU operation.

3. Materials Research Using Neutron Beams

The NRU reactor is equipped with beam ports to allow neutrons produced in the reactor to be used outside the reactor as tools to probe materials. Neutron beams are versatile and irreplaceable tools that are used for discovery research and for research needed by both nuclear and non-nuclear industries. AECL's neutron beamlines are presently managed as an international user facility, via the Canadian Neutron Beam Centre (CNBC).

Thermal neutrons produced in NRU have wavelengths in the range of 0.5 – 5 Å, which is ideal for probing atomic arrangements in many materials, including stress in metals. Thermal neutrons having energies in the range 3 meV – 300 meV are well suited to measure the vibrational energies of atoms in solids. Neutrons have a magnetic moment and interact with the spatial variation of the magnetization in materials on an atomic scale, which is useful for studying magnetic structures and excitations. Neutrons interact with the nucleus of an atom, rather than with its electron distribution; the scattering length for neutrons is not a monatomic function of atomic number, as is the case for x-rays. Neutrons can thus detect light atoms in the presence of heavy atoms or distinguish between two similarly-heavy atoms, both of which are often challenging for x-rays. Notably, hydrogen and deuterium have a greatly different propensity to scatter neutrons, which is useful for studying biological samples and polymers by contrast matching; i.e., by substituting one for the other. Neutrons are non-destructive and highly penetrating; they can probe the interior of bulk materials while passing through other equipment on the beamline, which is extremely useful for measurements in complex conditions of temperature, pressure, magnetic fields, compression, tension, or other experimental parameters. Finally, neutrons are a weak probe of matter (i.e., the number of ways neutrons interact with materials is not large). Thus, the properties that can be measured with neutrons are often determined easily and unambiguously because there are limited factors that can contribute to the data and thereby complicate interpretation of results [6].

The NRU reactor enjoys a strong history in using neutron beams to study materials. Bertram Brockhouse shared the 1994 Nobel Prize in Physics for his pioneering work to develop neutron scattering techniques, starting at the NRX reactor in 1950 and subsequently at the NRU reactor (1957-1962). In the 1980s, AECL scientists developed a method to measure internal stresses, non-destructively, with neutron beams, and subsequently helped to develop the ISO standard for such measurements. This method has proven to be valuable to heavy industries where reliability of materials is important to safety and cost-effectiveness. Both the Stress Scanner and Brockhouse's Triple-Axis Spectrometer have been replicated at every major neutron beam facility around the world.

The nuclear industry has benefited from stress measurements using neutrons. For example, over the past 15 years, stress analysis of bends in carbon steel pipes, known as feeder tubes in CANDU reactors, has been a high-impact research program. The Point Lepreau reactor had an unplanned shutdown for two months in 1997 and a second unplanned shutdown 2001 due to heavy-water leaks in feeder tubes. The neutron diffraction component of the failure analyses provided clear evidence that residual stress played a significant role. These incidents led to follow-up R&D programs to manage feeder cracking and to assure safe, reliable and economic operation of the CANDU reactor fleet. As part of these programs, neutron diffraction has been used to examine stress in as-fabricated and ex-service feeders representing various manufacturing processes, wall thicknesses, types of bends, and welding methods. The impacts of these programs are reviewed from the perspective of neutron scattering in a second paper [7] and include increased assurance for relicensing and sales of CANDU reactors.

Today, CNBC operates six neutron beamlines at NRU for access by the research community. Each year, over 200 scientists, engineers, and students from universities, government labs, and industry participate in research depending on access to the beam lines. Over the past 3 years (2011-2013), CNBC research participants included more than 500 individuals from over 70 departments in 30 Canadian universities and from over 100 foreign institutions in 20 countries (Figure 2) [8]. The CNBC enables industrial research in sectors such as nuclear energy, aerospace, automotive, oil and gas, defence, and primary metal production.

While beamline users represent the spectrum of materials research, including engineering, physics, chemistry, and life sciences, the CNBC has developed special strengths and collaborative networks in selected areas, including thermo-mechanical deformation of materials; solidification and crystallographic phase transitions; residual stresses in engineering components; structures and dynamics in quantum materials; hydrogen storage materials; thin magnetic films and multilayers; membrane biophysics; and electrochemistry and corrosion at surfaces.

