Nuclear Fuel Waste Projections in Canada – 2023 Update

NWMO-TR-2023-09 R001

December 2023

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ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2023 Update**
Report No.: **NWMO-TR-2023-09 R001**
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Abstract

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2023 and forecasts the potential future nuclear fuel waste from the existing reactor fleet as well as from proposed new-build reactors. While the report focuses on power reactors, it also includes prototype, demonstration and research reactor fuel wastes held by AECL, which are included in the NWMO mandate.

As of June 30, 2023, a total of approximately 3.3 million used CANDU fuel bundles (about 62,830 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of about 76,691 bundles since the 2022 NWMO Nuclear Fuel Waste Projections report.

For the existing reactor fleet, the total projected number of used fuel bundles produced to end of life of the reactors is approximately 5.6 million used CANDU fuel bundles (approximately 106,900 t-HM). The projection is based on published plans, as of December 2023 to refurbish and extend the life of all Darlington and Bruce reactors, as well as continued operation of Pickering A until 2024 and Pickering B until the end of 2026.

Used fuel produced by potential new-build reactors, including small modular reactors (SMRs) will depend on the size and type of reactor and number of units deployed. New-build plans are at various stages of development. Decisions on future reactor refurbishment, new nuclear build or advanced fuel cycle technologies will be made by the nuclear utilities in Canada. The impacts of these decisions on projected inventory of nuclear fuel waste are discussed and will be incorporated into future updates of this report when there is reasonable certainty in the amount and timing of the additional nuclear fuel waste.

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1. INTRODUCTION

1.1 BACKGROUND

The Nuclear Waste Management Organization (NWMO) is responsible for the long-term management of Canada’s nuclear fuel waste (Canada 2002).

The NWMO will continually review and adjust its implementation plans as appropriate consistent with the external environment. As part of this process, the NWMO annually publishes the current and future potential inventories of used fuel amounts and types from existing and future reactors (Reilly 2022). This document provides an update of the current inventories from existing operating stations as of June 2023 and the projected inventories using available information as of December 2023.

Decisions on new nuclear reactors, advanced fuel cycles or other changes in energy choices will not be made by the NWMO. They will be made by the utilities in conjunction with government and regulators. However, it is important that the NWMO is prepared for these potential changes so that the NWMO can plan for the long-term management of used fuel arising from such decisions. As part of this, the NWMO maintains a watching brief on alternative technologies (NWMO 2023).

1.2 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2023 and forecasts the potential future nuclear fuel waste from the existing reactor fleet. The report focuses on power reactors and includes information on prototype, demonstration and research reactor fuel wastes held by Atomic Energy of Canada Limited (AECL).

The report also discusses used fuel that would result from operation of potential new reactors in Canada, including small modular reactors (SMRs). Note that information included in this report reflects the fuel characteristics, and the fuel wastes accepted for disposal may be different.

1.3 CHANGES SINCE THE 2022 REPORT

The primary changes to the Canadian nuclear landscape since the 2022 report are:

a) An increase in the total amount of used fuel currently in storage, due to another year of reactor operation.

b) Darlington Unit 3 refurbishment was completed ahead of schedule in July 2023 (OPG 2023a).

c) Darlington Unit 4 refurbishment started in July 2023 and is expected to be completed in Q4 of 2026 (OPG 2023b).

d) Darlington Unit 1 continues refurbishment and is expected to be completed by Q2 of 2025 (OPG 2022a).

e) Bruce Power continues the major component replacement at Unit 6 with fuel channel assembly installation completed in October 2022 (Bruce Power 2022). Unit 6 refurbishment started in January 2020 and is expected to be complete in Q4 of 2023.

f) Bruce A Unit 3 was shut down in March 2023 (Bruce Power 2023a), completed defueling in April 2023 and major component replacement is expected to be completed in 2026 (Bruce Power 2023b).

g) OPG submitted an application in June 2023 to the Canadian Nuclear Safety Commission (CNSC) to extend commercial operation of Units 5–8 at the Pickering Nuclear Generation Station (Pickering B) until December 31, 2026. The current licence allows commercial operation until December 31, 2024 (CNSC 2023a).

h) OPG is conducting a feasibility assessment on the potential for refurbishing Pickering B Units 5-8. As of August 2023 OPG completed the assessment stage, which included scope development, initial cost estimates, schedule development, risk assessments, economic evaluations and regulatory strategies. (Ontario 2022 and OPG 2023c).

i) New Brunswick Power (NB Power) in partnership with ARC Clean Technology Canada is proceeding with work to deploy one ARC-100 SMR at the Point Lepreau nuclear site. In June 2023, NB Power submitted an Environmental Impact Assessment (EIA) registration document to the Department of Environment and Local Government (DELG) (New Brunswick 2023), and a Licence to Prepare Site application to the CNSC (NB Power 2023).

The combined effects of these changes on the current and projected used fuel inventory are:

a) An increase in the total amount of used fuel currently in storage from June 30, 2022 to June 30, 2023.

	June 30, 2022	June 30, 2023	Net change	
Wet storage	1,418,651	1,395,152	-23,499	bundles*
Dry storage	1,771,950	1,872,140	100,190	bundles
TOTAL	**3,190,601**	**3,267,292**	**76,691**	**bundles**

** Note: A negative number means more used fuel was transferred from wet to dry storage than was produced during the year.*

b) No significant change in the overall projected future total number of used fuel bundles produced by the existing reactor fleet for the reference forecast (5.6 million bundles). A small increase of the overall projected total is observed for a high forecast (6.0 million bundles), assuming Pickering B extended commercial operation, including potential refurbishment plans considered by OPG. These projections are detailed in Section 2.

