Natural Uranium Equivalent Fuel
An Innovative Design for Proven CANDU Technology

F. Pineiro[1], K. Ho[1], A. Khaial[1], M. Boubcher[1], C. Cottrell[1], S. Kuran[1], Z. Zhenhua[2] and M. Zhiliang[2]
[1] Candu Energy Inc., Mississauga, Ontario, Canada
fabricia.pineiro@candu.com
[2] Third Qinshan Nuclear Power Company, Haiyan, Zhejiang, China

Abstract

The high neutron economy, on-power refuelling capability and fuel bundle design simplicity in CANDU® reactors allow for the efficient utilization of alternative fuels. Candu Energy Inc. (Candu), in collaboration with the Third Qinshan Nuclear Power Company (TQNPC), the China North Nuclear Fuel Corporation (CNNFC), and the Nuclear Power Institute of China (NPIC), has successfully developed an advanced fuel called Natural Uranium Equivalent (NUE). This innovative design consists of a mixture of recycled and depleted uranium, which can be implemented in existing CANDU stations thereby bringing waste products back into the energy stream, increasing fuel resources diversity and reducing fuel costs.

1. Introduction

With the continuous growth of the energy industry, there is an increasing worldwide demand for nuclear power. To secure the long-term availability of nuclear fuel resources that such demand requires, several countries are engaged not only in the improvement of current technologies, but also in the development and implementation of alternative technologies. The implementation of recycled uranium (RU)-based fuels in CANDU reactors is proposed as a viable, efficient alternative to ensure resources availability as well as reducing fuel costs and bringing otherwise waste products back into the energy stream.

Candu, in collaboration with its Chinese partners, has developed an advanced fuel called Natural Uranium Equivalent (NUE). NUE fuel consists of a mixture of RU and depleted uranium (DU), designed to have similar neutronic characteristics as natural uranium (NU), which allows for its implementation in the proven CANDU reactor without the need for modifications. Currently, CANDU 6 reactors operate successfully in five countries, delivering over 22,000 MW of clean air energy.

2. The CANDU Reactor Advantage

The proven CANDU 6 reactor, with over 150 reactor-years of safe operation and ranked among the world's top performing reactors, has unique characteristics which make it the perfect candidate for the use of advanced fuels. These attributes include:

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- Inherent high neutron economy
- On-power refuelling capability that enables power shaping in the reactor core
- Versatile design of reactor core components
- Simple fuel bundle design.

The features of the CANDU reactor enable the use of NU fuel as well as advanced fuels such as RU-based fuels, low-enriched uranium and thorium (LEU/Th) fuel and plutonium-thorium (Pu/Th)-based fuels. In addition to the full-core implementation of these alternative fuel cycles, advanced fuels can be tested through irradiation testing in selected channels of operating CANDU reactors, thereby providing a technological low-risk approach for fuel evaluation and implementation. CANDU reactors' advanced fuels utilization capability promotes the development of closed fuel cycle technologies, which take advantage of otherwise waste products and effectively re-introduce them into the energy stream for clean power generation.