Looking to the future, there are prospects of increasing the capacity for experiments by the neutron beam user community. For example, increasing neutron flux at the beam holes could decrease the time required for each measurement by as much as 15-30%. Neutron beam research capability could also be increased by upgrading and adding beamlines. Industry clients and academics who conduct applied research would be better served if a prototype for a next-generation neutron stress scanner using a "white-beam" replaced CNBC's oldest beamline at the E-face. There is potential to expand the range of users in areas such as nanotechnologies, life sciences and health technologies, by building a new beamline that is optimized for research on soft materials (e.g., biological, medical, and polymeric materials) at the T-face of the reactor. Services to the nuclear sector and other industries could be enhanced by building a neutron imaging beamline at the N or Q faces. The capacity to image (neutron radiograph) irradiated nuclear fuel for research and quality assurance purposes could be valuable to the nuclear sector, just as other industries use neutron imaging for quality assurance; for example, the aerospace industry uses neutron radiography to ensure internal integrity of turbine blades.

Figure 2 Illustration of the distribution of the CNBC user community by Canadian university and foreign country.

4. Isotope Production

The NRU reactor is one of the world’s leading producers of medical radioisotopes used to diagnose and treat cancer and other life-threatening diseases affecting millions of people worldwide each year. Mo-99 has the highest demand, due to its short half-life and that of its desired daughter product, Tc-99m, used for medical diagnosis (imaging) of the heart, brain, thyroid, lungs, liver, kidneys, spleen and bone marrow. For many years, NRU produced over 60% of the world’s Mo-99, setting a record for 6-day production in 2007 May. With heavy reliance on NRU, a worldwide Mo-99 shortage occurred when NRU was shut down for ~ 15 months in 2009/10 for reactor vessel repair. As a result, other facilities increased production and alternative sources were investigated to reduce dependence on NRU. Although the Canadian government has recently announced that NRU will not produce Mo-99 after 2016, production of other radioisotopes for medical and industrial purposes will continue, including I-125 (prostate cancer therapy, radioimmunoassay and bone densitometry), high specific activity Cobalt-60 (cancer therapy), I-131 (thyroid diagnosis and therapy), and Ir-192 (industrial radiography and cancer therapy).

The use of radioisotopes for medical and industrial applications was just beginning when NRU commenced operation in 1957. NRU’s large physical size and high thermal flux proved to be ideal for the production of many radioisotopes; as a result, irradiations quickly began in various facilities following the startup of the reactor. The versatile Hydraulic Capsule Facility (HCF) and Multi-Capsule Rod (MCR) were used to develop many products. These two facilities facilitated production of multiple products in parallel. Other isotopes required the development of specialized rods and capsules to hold larger target volumes, provide extra cooling, or to maximize exposure to neutrons. Co-60 production began in the NRU control system, where cobalt was used for both neutron control and production of this important isotope. NRU’s high neutron flux allows Co-60 to be produced to very high specific activity, which is used exclusively for cancer radiation therapy. C-14 and I-131 production soon followed. In 1969, a new facility was added, allowing the irradiation of xenon gas for the production of I-125, which continues to this day. Production of Mo-99/Tc-99m began in 1970 in NRU (and NRX), and by the end of the decade, it became the dominant radioisotope produced, both within AECL and worldwide. The Mo-99/Tc-99m business continued to grow rapidly; by 1995, AECL was producing the majority of the world's growing demand.

From 1970 to 1999, many other isotopes such as Ir-192, Xe-133, Au-198, Po-210, Sm-153, Y-90, Ni-63 and Cl-36 were produced in NRU. Neutron transmutation doping of silicon crystals was also carried out. Production of some was discontinued as markets adjusted to competition from other reactors and products; C-14 and Po-210 are two notable examples. Because of the importance and short half-life of Mo-99, the operating schedule of the reactor is dictated to a large extent by Mo-99 demand patterns. Xe-133 is produced as a by-product of the Mo-99 process.