Note that these projections do not include any potential fuel waste resulting from operation of new reactors. Projections from potential fuel waste resulting from operations of new reactors are detailed in Section 3.

2. INVENTORY FROM EXISTING REACTORS

2.1 CURRENT INVENTORIES

Table 1 summarizes the current inventory of nuclear fuel waste in Canada as of June 30, 2023. The inventory is expressed in terms of number of CANDU used fuel bundles and does not include fuel which is currently in the reactors (which is not considered to be “nuclear fuel waste” until it has been discharged from the reactors).

As of June 30, 2023, there are approximately 3.3 million bundles in wet or dry storage. This is equivalent to approximately 62,830 tonnes of heavy metal (t-HM). Further details on the existing reactors can be found in Appendix B and fuel types in Appendix C.

Figure 1 summarizes the history of wet and dry storage of used fuel in Canada to the end of June 2023. Initially, all fuel was wet-stored in the station used fuel storage bays. Dry storage was initiated in the 1970s at shutdown AECL prototype reactors. Starting in the 1990s, older fuel in the wet bays at the operating power reactors has been transferred to dry storage on an ongoing basis. In the future, the inventory in wet storage will remain relatively constant (since wet bay space is fixed), while the inventory in dry storage will continue to grow over time.

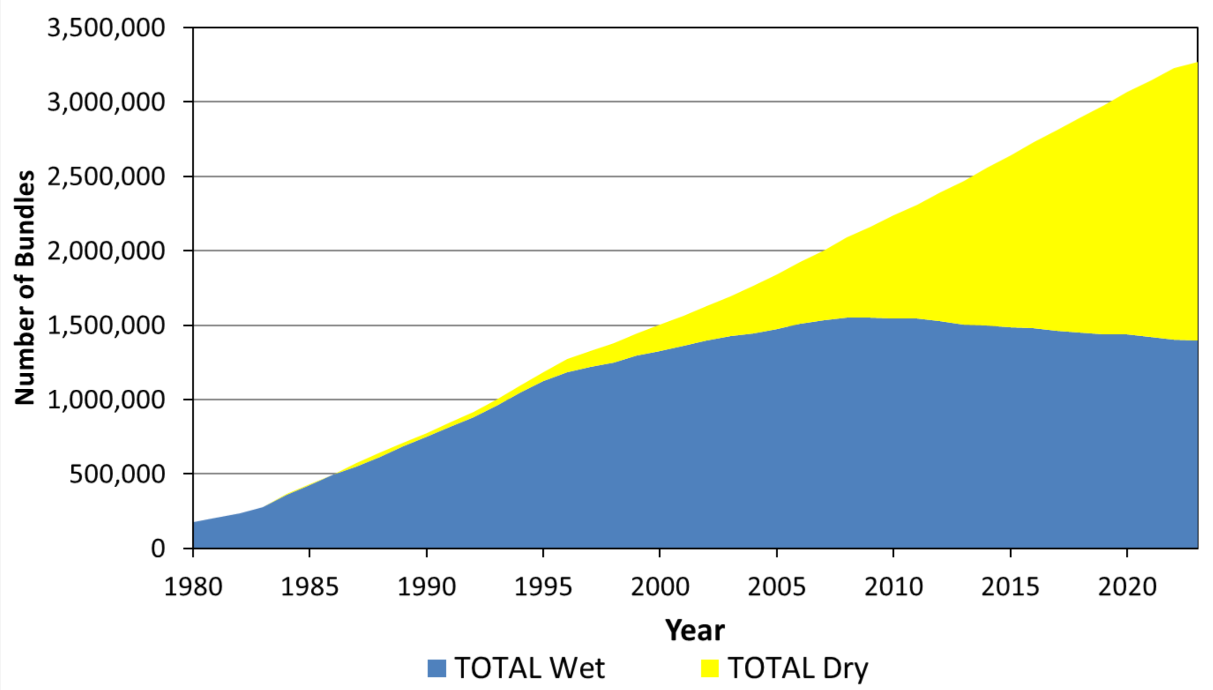


Figure 1: Summary of Used Fuel Wet and Dry Storage History

Table 1: Summary of Nuclear Fuel Waste in Canada as of June 30, 2023

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)	Current Status
Bruce A	OPG(1)	338,619	295,296	**633,915**	- 3 units operational - 1 unit undergoing refurbishment See Note (2)
Bruce B	OPG(1)	339,862	471,158	**811,020**	- 3 units operational - 1 unit undergoing refurbishment See Note (2)
Darlington	OPG	301,232	338,981	**640,213**	- 2 units operational - 2 units undergoing refurbishment See Notes (3)
Douglas Point	AECL	0	22,256	**22,256**	- permanently shut down 1984
Gentilly 1	AECL	0	3,213	**3,213**	- permanently shut down 1977
Gentilly 2	HQ	0	129,925	**129,925**	- permanently shut down 2012
Pickering A	OPG	376,162	469,327	**845,489**	- 2 units operational - 2 units non-operational since 1997 (permanently shut down 2005)
Pickering B	OPG				- 4 units operational
Point Lepreau	NBPN	39,277	131,397	**170,674**	- 1 unit operational
Whiteshell	AECL	0	2,301	**2,301**	- permanently shut down 1985 See Note (4)
Chalk River	AECL	0	4,886	**4,886**	- predominately fuel bundles from the NPD reactor (permanently shut down 1987) and natural UO_2 fuel from other reactors
		~0	~3,400	**~3,400**	- research fuels; see Note (5)
	Total	**1,395,152**	**1,872,140**	**3,267,292**	

Notes:

AECL = Atomic Energy of Canada Limited
HQ = Hydro-Québec
NBPN = New Brunswick Power Nuclear
OPG = Ontario Power Generation Inc.