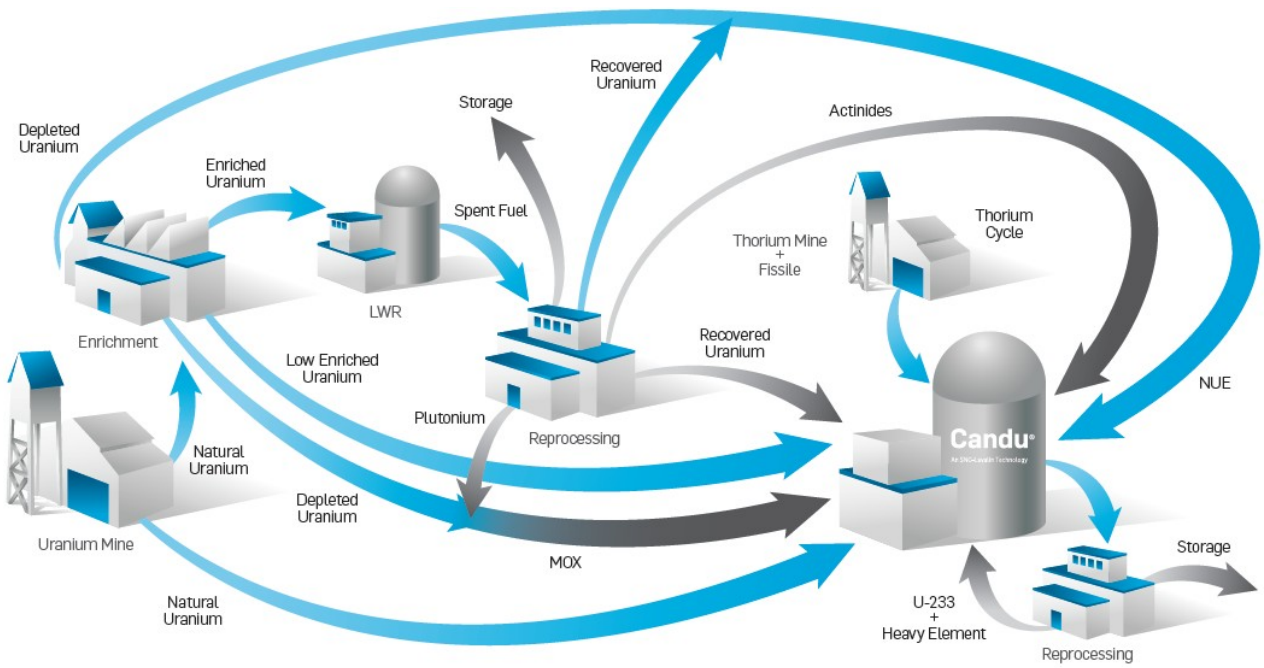

Figure 1 CANDU Reactor Technology's Fuel Cycle Capability

3. NUE Fuel Design and Manufacturing

NUE fuel is an innovative fuel design that works in synergy with current and planned light water reactors (LWR) reprocessing technologies around the globe by blending recycled resources (i.e., RU) with waste products (i.e., DU). The mixture is used for the fabrication of fuel pellets that are inserted into the standard 37-element fuel bundle assembly (Figure 2).

NUE fuel takes advantage of the large worldwide stocks of RU, which are mostly kept in storage. About 90,000 tonnes of RU have been thus far reprocessed from commercial power reactors, and the current global fuel recycling capacity is of about 4,000 tonnes per year [1]. The isotopic compositions of RU used in NUE fuel varies depending on its initial enrichment, fuel exit burnup, type of fuel used and subsequent processing.

The world stocks of DU are estimated to be 1.2 million tonnes [2] and are expected to grow further with the continuous increase of nuclear power capacity.