As mandated recently by the Government of Canada, AECL production of Mo-99 will cease at the end of the NRU's current operating license (2016). This will liberate considerable space in the central, high flux region of the core, and allow more freedom in the operating schedule of the reactor. NRU has tremendous potential to produce large quantities of radioisotopes, for medical and industrial use. There is current interest in increasing the production of Ir-192, Co-60, as well as other medical and industrial radioisotopes.

5. Nuclear Materials Testing

Since 1958, the NRU reactor has been used to obtain data to understand and quantify the effects of irradiation on the dimensions and properties of reactor components throughout their in-service lives and to develop improved designs and components.

The NRU reactor irradiation facilities have several important features, setting it apart from other materials irradiation facilities: (1) the large-volume core – large numbers of material test specimens can be irradiated in multiple facilities with a wide range of temperature and neutron flux spectra [9] (Table 1); and (2) the U1 and U2 high-pressure/high-temperature experimental loops, providing an environment where test materials are subjected to simulated power reactor conditions.

Table 1 NRU facility materials testing parameters (compared to CANDU power reactor).

	Total Flux ($n/cm^2/s$)	Flux E>1MeV ($n/cm^2/s$)	Flux E<0.625 eV ($n/cm^2/s$)	Damage for Zr-2.5Nb (dpa/yr)*	Temperature (^oC)
NRU Mk 4 FN rod	3.18E+14	2.14E+13	2.07E+14	1.05	250-360
NRU Mk 7 FN rod	5.20E+14	7.06E+13	2.06E+14	3.41	55
NRU MTB	3.40E+14	5.53E+13	1.22E+14	2.69	250-310
NRU HCF	2.17E+14	6.05E+11	2.02E+14	0.04	55
CANDU6 pressure tube (mid-burnup)	3.44E+14	2.58E+13	1.88E+13	1.34	265-310

* calculations performed using the SPECTER code [10]

In addition to the irradiation of experimental and prototype fuels (Section 6), material testing is also performed in the U1 and U2 loops using material test bundles (MTBs). The loops typically operate at high pressure (up to 10.9 MPa) and high temperature (up to 308°C). The loops can operate outside normal chemistry conditions to accommodate chemistry, corrosion and materials testing.

The MTB design is based on the CANDU 37-element bundle geometry, with the centre element and inner ring of elements removed. Materials specimen holders can accommodate large numbers of various specimens, such as compact tension, cantilever beam and tensile specimens, as well as smaller specimens for stress relaxation, irradiation growth, or corrosion tests.

The fast neutron (FN) rod assembly is a special NRU fuel rod with a cylindrical central cavity in which ‘dry’ instrumented test rigs (or inserts) containing material test specimens are suspended and irradiated in a gas environment (typically, helium). Two FN rod types are available for materials irradiations: the Mk-4 natural uranium and the Mk-7 enriched uranium rods. The Mk-4 central cavity is 72 mm in diameter and 1.5 m long, while the Mk-7 is 73 mm in diameter and 0.8 m long. Annular fuel bundles surround the cavity. Dry Mk-4 FN rod facilities (helium environment) utilize electric heaters to control temperature. Specimens are placed in baskets and can be irradiated within the fuelled area of the FN rod, as well the region above the fuelled area (still within the reactor core) at a lower fast flux (an order of magnitude less than in the fuelled area). These facilities facilitate the irradiation of large numbers of specimens over a wide range of temperatures and flux. The FN Insert Cooling Circuit (a low-pressure low-temperature water system) has been used for wet inserts, where specimens are cooled by low-pressure light water at about 55^{o}C. The inserts are suspended in flowing coolant inside a tube installed in the cavity of the FN rod.

Some of the NRU reactor’s in-core positions are available for materials irradiation research including multi-capsule rods (MCR), cobalt carrier rods (CCR) and the hydraulic capsule facility (HCF). The HCF, CCR and MCR are ideal for studying in-core effects of thermal neutron absorption, small amounts of displacement damage and low temperature (55^{o}C). The in-reactor portion of the HCF accommodates up to 20 aluminum capsules, each measuring about 60 mm in length with an overall diameter of about 20 mm. The CCR and MCR have larger irradiation cavities than the HCF, enabling them to irradiate greater amounts of materials.