1) OPG is responsible for the used fuel that is produced. Bruce reactors are leased to Bruce Power for operation.

2) Bruce Units 3-8 are currently undergoing refurbishment, unit-by-unit. The Bruce A Unit 3 was shut down in March 2023 and is expected to be completed in 2026. Bruce B Unit 6 was shut down in Jan 2020 and refurbishment is expected to complete in Dec 2023.

3) Refurbishment of the Darlington Unit 2 was completed in Jun 2020, and the refurbishment of Unit 3 was completed in July 2023. Refurbishment of Darlington Unit 1 started in Feb 2022 and is expected to be complete by June 2025. Refurbishment of Darlington Unit 4 started in July 2023 and is expected to be completed in 2026.

4) This value includes UO2 and uranium carbide bundles from the WR-1 reactor, 360 natural UO2 bundles from the Douglas Point reactor, miscellaneous CANDU bundles, and various experimental fuel types, commercial fuel pieces, and hot cell remnants in CANDU-bundle sized cans.

5) This estimate is the mass-based estimate of the number of bundle equivalents in the AECL inventory and includes the majority of the research reactor and experimental fuel in the AECL fuel inventory. The remaining inventory items will be assessed with respect to their suitability for disposal in the APM DGR and have therefore been excluded at this time.

2.2 PROJECTED NUCLEAR FUEL WASTE

Forecasts of future nuclear fuel waste are summarized in Table 2. The forecasts are based on the NWMO's assumptions used for planning purposes only and may differ from the business planning assumptions used by the reactor operators.

Two scenarios are provided in the estimates of this year's projections. These estimates are based on published plans, as of December 2023 for refurbishment and life extension for the current reactor fleet, use conservative assumptions, and include a number of uncertainties, as described below.

Reference (Low) Scenario

1. Only existing CANDU stations are included in this forecast, with the following assumptions regarding refurbishment: (Ontario 2022, OPG 2021a, Bruce Power and IESO 2015, NB Power 2019):

   - Reactors that have been permanently shut down do not restart (Gentilly-2, Pickering A Units 2 and 3).
   - Reactors that have been refurbished (Bruce A Units 1 and 2, Darlington Units 2 and 3, and Point Lepreau) and reactors that will be refurbished (Darlington Units 1 and 4, Bruce A Units 3 and 4 and Bruce B) with new sets of pressure tubes and other major components will operate for about 30 effective full power years (EFPY).
   - Pickering A Units 1 and 4 will operate until the end of 2024 and Pickering B Units 5–8 will operate until the end of 2026[1].

2. Fuel in reactor core is removed prior to a refurbishment and not re-used. No fuel is generated during the refurbishment period. End-of-life total includes final reactor core fuel.

3. The forecast for each station is calculated as *[(June 2023 actuals) + (number of years from June 2023 to end-of-life) * (typical annual production of fuel bundles)]*, rounded to nearest 1,000 bundles.

   The forecast annual production of fuel bundles is a conservative estimate for each station, resulting in a conservative projection of the overall total. An analysis of the last 5-year forecast vs actuals across all units indicates the forecast total was high by up to 10,800 bundles/year. Projected to the end of operations and applying the 5-year average on a station-by-station basis, this could indicate the current total is high by up to 235,000 bundles.

4. Units are assumed to operate until December 31 of the shutdown year.

[1] Ontario has asked OPG to update its feasibility assessment for refurbishing Pickering B units at the Nuclear Generating Station, based on the latest information, as a prudent due diligence measure to support future electricity planning decisions. Refurbishment of Pickering Nuclear Generating Station could result in an additional 30 years of operations and used fuel arisings, which is considered in the High Scenario.

The forecast conservatively assumes operation to end of year of shutdown. If an earlier (mid-year) shutdown were assumed for all stations, the total would be reduced by about 46,000 bundles.

5. Units operate to current end of life dates.

   Changes to the estimated end-of-life dates for refurbished reactors would result in changes to the overall forecast. For example, a potential 3-year extension or reduction of operation of all stations relative to current plans, assuming the highest typical annual bundle production, would affect the total bundle count by +/- about 92,000 bundles per year. Assuming a future 3-year extension/reduction for all units would affect the bundle count by about +/- 280,000 bundles.

6. Total mass of heavy metals (e.g., uranium) in fuel is based on an average bundle mass of heavy metal specific to each reactor type.

<u>High Scenario</u>

1. Similar to the reference (low) scenario, only existing CANDU stations are considered and the assumptions regarding refurbishment remain the same, with one exception (Ontario, 2022):

   - Pickering B Units 5–8 will be refurbished and operate for an additional 30 EFPY until 2060.

2. Projecting to the end of operations and applying the uncertainty in the 5-year average (bullet 3 from the above reference (low) scenario assumptions) on a station-by-station basis indicates the forecast total could be high by up to 303,000 bundles including refurbished Pickering B.