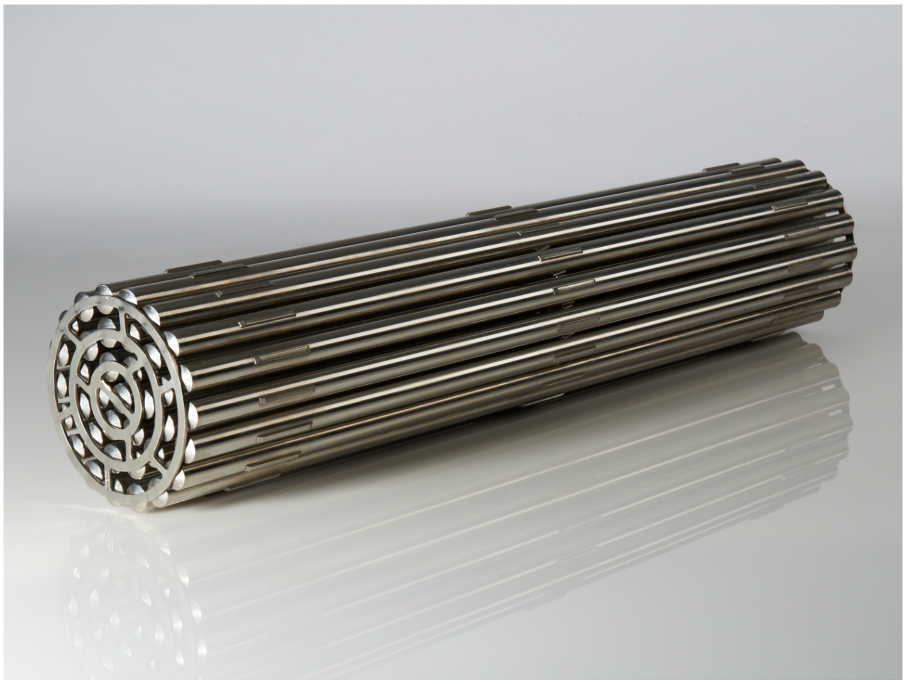

Figure 2 CANDU Reactor Standard 37-Element Fuel Bundle

The use of RU and DU in existing CANDU reactors increases the uranium utilization rate, relieves recycling facilities from the burden of high storage and monitoring costs and provides an environmental benefit by reducing the volume of spent fuel. In addition, NUE fuel provides a significant economic advantage over NU, since RU is generally priced lower than NU and DU costs are almost negligible [3].

4. NUE-fuelled CANDU Reactor Core Behaviour

NUE fuel behaves similarly to NU fuel, and can hence be used for full-core implementation in existing CANDU reactors. Comprehensive technical analyses have been carried out to ensure that the behaviour of the reactor core remains unchanged when fuelled with NUE, and thus little or no changes are required to the reactor design, safety parameters and licensing case. The analyses' results showed that an NUE-fuelled CANDU reactor behaves equivalently to an NU-fuelled CANDU reactor such that all core components including reactivity devices, fuel channel assemblies and safety systems (Figure 3) remain adequate and do not need to be modified.

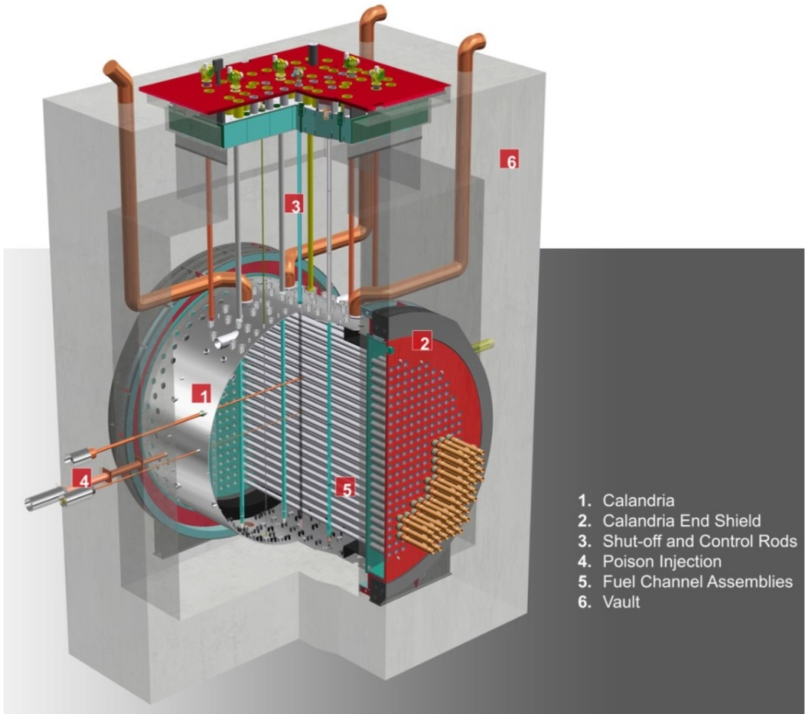

Figure 3 CANDU Reactor Core

4.1 Radiation Physics

The only minor changes to the nuclear power plant required for the implementation of NUE fuel are related to radiation physics. The current CANDU procedure allows for fresh NU fuel bundles to be handled by hand and to be visually inspected prior to fuelling by the operators. Due to gamma activity arising from the presence of ^{232}U daughter products in RU, the dose rates on contact with NUE fuel are about six times higher than those with NU fuel. The implementation of minor localized shielding features, however, is sufficient to maintain radiation exposure of operators below the regulatory limits. These minor enhancements are required for the new fuel storage room and the new fuel loading room. The spent fuel handling and spent fuel storage only require minor procedural changes, since the decay heat of NUE fuel upon core discharge is equivalent to that of NU fuel and is only slightly higher after long decay times (~6 years).

