Mo-99 Production – Neutron Capture-Based Production via Power Reactor and Potential Market Penetration

Andrew Lukomski and Jamie Leebody
Laurentis Energy Partners, 889 Brock Road, L1W 3J2, Pickering, Canada

Michael Flagg
BWXT Medical, 447 March Road, K2K 1X8, Kanata, Canada

ABSTRACT

Historically, the production of molybdenum-99 (Mo-99) via neutron capture has been limited, stemming from lower reaction efficiencies and extraction capacities based on low specific activity. A breakthrough in technetium generator technology, developed by BWX Technologies Ltd. (BWXT), based in the United States, has regained attention as a viable method for high-volume uranium-based Mo-99 production. Through a teaming arrangement with Laurentis Energy Partners Inc, based in Pickering, Ontario, a commercial CANDU (Canadian Atomic Natural Deuterium Uranium) nuclear reactor near Toronto, Canada, will generate Mo-99 via neutron capture with subsequent processing at a local BWXT facility – both technologies being a first of their kind in the industry. Given the scale of power reactors, additional operating and safety considerations beyond those incorporated in research reactors will be required for the production and handling of Mo-99. This paper discusses non-proprietary aspects of neutron capture-based Mo-99 production through a commercial reactor in support of potential market expansion in other CANDU-type heavy water reactors or other future reactor designs.

Introduction

"The most dangerous phrase in the language is "we've always done it this way" – Grace Hopper

The production of molybdenum-99 (Mo-99) is at a crossroads. On one path, lies the traditional, ageing, research reactors nearing their end of life and on the other, a new generation of production technologies on the verge of transforming the medical isotope industry. Within this new landscape, a new concept for Mo-99 production has been fostered, stemming from innovations across several industry areas and a collective desire to resurrect Canada's position as a global supplier of Mo-99.

BWX Technologies Ltd. (BWXT), based in Lynchburg, Virginia is the developer of a new technology for Mo-99 production based on neutron-capture of natural molybdenum. Using a proprietary process, technetium -99m (Tc-99m) generators will extract product from low-specific activity Mo-99. In a first of its kind industry system, the irradiated molybdenum will be provided through a teaming arrangement with Laurentis Energy Partners Inc. (Laurentis), based outside of Toronto, Ontario, from a commercial power nuclear reactor. Operated by Ontario Power Generation Inc. (OPG), a world leader in nuclear and clean energy production, a CANDU (Canadian Deuterium Uranium) reactor at the Darlington Nuclear Generating Station (DNGS), located approximately 80km east of Toronto will produce the Mo-99. The Target Delivery System (TDS) will enable targets filled with natural molybdenum to be transported into the reactor for an irradiation cycle after which they will be shipped to the local BWXT processing facility outside of Ottawa prior to distribution to customers world-wide.

Production of Mo-99 through a commercial power reactor introduces additional considerations including reactor accident analyses, operational processes to integrate isotope production with normal operational cycles and management of large volumes of irradiated isotopes from the facility. Safety of the nuclear power plant and appropriate priorities must be established to ensure the future stability of power and Mo-99 supply.

Brief Background on CANDU Reactors

The CANDU commercial reactor concept evolved in the early to mid-1960's amidst an international acceleration of the adoption of nuclear power for safe, civilian purposes. At this time, the National Research Universal (NRU) research reactor, the backbone of Canadian medical isotope production for over 50 years, was already in service at Atomic Energy of Canada Limited's (AECL) Chalk River research facility. Using heavy water as both a coolant and moderator coupled with natural uranium as a fuel, the Pressurized Heavy Water Reactor (PHWR) reactor concept was cemented in the early 1960s with construction of the Pickering Nuclear Generating Station in the late 1960-70s. This was followed by larger facilities such as the Bruce Nuclear Generating Station (BNGS) in the late 1970s, mid-1980s and finally the DNGS in the late 1980s, early 90s. Several variations of the CANDU-style reactor were developed, with a total of 18 CANDU reactors operating in Ontario and 28 CANDU or derivative reactors on the global stage in countries such as Argentina, Romania, China and South Korea today.