3. All other assumptions used for the reference (low) scenario remain the same.

In summary, 5.6-6.0 million used fuel bundles existing and forecasted represents the best estimate range based on published plans for the existing CANDU stations, as of December 2023. The reference scenario, approximately 5.6 million used fuel bundles is considered as the reference scenario for NWMO planning purposes.

The associated uncertainty for the reference and high scenarios could include +/- 0.28 million bundles (based on 3-year early or delayed shutdown of all current units), up to -0.24-0.30 million bundles (based on conservatism in projection), and about -0.05 million bundles (for mid-year end-of-life shutdown vs assumed end-of-year shutdown).

The forecast is subject to potential changes on annual basis, to account for reactor operators' updated plans for refurbishment and life extension, as well as for adjustments in calculations to reflect the most up-to-date numbers of bundles in storage versus previous year's projections. Further details are provided in Appendix A.

Table 2: Summary of Projected Nuclear Fuel Waste from Existing Reactors

Location	Waste Owner	Total June 2023	Typical Annual Production	Reference (low) Scenario [7]	High Scenario [7]
		(# bundles)	**(# bundles)**	**(# bundles)**	**(# bundles)**
Bruce A	OPG	633,915	20,500 [1]	1,236,000	1,236,000
Bruce B	OPG	811,020	23,500 [1]	1,695,000	1,695,000
Darlington	OPG	640,213	22,000 [1]	1,283,000	1,283,000
Douglas Point	AECL	22,256	0 [2]	22,256	22,256
Gentilly 1	AECL	3,213	0 [2]	3,213	3,213
Gentilly 2	HQ	129,925	0 [2]	129,925	129,925
Pickering A	OPG	845,489	7,200 [3]	935,000	1,370,000
Pickering B	OPG		14,500 [1]		
Point Lepreau	NBP	170,674	4,800	259,000	259,000
Whiteshell	AECL	2,301	0 [2]	2,301	2,301
Chalk River	AECL	~8,286	0 [4]	~8,286	~8,286
TOTAL (bundles) [5]		**3,267,292**	**92,500**	**5,574,325**	**6,009,325**
(t-HM)[7]		***62,830***	***1,780***	***106,890***	***115,580***

Notes:

1) Based on 4 reactors operating.
2) Reactor is permanently shut down and not producing any more fuel.
3) Based on 2 reactors operating.
4) Future forecasts do not include research fuels. Chalk River does not produce any CANDU power reactor used fuel bundles. However, it may receive bundles from power reactor sites from time to time for testing. This will not affect overall total numbers of bundles, since they will be subtracted from the reactor site.
5) Totals may not add exactly due to rounding to nearest 1,000 bundles for future forecasts.
6) “tonnes of heavy metals” (t-HM) based on an average of bundle mass specific for each reactor type.
7) Assumes units operate until December 31 of the shutdown year and the core is defueled in the following year.

3. INVENTORY FROM POTENTIAL NEW REACTORS

There are two categories of proposed new reactor projects:

- projects which have received or are currently undergoing regulatory approvals; and
- potential projects which have been discussed by various implementing organizations (proponents), but which do not have any regulatory approvals underway.

This report focuses on the first category. However, it does not assess the probability of any of these projects proceeding. Execution of each project rests entirely with the proponent.

At this time, proposed new projects are not CANDU reactors and do not produce used CANDU fuel bundles. They are also higher burnup than used CANDU fuel, so typically produce less mass of used fuel for a given amount of electric power. However, these other used fuel wastes are not directly comparable to used CANDU fuel on a mass basis as they would generally be producing more decay heat and contain more radioactivity per unit fuel mass. These are characteristics that are important for repository design, in addition to fuel mass (or volume).

In order to better visualize the characteristics of this potential future inventory with respect to disposal, the inventory is presented here on an equivalent thermal power basis. That is, how many used CANDU bundles would be generated in producing an equivalent amount of thermal power? This number of CANDU bundles would have experienced a similar amount of fission, and therefore have a roughly similar amount of decay heat and radioactivity as the new types of used fuel. In this report, this equivalency is used to illustrate the potential impacts of these new reactors on the inventory of fuel wastes requiring long-term management.

Decisions on new nuclear reactors, advanced fuel cycles or other changes in energy choices will not be made by the NWMO. They will be made by the utilities in conjunction with government and regulators. The NWMO will continue to monitor these developments and the implications of new reactors as part of its Adaptive Phased Management approach.

3.1 PROJECTS WHICH HAVE RECEIVED OR CURRENTLY UNDERGOING REGULATORY APPROVALS

There are three small modular reactor projects (SMRs) currently undergoing regulatory reviews. These projects total approximately 1,315 MWe of new reactors operating for 40 to 60 years, which could result in approximately an additional 510,000 equivalent CANDU bundles, based on a simple correlation of electric power to CANDU bundles on a thermal power basis. The details of these projects are summarized below.

3.1.1 Ontario Power Generation

Ontario Power Generation (OPG) holds a Nuclear Power Reactor Site Preparation Licence that allows preparation of the Darlington nuclear site for future construction and operation of up to 4 new reactors, with a maximum combined net electrical output of 4,800 MWe (OPG 2021b).