4.2 Refuelling

Refuelling simulations were carried out to ensure that the CANDU reactor could be fuelled with NUE fuel within the current envelope for safe operation. Analyses were performed to prove that a CANDU reactor can transition on-power (i.e., without the need to shut down the reactor) from NU to NUE fuel and vice-versa. The maximum channel and bundle powers found in the transition analysis and during normal NUE refuelling operations did not exceed current operational limits, and the reactivity devices in the core remained within normal operating conditions. Other refuelling parameters such as the eight bundle shift refuelling scheme, were kept the same in the NUE-fuelled core as those for the NU-fuelled core, due to the large similarities between the two fuels. No changes to the CANDU reactor fuelling machines (Figure 4) are required.

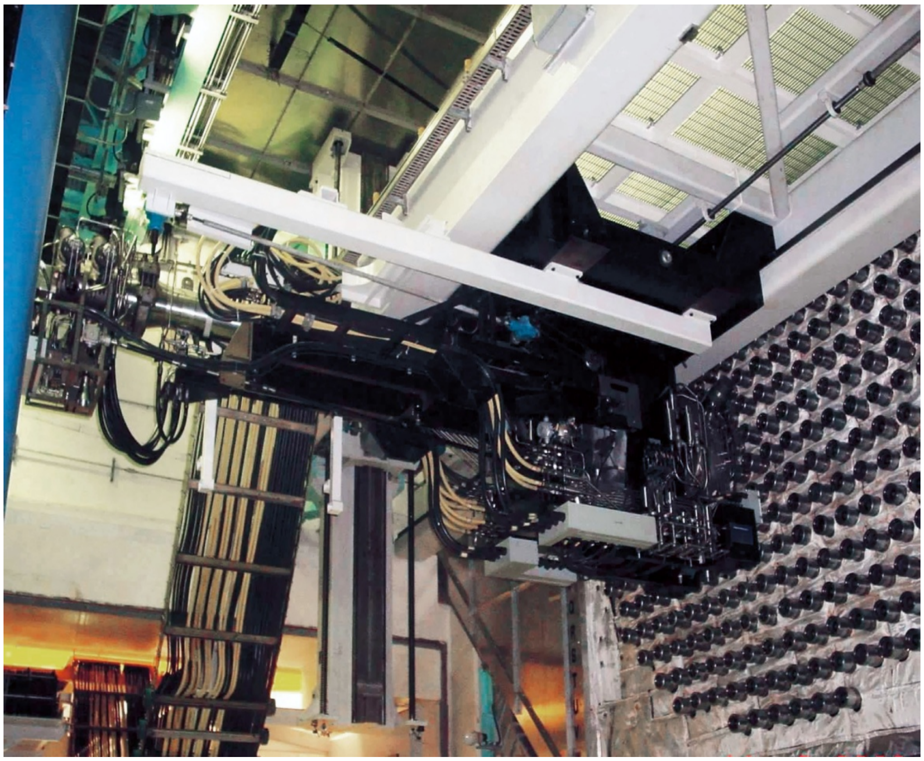

Figure 4 CANDU Reactor Fuelling Machine

4.3 Regional Overpower Protection

The Regional Overpower Protection (ROP) system in CANDU reactors is designed to detect and prevent overpower conditions that could impact fuel integrity by initiating a timely reactor shutdown. The ROP system of the NU-fuelled CANDU reactor was shown to be adequate for the NUE-fuelled CANDU reactor. The ROP margins to trip are not affected by the implementation of NUE fuel in the entire core.

4.4 Safety Systems

Several safety analyses were carried out for the limiting cases of the NUE-fuelled CANDU reactor to confirm that the impact of its full-core implementation is negligible. The assessments included the limiting accident scenarios such as a Large Loss-Of-Coolant Accident (LOCA) with 100% pump suction break, a small LOCA with 2.5% reactor inlet header break, loss of forced circulation: single pump trip for initial core power of 90% full power, and steam and feedwater circuit event: loss of feedwater pumps. The results remained similar to those obtained for the NU-fuelled core and thus showed that there is no significant impact arising from the use of NUE fuel in the CANDU reactor. Sufficient margins to the safety limits are always maintained, and hence the current safety case is not affected.

5. NUE Test Irradiation

Based on the comprehensive technical analyses that demonstrate the negligible impact of implementing NUE fuel in a CANDU reactor as well as manufacturing activities to determine how to best fabricate the fuel, TQNPC obtained the necessary licensing from the Chinese regulating body to carry out a test irradiation of NUE fuel bundles in selected channels of the Qinshan CANDU reactors located in Haiyan, China (Figure 5).