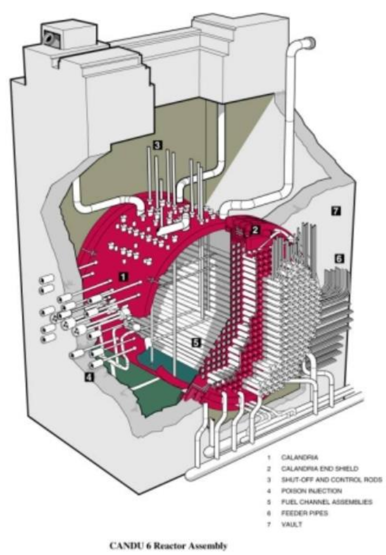

Figure 1. CANDU Core Schematic (Source: Canadian Nuclear FAQ)

A key distinguishing feature of the CANDU reactor is its cylindrical core, referred to as a the calandria, which is rotated axially on its side and has individual fuel channels through which coolant passes. The moderator flows throughout the calandria around the individual channels. Reactivity mechanisms along with control/shutdown mechanisms enter from the top of the reactor.

Certain CANDU facilities were designed with a containment structure within which the majority of all nuclear related systems were enclosed within. Other facilities, such as the DNGS and BNGS were developed to maximize access to nuclear related systems during normal operation, including access to the reactivity control mechanisms located on the Reactivity Mechanism Deck (RMD). Access to these areas, coupled with suitable reactor configurations, allowed for the proposal of a new concept for isotope irradiation: a combined commercial power reactor and isotope irradiation system, capable of generating significant volumes of Mo-99.

The DNGS operates four (4) CANDU units with a combined output of approximately 3,500 MWe, each with 480 fuel channels. Due to the individually pressurized channels, the reactor is fueled online allowing it to continue operation between maintenance outages occurring approximately every three years. Each fueling activity is the result of thorough planning. Engineering teams balance requirements of flux profiles and thermal power output in each reactor zone to ensure they remain within the safe operating envelope. These ongoing perturbations are integrated into the regular operating plan of the plant and influence scheduling of maintenance activities. This is especially true for instrumentation and control activities, typically involving maintenance on channelized systems which are sensitive to reactivity changes.

Two of the four reactors are undergoing refurbishment projects as of fall 2022 with Unit 2 already complete and Unit 4 to be completed by 2026. This will extend operations at the plant to at least 2050, providing a reliable, carbon free electricity supply for the province of Ontario.

Background on BWXT and Laurentis

Known for its long history in nuclear power plant construction, equipment manufacturing and nuclear fuel production, BWXT has built up its network within the global isotope medicine industry in recent years. Its acquisition of an isotope processing facility near Ottawa, Ontario has positioned in close proximity to the DNGS as well as international airports and other major transportation routes. In 2018, BWXT developed its proprietary method for Tc-99m generators which would rely on Mo-99 produced via neutron capture technology, eliminating the need for highly enriched uranium in the supply chain and associated concerns for non-proliferation and waste streams.

Laurentis, previously known as Canadian Nuclear Partners Inc., is a wholly-owned subsidiary of OPG, and has played a key role in the management of OPG’s existing isotope portfolio, including cobalt-60, tritium and heavy water management services. Along with a connection to OPG and having access to the DNGS, the experience in managing such isotope supply chains has positioned Laurentis as a key player in the global isotope network. The most recent example of isotope expansion includes the 2021 start of helium-3 supplier services, the only global civilian source of this rare gas, a by-produce of commercial nuclear power processes. Under its agreement with BWXT, Laurentis will be responsible for providing irradiation services for molybdenum along with management of the nuclear safety and regulatory coordination associated with project implementation and ongoing operations.