In December 2021 OPG announced a partnership with GE Hitachi Nuclear Energy (GEH). OPG has selected GEH to further develop the BWRX-300 SMR (small modular reactor) design to be constructed at the Darlington nuclear site by 2030 (OPG 2022b). In September 2022, OPG began non-nuclear site preparation activities for an SMR at Darlington and submitted an application to the CNSC for the Licence to Construct in October 2022 (OPG 2022c). In July 2023, the Ontario government announced it will work with OPG to commence planning and licensing for three additional SMRs, for a total of four SMRs at the Darlington nuclear site (Ontario 2023a).

The BWRX-300 is a light water reactor (LWR), specifically a boiling water reactor (BWR), utilising low enriched fuel. The fuel is proposed to be based on Global Nuclear Fuel’s (GNF) GNF2 product line and is described in Appendix C.3. It is estimated that over the reactor’s expected 60-year lifetime it could result in about 2,400 GNF2 used fuel assemblies (roughly 440 t-HM initial). Based on a simple correlation to CANDU bundles on a thermal power basis, it is estimated that this would be equivalent to about 117,000 CANDU equivalent used fuel bundles per reactor, totalling approximately 470,000 CANDU equivalent fuel bundles for four proposed BWRX-300s at the Darlington nuclear site.

GNF2 BWR fuel is the same type of fuel that is being planned for handling and disposal in Sweden, Finland, and Switzerland, as all three of these countries have BWR reactors discharging BWR fuel (IAEA 2019).

3.1.2 Global First Power

Global First Power (GFP), a partnership between Ultra Safe Nuclear Corporation (USNC) and OPG, propose to construct and operate a Micro Modular Reactor (MMR) plant on AECL property at the Chalk River site. Canadian Nuclear Laboratories (CNL) and GFP signed a hosting agreement formalizing the framework under which CNL and GFP will cooperate with respect to licensing, design, siting, and other matters with respect to advancement of the SMR project (CNL 2020a).

In April 2019, GFP submitted to the CNSC an initial application for a Licence to Prepare Site for a SMR at the Chalk River site (GFP 2019a) and followed up with the submission of Part 1 of the full application in July 2023 (GFP 2023a). The CNSC’s assessment of GFP’s application is ongoing.

The MMR is a high temperature gas-cooled reactor (HTGR). The original proposal was a 5 MWe (15 MWth) reactor with an anticipated operational life of 20 years and a single fuel loading at reactor start-up (GFP 2019b). In 2023, the concept was revised to 15 MWe (45 MWth) and 40 years operation with refueling (USNC 2023, GFP 2023b).

At this stage there is limited information about the MMR fuel and its fuel waste characteristics. The fuel contains low-enriched uranium of a potential range 9.9-19.75% U-235 (USNC 2023) and is manufactured with TRI-structural ISOtropic (TRISO) fuel particles. The TRISO fuel particles are assembled into a Fully Ceramic Micro-encapsulated (FCM™) fuel pellet. The pellets are proposed to be stacked in vertical channels within hexagonal graphite blocks, comprising an MMR fuel element (GFP 2019b). The MMR fuel is described in Appendix C.3.

The MMR fuel is substantially different than CANDU fuel and the quantities and characteristics of potential fuel wastes have not been published at this time. It is estimated that the amount of used fuel that could result after 40 years operation of one 15 MWe (45 MWth) MMR at the Chalk River site, would be equivalent to about 4,300 CANDU used fuel bundles based on a simple correlation to CANDU bundles on a thermal power basis.

The NWMO continues to monitor the progress of the regulatory approval process of this project. As more information becomes available, additional details on TRISO fuel and potential fuel waste inventories from the proposed MMR will be included in future versions of this report.

3.1.3 New Brunswick Power

New Brunswick Power (NB Power) in partnership with ARC Clean Technology Canada is proceeding with work to deploy a SMR. Planning and project development are underway to deploy one ARC-100 reactor at the Point Lepreau nuclear site.

On June 30, 2023, NB Power submitted an Environmental Impact Assessment (EIA) registration document to the Department of Environment and Local Government (DELG) (New Brunswick 2023), and a Licence to Prepare Site application to the CNSC (NB Power 2023).

The ARC-100 is a 100 MWe sodium-cooled, fast flux, pool-type reactor that builds on the 30-year operation of the EBR-II reactor, which was built and operated by the Argonne National Laboratory in the U.S. from 1964-1994 (ARC Clean Technology 2023). The fuel is metallic with an average enrichment of 13.1% U-235; details of the fuel are described in Appendix C.3.

It is estimated that over the reactor's expected 60-year lifetime it could result in 297 ARC-100 metallic fuel assemblies (ARC Clean Technology 2023). Based on a simple correlation to CANDU bundles on a thermal power basis, it is estimated that this would be equivalent to about 40,000 CANDU equivalent used fuel bundles for one ARC-100 reactor at the Point Lepreau nuclear site.

The NWMO continues to monitor the progress of the regulatory approval process of this project. As more information becomes available, additional details on ARC-100 metallic fuel assemblies and potential fuel waste inventories from the proposed SMR will be included in future versions of this report.