The future is envisioned to involve advanced materials development to facilitate advances in science and technology that will benefit Canada and the world. Such materials will require irradiation testing under various conditions.

For support of the Canadian Super Critical Water Reactor (SCWR) concept, programs in the NRU reactor are envisioned to study the behaviour of candidate SCWR fuel and fuel channel materials [11, 12].

6. Fuel Irradiation Testing

AECL develops nuclear technologies that support generation of clean, safe energy. This includes the development of advanced nuclear fuel technologies to ensure sustainable energy sources for Canadians and the world. The Fuel Development Branch leads AECL’s development of advanced nuclear fuels, including irradiation testing in the NRU reactor. This is primarily performed in the U1 and U2 loop test facilities that simulate conditions of commercial power reactors [1].

The U1 and U2 loops commenced operation in the early 1960s and have been used over the past ~ 50 years for the development of various fuel cycles and the demonstration of various fuel designs, including the 7, 19, 28 and 37-element fuel bundles that have been used in commercial CANDU power reactors. The 43-element CANFLEX fuel bundle, being designed for advanced fuel cycles characterized by extended burnups, was also developed in the NRU loop facilities [13].

Table 2 Summary of key irradiation tests conducted in the NRU loops over the past 20 years.

Fuel Experiment	Description	Status
BDL-419	$(U, Pu)O_2$ MOX (high burnup)	on-going
BDL-422	$(Th, Pu)O_2$ (high burnup)	complete
BDL-436	SEU/BNA (Low-Void Reactivity Fuel; LVRF)	complete
BDL-437	CANFLEX SEU (high power/burnup envelope)	complete
BDL-438	SEU/BNA (Low-Void Reactivity Fuel; LVRF)	complete
BDL-439	CANFLEX SEU/BNA (high-burnup LVRF)	complete
BDL-440	CANFLEX NU simulation (power ramp)	complete
BDL-441	$(U, Pu)O_2$ MOX (PARALLEX weapons grade Pu)	complete
BDL-443	high-burnup SEU	on-going
BDL-445	SEU power ramps	on-going
BDL-446	$(U, Pu)O_2$ MOX (MOX pellet fabrication/Pu homogeneity)	complete
BDL-447	$(U, Pu)O_2$ MOX (PARALLEX weapons grade Pu)	on-going
DME-210	high-burnup UO_2 power ramp failure	complete
DME-213	advanced cladding & appendage attachment	on-going
DME-214	UO_2 + BNA test	complete
DME-215	graphite coating Zr-4 fuel sheath SCC mitigation	on-going
DME-217	high burnup SEU pellet geometry test	on-going
DME-220	DUPIC (direct use of spent PWR fuel in CANDU)	complete
DME-221	high burnup ThO_2 & $(Th, U)O_2$	on-going
DME-222	demonstration of 42-element demountable bundle technology	on-going
DME-224	ZrO_2-BNA pellet technology	on-going

Various fuel cycles have been developed and demonstrated in the NRU loops, including slightly-enriched UO_2 (SEU; having higher burnups that natural UO_2), thoria and MOX (mixed-oxide; Pu-bearing) [13-18]. These fuel cycles provide reliable and safe options for nuclear energy generation that exploit the world's natural resources of uranium and thorium, as well as using plutonium generated from the irradiation of uranium. AECL is continuing to develop thoria-based fuel technology under its Thoria Roadmap Project, by identifying and addressing gaps in various thoria science and technology areas, and supports initiatives for using Pu stockpiles for nuclear energy generation. This includes irradiation testing of thoria and MOX fuels in the NRU loops. AECL has also undertaken the development of burnable neutron absorber (BNA) technology, to support the optimization of fuel designs for coolant void reactivity [13, 14]. Table 2 summarizes key fuel development tests conducted in the NRU loop facilities since 1994.