While the primary irradiation services for Mo-99 will be conducted at the DNGS, BWXT also entered into an agreement with the Missouri University Research Reactor (MURR) which has been used for testing, validation to date and would augment the production by Laurentis, as needed, to meet commercial demands along with development of any new production lines in the future. The Mo-99 TDS is scheduled to be fully operational in 2023.

Target Delivery System Overview

Now known as the Target Delivery System, the concept of the irradiation system evolved over the design phase. As a first of its kind system in the industry, design decisions stemmed from prototype testing influencing the propulsion system's transport fluid, material selection and system operating speeds. Each design consideration fed into downstream operational and safety analysis to demonstrate ongoing safe reactor operation, a standard condition to maintain a power reactor operating licence. The system has been designed with as much automation as possible to minimize personnel interface with equipment and improve safety conditions.

The foundation of irradiation is the target capsule, a zirconium-based enclosure filled with natural molybdenum. These targets are produced by BWXT's affiliate, BWXT Nuclear Energy Canada Inc. in Peterborough, Ontario. The target shown in Figure 2 is designed to navigate the tight tolerances of the flight tubes by which they are transported throughout the system. Based on the design of the system, multiple reactor positions are available to irradiate targets at a given time.

BWXT

Figure 2. Target Capsule

The TDS itself is located outside of the containment structure with portions of the system extending inside the reactor. An airlock provides the boundary between the reactor and the accessible areas. Shielded flight tubing will be installed between the auxiliary equipment areas down to the RMD where the majority of other reactivity controls for the reactor are currently installed. The propulsion system will transport the targets between the airlock and the newly installed TDS elevators on the reactor deck. The elevator will then be lowered into the core by operator signal from the field control panel, remaining there for the seven-day irradiation cycle.

Following harvesting of the targets from the reactor, they will be transported through the system to the transport flask loader via automatic operation. Dedicated maintenance staff will seal the flask, overseen by radiation protection staff performing scans and sampling to ensure worker dose remains within acceptable limits. The entire harvesting process is expected to take approximately five hours. The route between the irradiation facility and the processing centre is approximately four hours by road and passes through low density population areas.