3.2 POTENTIAL PROJECTS AND DEVELOPMENTS

3.2.1 Small Modular Reactors

Natural Resource Canada (NRCan) initiated the SMR Roadmap project with interested provinces, territories and power utilities to identify the opportunities for on and off-grid applications of SMRs in Canada. The SMR Roadmap report was published in 2018, with recommendations in areas such as waste management, regulatory readiness and international engagement (SMR 2018). The Government of Canada launched Canada's SMR Action Plan in 2020 (NRCan 2020), and in 2022, four provinces identified the following streams to support SMR technology readiness (Ontario, New Brunswick, Alberta and Saskatchewan 2022):

- *"Stream 1 – a grid-scale SMR project of 300 MWe constructed at the Darlington nuclear site in Ontario by 2028, followed by up to four subsequent units in Saskatchewan between 2034 and 2042.*
- *Stream 2 – two fourth-generation, advanced SMRs that would be developed in New Brunswick. ARC Clean Energy is targeting to be fully operational at the Point Lepreau nuclear site by 2029, and Moltex Energy will have both its spent fuel recovery system and reactor in operation by the early 2030s, also at the Point Lepreau site.*

- *Stream 3 – a new class of micro-SMRs designed primarily to replace the use of diesel in remote communities and mines. A five-MWe gas-cooled demonstration project is under way at Chalk River, Ontario, with plans to be in service by 2026".*

There are various degrees of uncertainty with respect to the future implementation of these projects, including the number of reactors that could be considered for operation under each stream. For illustrative purposes, an estimate of the fuel waste that could result from the operation of these SMRs is provided below, using a simple correlation to CANDU bundles on a thermal power basis:

- The Stream 1 Darlington project is discussed in Section 3.1.1 and could produce about 117,000 CANDU equivalent used fuel bundles per BWRX-300 reactor. Assuming four such reactors operating for 60 years at the Darlington site could result in approximately 470,000 CANDU equivalent used fuel bundles. Assuming four reactors at Darlington and four similar reactors operating in Saskatchewan for 60 years, could result in approximately 940,000 CANDU equivalent used fuel bundles in total.
- The Stream 2 has two projects:
    - The ARC-100 project is discussed in Section 3.1.3 and could produce about 40,000 CANDU equivalent used fuel bundles, assuming one reactor operating for 60 years.
    - Moltex Energy's proposed Stable Salt Reactor - Wasterburner (SSR-W) 300 MWe reactor at Point Lepreau is designed to utilise molten salt fuel produced by reprocessing CANDU used fuel (IAEA 2022). Details of the residual salt fuel wasteform are not available at the time of writing this report; however, based on a simple correlation to CANDU bundles on a thermal power basis, it is estimated that one SSR-W operating for 60 years could produce about 106,000 CANDU equivalent used fuel bundles.
- The Stream 3 micro-SMR project at Chalk River is discussed in Section 3.1.2 and it is estimated that one MMR operating for 40 years could produce approximately 4,300 CANDU equivalent used fuel bundles. Additionally, in November 2023 the Government of Saskatchewan announced $80 million for the Saskatchewan Research Council to pursue the deployment of an eVinci microreactor, which will be built by Westinghouse Electric Company and expected to be operational by 2029 (Saskatchewan, 2023). A 13 MWth eVinci microreactor operating for 40 years could produce approximately 1,300 CANDU equivalent used fuel bundles.

The CNSC continues the pre-licensing reviews for a variety of SMR designs (CNSC 2023b).

CNL looks to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada, and recently issued the 4th call for proposals of its Canadian Nuclear Research Initiative program (CNRI) (CNL 2023). CNRI is designed to accelerate the development and deployment of SMRs and advanced reactor designs. At present, four proponents are in various stages of CNL's review (CNL 2022a). Global First Power is in stage 3 for the proposed 15 MWe MMR (high-temperature gas reactor) and has submitted an application for a licence to prepare site (see Section 3.1.2). Three other proponents have completed CNL's pre-qualification stage and have been invited to enter CNL's next stage of detailed review; these are U-Battery Canada Ltd. (4 MWe high temperature gas reactor), StarCore Nuclear (14 MWe high-temperature gas reactor), and Terrestrial Energy (190 MWe integral molten salt reactor). No licensing activities have been initiated for these three proposals. CNL has also formed partnerships with Moltex Energy (CNL 2020b), Ultra Safe Nuclear Corporation (CNL 2020c), New Brunswick Power (CNL 2020d), Terrestrial Energy (CNL 2020e), and ARC Canada (CNL 2022b) to research SMR fuels and advance SMR technology in Canada.

3.2.2 Large-scale Reactors

In July 2023, the Ontario government announced it is starting pre-development work with Bruce Power to site a new large reactor project (Ontario 2023b). Bruce Power is planning to start community engagement and conduct the environmental assessment for federal approval to determine the feasibility of siting up to 4,800 MWe of new nuclear generation on its current site (Bruce Power 2023c).

The specific reactor technology that could be selected for this project is under evaluation (Bruce Power 2023d). For illustrative purposes and similar to the discussion above, operation of 4-6 CANDU reactors (4,800 MWe) operating for 60 years could result in about 2.15 million CANDU used fuel bundles, based upon a simple correlation to existing CANDU bundles and on a basis of thermal to electric power efficiency of existing CANDU reactors.

4. SUMMARY OF PROJECTED USED FUEL INVENTORY

As of June 30, 2023 there are approximately 3.3 million used fuel bundles in wet or dry storage.