Figure 5 Qinshan CANDU Reactors in Haiyan, China

Following the successful manufacture of 26 NUE fuel bundles in the CNNFC fuel manufacturing facility, which meet pre-established fuel technical specifications, 24 bundles were used for irradiation testing and two were retained for archiving. Irradiation testing started in March 2010, in Qinshan Unit 1, where the selected 24 NUE fuel bundles were inserted into two high-power fuel channels. All NUE fuel bundles were removed from the reactor in spring of 2011.

Continuous monitoring was done during the test irradiation of the NUE fuel bundles to ensure that their performance was as predicted, and that it met pre-established acceptance criteria. The resulting data was compared to that of regular operation with NU fuel and proved the irradiation testing to be successful. In particular, the liquid zone controllers (LZC) remained within normal operation ranges and the bundle and channel powers remained under the licensing limits. There were no indications of any abnormal behavior in the channels that contained NUE fuel relative to those containing NU fuel.

Following the irradiation testing, the irradiated NUE fuel bundles were visually examined for defects or anomalies in an in-bay inspection. This examination consisted of the inspection of both NU and NUE fuel bundles, as well as bundle disassembly and element inspection. The reference NU fuel bundles were directly compared to the NUE fuel bundles as they were retrieved from similar locations of the reactor core. No anomalies or defects were found in the inspection, which suggested that the NUE fuel bundle performed the same as the NU fuel bundle: all fuel element sheath-to-endcap welds were clean and defect free, pellet interface circumferential ridging was distinct and no sheath swelling was observed.

A Post Irradiation Examination (PIE) was carried out to further confirm that the performance of the NUE fuel bundles was adequate and as expected. Twelve elements separated from two NUE fuel bundles were shipped from TQNPC to NPIC (the hot-cell facility). The PIE confirmed that NUE fuel behaved similarly to NU fuel. The conclusions were the following:

- Overall appearance of NUE fuel was consistent with that of NU fuel.
- No anomalies were found on the bundle elements' sheaths.
- Normal strains on the pellets and ridge heights were found.
- NUE fuel element elongation (due to irradiation growth) was consistent with typical NU fuel bundles.
- No indication of potential sheath failure due to fission gas release or gas over-pressure was found.
- Thermal behavior was as expected since grain sizes of both NUE and NU fuels were similar. This also indicates that homogeneity of the NUE pellet was well maintained from the mixing of RU and DU during manufacturing. No thermal hot spots were found.
- Sheath microstructures were consistent with those typically found for CANDU fuel operation.
- Burnup results were consistent with predicted values, NUE fuel operated as designed and maintained similar CHF behavior as NU Fuel.

6. NUE full-core implementation

Based on the successful NUE fuel demonstration irradiation, TQNPC signed a commercial contract with Candu to pursue a full-core implementation of NUE fuel in their Qinshan reactors. A licensing application was submitted to the Chinese nuclear regulator for conversion of the Qinshan reactors to NUE fuel, providing comprehensive technical analyses, which demonstrate that NUE fuel does not cause any changes to the CANDU reactor performance and that the current NU-based safety case remains applicable.

7. Conclusions

The world-wide growing demand of nuclear power has given rise to an increasing interest in the development of alternative technologies that are capable of utilizing unconventional resources for nuclear power generation.

CANDU reactors are an excellent option for the utilization of advanced fuels. NUE fuel, a mixture of RU and DU, is a feasible alternative which can be implemented in existing CANDU reactors. This advanced fuel forms a strong synergy with LWRs, improves the overall uranium utilization rate, allows for the re-introduction of waste products into the energy stream, and reduces fuel costs.

The successful irradiation testing of NUE fuel bundles in the Qinshan CANDU reactors has demonstrated the feasibility of the fuel's utilization in the proven CANDU reactor design. This low-risk technological approach is a breakthrough in the path towards the development of closed fuel cycle technologies. As a result of the NUE project's success, Candu in co-operation with its Chinese partners has developed the Advanced Fuel CANDU Reactor (AFCR), which is capable of utilizing a high burnup RU-based fuel and LEU/Th fuel. The NUE and AFCR projects are part of a strategic plan to further reduce the dependency of countries like China on NU, while providing significant performance and economic advantages [4].

8. Acknowledgments

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9. References

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