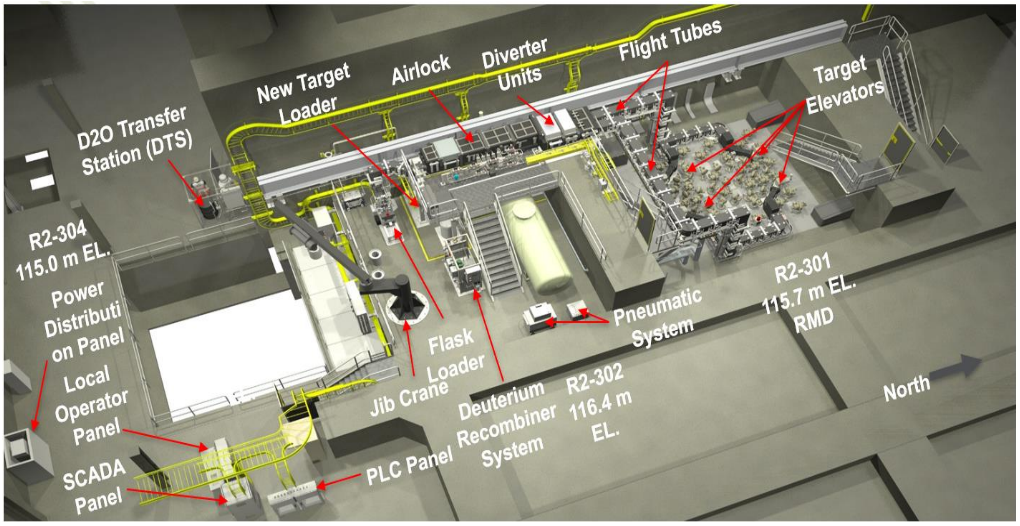

Figure 3. Overview of the Target Delivery System

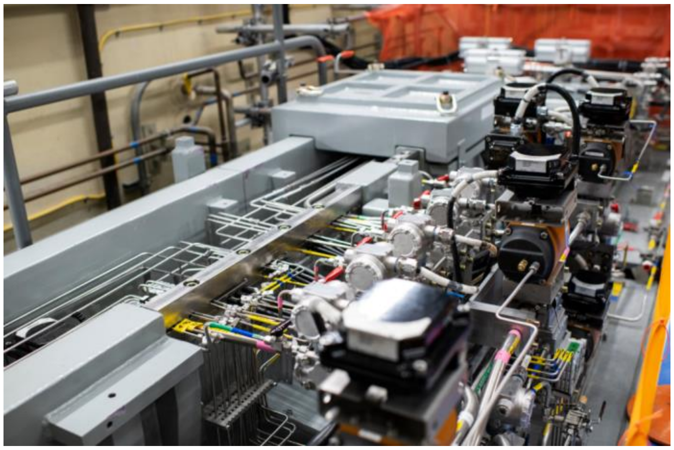

Figure 4. Airlock Auxiliaries Installed at DNGS

Based on the inclusion of maintenance isolation valves, a large portion of the TDS will be accessible at all times allowing periodic inspections and other maintenance activities to proceed in parallel with normal reactor operations. Design of the system has been based on maintenance cycles aligned with operation of the reactor where every three years, there will be a planned maintenance shutdown. A thorough suite of tooling has also been developed by BWXT to facilitate maintenance.

Training for the various work groups involved in ongoing operations is mandatory, in accordance with OPG's commitment to safe reactor operation and adhering to Canada's regulatory standards. Both field and main control room staff operating staff have been provided with training simulators (see Figure 5) to augment continuing training cycles. The design of the DNGS ensures the Main

Control Room (MCR) is located at a distance from the reactor. This allows distinct control panels between the MCR and the Field Control Panel to ensure that all changes in reactivity are approved from inside the MCR prior to any field operations proceeding. All design aspects have considered human factors engineering and user requirements generated throughout the design process.

General training has also been provided to remaining station staff through computer-based training tools, recognizing the fundamental shift in operation for one of the DNGS units. To the extent possible, dedicated crews will be responsible for operating the TDS, providing a level of independence for isotope production relative to other station priorities.

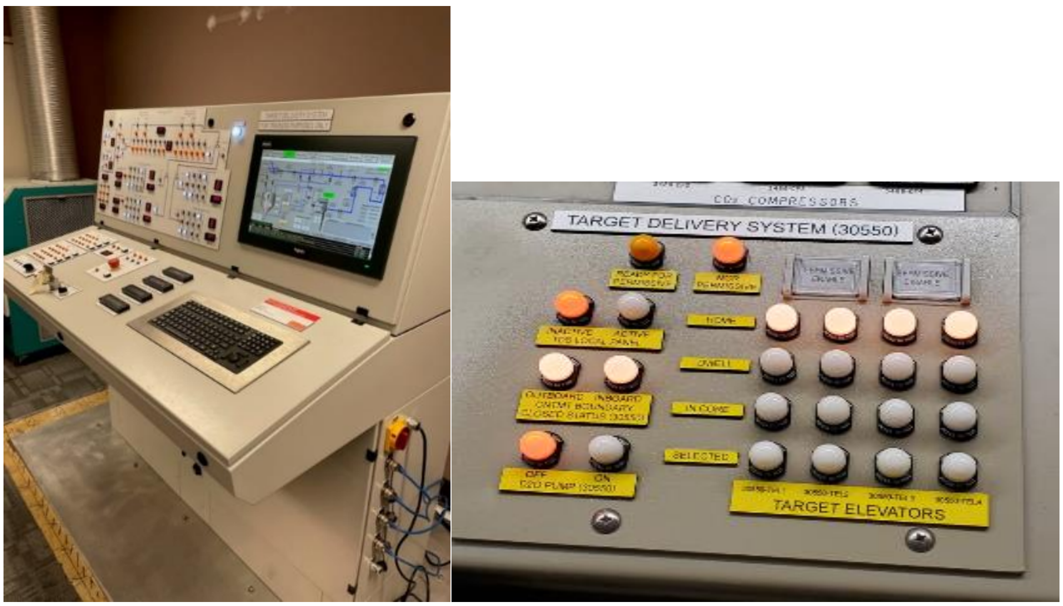

Figure 5. Field Control Panel Simulator and Main Control Room Simulator Interface