Based on currently announced and potential refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, two scenarios are considered (see Section 2.2 for details):

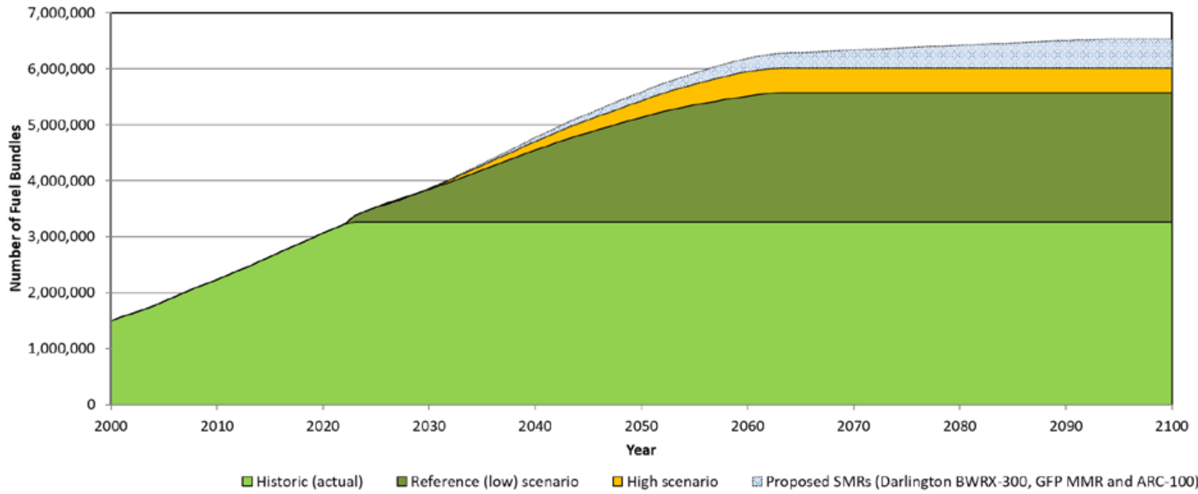
- A reference (low) scenario forecast projects a total of approximately 5.6 million bundles.
- A high scenario forecast projects a total of approximately 6.0 million bundles.

Its associated uncertainty could include: +/- 0.28 million bundles (based on 3-year early or delayed shutdown of all current units), up to -0.24-0.3 million bundles (based on conservatism in projection for low or high scenario), and -0.05 million bundles (for mid-year end-of-life shutdown vs assumed end-of-year shutdown).

In addition, there are a number of new projects that are in various stages of planning. The SMRs that are in early licensing could add approximately +0.51 million equivalent CANDU used fuel bundles from four BWRX-300 units at Darlington site, one GFP MMR at Chalk River site, and one ARC-100 reactor at Point Lepreau site.

The existing and projected inventory from current CANDU reactor operations, CANDU reactors approved and potential refurbishment, and proposed SMRs currently undergoing regulatory review described in Section 3.1, is summarized in Figure 2.

In summary, the approximate 5.6-6.0 million used fuel bundles forecasted represents the best estimate range based on utility published plans, as of December 2023 for the existing nuclear fleet. The reference (low) scenario, approximately 5.6 million used fuel bundles is considered as the reference scenario for NWMO planning purposes.



Notes:

1) The existing fuel as of end of June 2023, is shown in the light green shaded area.
2) The reference (low) scenario forecast (dark green shaded area) shows the additional fuel bundles that would be generated based on the announced refurbishment and life extension projects for the existing Canadian reactor fleet.
3) The high scenario forecast (orange shaded area) shows the additional fuel bundles that would be generated from Pickering B being refurbished and continuing operation for 30 years, until 2060.
4) Potential inventory from the proposed SMRs (blue hatched area) shows the estimated additional CANDU equivalent fuel bundles that could be generated from SMRs currently undergoing regulatory approvals, assuming four BWRX-300s at Darlington site, one MMR at Chalk River site, and one ARC-100 at Point Lepreau site.

Figure 2: Summary of Projected Used Fuel Inventory

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APPENDIX A: USED FUEL FORECAST DETAILS

Two scenarios are provided in the estimates of this year's projections. These estimates are based on published plans, as of December 2023 for refurbishment and life extension for the current reactor fleet, use conservative assumptions, and include a number of uncertainties.

Table A1 provides details for the assumed dates of refurbishment and shutdown of each reactor used to calculate the projections. Table A2 provides details on the used fuel forecasts from existing reactors.

Table A1: Refurbishment Schedule for Existing Reactors

Location	Unit	Refurbishment Schedule (Start-End)	
		Reference (low) Scenario	High Scenario
Bruce A	1	Complete	
	2	Complete	
	3	01/2023 – 06/2026	
	4	01/2025 – 12/2027	
Bruce B	5	07/2026 – 06/2029	
	6	01/2020 – 12/2023	
	7	07/2028 – 06/2031	
	8	07/2030 – 06/2033	
Darlington	1	01/2022 – 06/2025	
	2	Complete	
	3	09/2020 – 03/2024	
	4	07/2023 – 12/2026	
Douglas Point	-	-	
Gentilly 1	-	-	
Gentilly 2	-	-	
Pickering A	1	Complete	
	2	-	
	3	-	
	4	Complete	
Pickering B	5	-	01/2027 – 12/2029
	6	-	01/2027 – 12/2029
	7	-	01/2027 – 12/2029
	8	-	01/2027 – 12/2029
Point Lepreau	1	Complete	
Whiteshell	-	-	
Chalk River/ NPD/other	-	-	