A major component of NRU's past experimental fuel irradiation program included a series of experiments designed to explore fuel and fission product behaviour during simulated loss-of-coolant accident (LOCA) events. The Blowdown Test Facility (BTF) was designed to incorporate all major LOCA phenomena in a single test to provide data for the development and validation of models and computer codes [1]. BTF was a unique instrumented facility operated in NRU as part of the U1 loop for the irradiation of CANDU-size fuel assemblies.

The NRU reactor has also been a key tool in the development of research reactor fuel. Initially, NRU was fuelled with U-Al alloys containing highly-enriched uranium (HEU). AECL began developing low-enriched uranium (LEU) fuel in the early 1980s [19], resulting in aluminum-clad fuel elements containing uranium-silicide particles dispersed in a continuous aluminum matrix being developed for use in NRU. Various LEU fuel designs were tested in NRU, including Al-U, Al-USiAl, and Al-U_3Si [20]. By 1986, demonstration irradiations of prototype NRU fuel rods containing U_3Si dispersion fuel had been successfully completed, resulting in U_3Si being selected as the reference driver fuel for NRU.

During 1987-90, a Nuclear Fuel Fabrication Facility was built and licensed at Chalk River Laboratories (CRL) to fabricate Al-U_3Si dispersion fuel for NRU. In 1993, NRU was fully converted from HEU to LEU. Al-U_3Si_2 dispersion fuel was developed at CRL during 1987-1993 to compliment the Al-U_3Si product line. In 1995, Al-U_3Si_2 was successfully irradiated in NRU. Since 2000, the NRU reactor has been used to develop U-Mo based LEU fuel, which will meet the requirements for higher U loadings and spent fuel reprocessing. The immediate goal is to develop U-Mo fuel to facilitate its direct substitution for U_3Si or U_3Si_2 fuel in NRU and its future replacement reactor [21-23].

7. NRU's Business Model

During the last 57 years, a vibrant Canadian nuclear industry has grown up around the wealth of knowledge generated by NRU. The Government of Canada's investment in NRU has paid huge social, environmental and financial dividends in healthcare, reduced CO_2 emissions and jobs created in Canada's nuclear sector. As with any industry that is founded with government investment, there comes a time to ask more of the private sector once the industry is established. The Government of Canada has clearly signaled that it is time for industry to acknowledge the fundamental importance of the NRU reactor to their continued success.

With this in view, AECL is currently undergoing a restructuring initiative led by the Government of Canada that will result in its Nuclear Laboratories being operated under a government-owned, contractor operator (GoCo) model. This restructuring initiative coincides with Mo-99 production ceasing in 2016 (at the end of NRU's current operating license). Post-2016 NRU operation is envisioned to be part of an industry-driven nuclear innovation agenda that will result in the Government of Canada partnering with investors to operate the NRU reactor. NRU is a large-scale Canadian investment in nuclear science and technology that will require a robust partnership with other organizations to continue its operation. AECL is exploring commercial opportunities for using NRU's facilities, including its numerous core lattice sites (some being made available by the end of Mo-99 production), pressurized water loops, neutron beam facilities and underwater storage facilities for irradiated nuclear material. Business opportunities, existing and new, include:

- production and sale of isotopes (other than Mo-99)
- commercial irradiation services for fuels and materials
- neutron beam analysis services for both nuclear and non-nuclear industry sectors
- storage and handling of irradiated nuclear materials
- training personnel to support education/learning institutions and the nuclear industry
- development of a joint international learning centre to conduct collaborative nuclear R&D

Thus, significant potential exists for NRU's operation to grow under the current restructuring initiative, providing a wide range of benefits to Canada and the world.

8. Summary & Conclusions

The NRU reactor has enjoyed 57 years of successful operation conducting fuel, materials and neutron beam research, while producing radioisotopes for medical and industrial applications. NRU is a principal source of Canadian nuclear science innovation, producing technology to develop and maintain a strong nuclear energy sector, while also supporting non-nuclear industries and businesses.

The current AECL restructuring initiative led by the Government of Canada is envisioned to provide an opportunity for NRU to operate beyond 2016 under an industry-driven, cost-shared business model.

This marks a new era for NRU, where business needs and partnerships shape the way this powerful and versatile resource for science and technology delivers benefits to Canada and the world.

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