Operation of the TDS has been demonstrated at BWXT's Peterborough facility and has been followed by testing of large portions of the system already installed at the DNGS. Licence amendments for the commercial reactor have been obtained by OPG, fulfilling a key regulatory milestone on the path to final implementation. Upon full installation of the system, extensive testing will be performed with the reactor at various power profiles to confirm reactor response as predicted by modelling. Full operation of the TDS is expected in late 2023, subject to health industry regulatory approvals.

With BWXT completing irradiation feasibility tests at the MURR reactor in 2021, processing trials are currently being completed for irradiated targets at the BWXT Medical facilities. This provides valuable experience in preparation for the shipment of targets from Darlington once TDS operations begin. Retrofits of the BWXT Medical processing facility have also progressed enabling high volumes of production to be accommodated for expanding demand, both for Mo-99 and other isotopes in the product lines.

Operational and Safety Considerations

One of the main challenges associated with the implementation of the TDS into Darlington's standard operational window has been minimizing the impact on normal reactor operations for the purpose of power generation. While existing isotope production methods on commercial reactors rely on harvesting of isotopes while the unit is shutdown, the TDS will operate with the reactor at full operation. The focus areas fall into four general areas:

1. Impact on reactor fueling schedules
2. Impact on reactor core reactivity
3. Impact on radiological controls and worker safety
4. Impact on environmental releases

In working with the engineering and operational planning departments early in the project lifecycle, reactor response assessments were conducted to demonstrate that insertion and removal of targets has a limited effect on core reactivity and is considered negligible after several minutes. This provides the operations team added flexibility when planning their fueling cycles since only one reactivity change is permitted on the reactor at any time. Further, prior to normal operations the TDS will undergo several evolutions where targets will be seeded and harvested to develop suitable operating experience influencing downstream operational planning.

The impact on core reactivity designated the TDS a reactor-core design change, requiring extensive challenges throughout the design phase including modeling, third party reviews, and simulator trialing. Representatives from Laurentis and OPG performed assessments throughout the evolution of the design and concluded that the implementation of the TDS would not introduce any new design basis accidents for the facility and that core reactivity impacts would be significantly smaller than insertion and removal of fuel bundles. The amount of reactivity impact from a single seed and harvest would introduce approximately 0.062mk of reactivity. This level of reactivity change still influences the overall mapping of fueling for the reactor core and necessitates updates to the reactor's fuel modeling tool which supports calculations to determine how to fuel the reactor.

The radiological component part of the TDS design followed the As Low As Reasonably Achievable (ALARA) principle typically applied in radiation protection. Selection of the shielding components resulted in extensive calculations to balance both safety aspects as well as cost. Final shielding materials were selected as lead and tungsten, implemented at strategic locations along the target flight paths to maximize protection to the worker and neighbouring equipment. New radiation monitoring equipment has also been installed to measure tritium along with gamma emissions from the targets as they pass through the flight tubing.

Finally, when considering the operation of the system, any release from a nuclear power station is closely assessed to mitigate impacts from radioactive particulates and other radionuclides such as tritium. As the targets interface directly with the heavy water moderator and fluid during their transportation through the system, they must be dried prior to being loaded into the flask. This ongoing drying activity has been modeled as a limited contribution to Darlington's overall emissions.

In summary, the TDS project team has developed a system that minimizes the impact on the reactor unit and allows workers to have as much flexibility as possible in operating the system.

Mo-99 Isotope Generator and Technical Development

In 2018, BWXT announced the development of a proprietary Tc-99m Generator technology featuring the ability to harvest Tc-99m from Mo-99 created by the neutron capture process, using natural molybdenum rather than enriched uranium targets. The proprietary process will mitigate radioactive waste streams and nuclear proliferation concerns and will significantly reduce production and waste costs relative to current market participants.

In terms of footprint and usability, BWXT-designed Tc-99m generators are intended to be drop-in replacements for those used in hospitals and radiopharmacies in North America every day.

BWXT invested heavily in the existing facility at its Kanata, Ontario location to establish a radioisotope processing plant as well as a Tc-99m generator production facility, which will take the irradiated targets from the DNGS or other reactors and ship out finished generators to customers. This facility operates under current Good Manufacturing Practices (cGMP) and is subject to oversight from the Canadian Nuclear Safety Commission (CNSC), Health Canada, the U.S. Food and Drug Administration (FDA), and other applicable regulatory bodies.

In September 2022, BWXT submitted a new drug application to FDA to request approval of its Tc-99m generator for diagnostic imaging. Upon receiving final approval from the FDA, BWXT Medical will enter commercial production.

Potential Market Penetration

The share of CANDU reactors within the global market is approximately 7% and is distributed across several global regions. Implementing the TDS at the DNGS raises the possibility of other CANDU units being untapped irradiation systems. A significant advantage of the CANDU reactor is its spatial design, allowing for a greater volume of material to be inserted into the core. While Mo-99 remains the highest demand diagnostic isotope, irradiation of different isotopes may be considered and integrated into the existing design of the TDS. A standardized design would mitigate the risk of replicating a system in a different CANDU unit.

While many of the Canadian CANDU units are over half-way through their design life cycle, it is probable that many will be considered for refurbishment, extending their life by 25-30 years. Challenges potentially complicating implementation is adequate access to the RMD for reactors built within a larger containment structure and the availability of space to support penetrations into the reactor. Further, the availability of penetrations on the reactor is another pre-requisite for TDS installation. While these challenges may add additional design efforts and extend the implementation schedule, the benefits of a local commercial power irradiation facility, which can irradiate a large volume of material cannot be underestimated.

The operating experience gained from the Darlington implementation will permeate into subsequent opportunities and further mitigate risks of implementation in other reactors. As BWXT continues to expand its product line, its teaming arrangement with Laurentis will offer an opportunity to irradiate targets with other materials, furthering a North American domestic supply of critical, life-saving diagnostic and treatment isotopes.

Table 1. Current Distribution of CANDU-Type Reactor

Country	Type of Reactor	Units	Net Capacity (MWe)
Argentina	CANDU	1	600
Canada	CANDU	19	13,513
China	CANDU	2	1,280
India	CANDU + CANDU-derived	2 + 16	277 + 3,480
Pakistan	CANDU	1	125
Romania	CANDU	2	1,305
South Korea	CANDU	4	2,579

Conclusion

Production of Mo-99 via neutron capture through a commercial nuclear power reactor is an innovative means to use existing infrastructure to reduce implementation time and costs associated with reinforcing the global Mo-99 supply chain.

The teaming arrangement between BWXT and Laurentis presents an opportunity to link expertise from individual industries and collaborate on current and future medical isotope industry projects. Operation of the TDS will provide a reliable supply of Mo-99 for several generations and will form the foundation for the irradiation of other isotopes using similar means. It has been shown through analyses and equipment testing, that irradiation using a commercial reactor is a feasible endeavor and that irradiation processes can be integrated into the already rigorous planning and execution operations in place at an operational facility. Coupled with the extensive operating experience from OPG, safe implementation of the TDS will form the basis for other operators to be able to replicate such a system.

Given the ageing state of the current Mo-99 supply chain, using existing commercial nuclear reactors should be considered. Existing CANDU infrastructure exists in many regions and should be considered as an option for isotope irradiation based on regional needs and operational configurations.