Table A2: Detailed Used Fuel Forecasts from Existing Reactors

Location	Unit	Startup	Total to June 2023	Typical Annual Production	Reference (low) Scenario		High Scenario	
			(# bundles)	(# bundles)	End-of-life	(# bundles)	End-of-life	(# bundles)
Bruce A	1	1977	633,915	20,500	2043	1,236,496	2043	1,236,496
	2	1977			2043		2043	
	3	1978			2061		2061	
	4	1979			2062		2062	
Bruce B	5	1985	811,020	23,500	2062	1,694,780	2062	1,694,780
	6	1984			2058		2058	
	7	1986			2063		2063	
	8	1987			2063		2063	
Darlington	1	1992	640,213	22,000	2053	1,283,183	2053	1,283,183
	2	1990			2049		2049	
	3	1993			2052		2052	
	4	1993			2055		2055	
Douglas Point		1968	22,256	0	1984	22,256	1984	22,256
Gentilly 1		1972	3,213	0	1977	3,213	1977	3,213
Gentilly 2		1983	129,925	0	2012	129,925	2012	129,925
Pickering A	1	1971	845,489	7,200	2024	934,651	2024	1,369,651
	2	1971			2005		2005	
	3	1972			2005		2005	
	4	1973			2024		2024	
Pickering B	5	1983		14,500	2026		2060	
	6	1984			2026		2060	
	7	1985			2026		2060	
	8	1986			2026		2060	
Point Lepreau		1983	170,674	4,800	2040	259,234	2040	259,234
Whiteshell		1965	2,301	0	1985	2,301	1985	2,301
Chalk River/ NPD/other			8,286	0		8,286		8,286
TOTALS (bundles)			**3,267,292**	**92,500**		**5,574,325**		**6,009,325**
(t-HM)			***62,830***	***1,780***		***106,890***		***115,530***

APPENDIX B: SUMMARY OF EXISTING CANADIAN REACTORS & FUEL STORAGE

Appendix B presents a summary of commercial, demonstration and research reactors in Canada. Table B1 presents a summary of commercial power reactors in Canada and their status. Table B2 presents a summary of prototype and demonstration reactors in Canada and their status. Table B3 presents a summary of research reactors in Canada and their status.

Commercial, prototype and some research reactors have storage facilities for used nuclear fuel. Table B4 presents a summary of dry storage facilities for used nuclear fuel and Figure B1 shows the location of the major storage locations in Canada.

Table B1: Nuclear Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type*	Current Status (2023)
Bruce Nuclear Power Development, Ontario				
Bruce A – 1	750	1977	37 element bundle	Refurbished and operating
Bruce A – 2	750	1977		Refurbished and operating
Bruce A – 3	750	1978		Undergoing refurbishment
Bruce A – 4	750	1979		Operating
Bruce B – 5	795	1985	37 element bundle; 37 element “long” bundle	Operating
Bruce B – 6	822	1984		Undergoing refurbishment
Bruce B – 7	822	1986		Operating
Bruce B – 8	795	1987		Operating
Darlington, Ontario				
Darlington 1	881	1992	37 element bundle; 37 element “long” bundle	Undergoing refurbishment
Darlington 2	881	1990		Refurbished and operating
Darlington 3	881	1993		Refurbished and operating
Darlington 4	881	1993		Undergoing refurbishment
Gentilly, Quebec				
Gentilly 2	635	1983	37 element bundle	Permanently shut down in 2012
Pickering, Ontario				
Pickering A – 1	515	1971	28 element bundle	Refurbished and operating
Pickering A – 2	515	1971		Non-operational since 1997; Permanently shut down in 2005
Pickering A – 3	515	1972		Non-operational since 1997; Permanently shut down in 2005
Pickering A – 4	515	1973		Refurbished and operating
Pickering B – 5	516	1983		Operating
Pickering B – 6	516	1984		Operating
Pickering B – 7	516	1985		Operating
Pickering B – 8	516	1986		Operating
Point Lepreau, New Brunswick				
Point Lepreau	635	1983	37 element bundle	Refurbished and operating

*Note: refer to Appendix B for description of fuel types, and their current storage status.

Table B2: Prototype and Demonstration Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type	Current Status (2023)
Bruce Nuclear Power Development, Ontario				
Douglas Point (CANDU PHWR prototype)	206	1968	19 element bundle	Permanently shut down in 1984; All fuel is in dry storage on site
Gentilly, Quebec				
Gentilly 1 (CANDU-BLW boiling water reactor prototype)	250	1972	18 element CANDU-BLW bundle	Permanently shut down in 1977; All fuel is in dry storage on site
Rolphton, Ontario				
NPD (CANDU PHWR prototype)	22	1962	19 element bundle; various prototype fuel designs (e.g. 7 element bundle)	Permanently shut down in 1987; All fuel is in dry storage at Chalk River

Table B3: Research Reactors

Location	Rating (MW(th))	Year In-service	Fuel Type	Comments
Chalk River, Ontario				
NRU	135	1957	various driver fuel and target designs (U-metal, U-Al, U_3Si-Al)	Permanently shut down in 2018. The majority of NRU fuel has been transferred to dry storage.
ZED-2	0.00025	1960	various uranium fuels	Operating
NRX	42	1947	various driver fuel and target designs (U-metal, U-Al, UO_2)	Permanently shut down in 1992
MAPLE 1	10	-	U_3Si-Al driver fuel; UO_2-targets	Never fully commissioned
MAPLE 2	10	-		
Whiteshell, Manitoba				
WR-1 (organic cooled reactor prototype)	60	1965	various research and prototype fuel bundle designs (similar size and shape to standard CANDU bundles; UO_2, UC)	Permanently shut down in 1985; Fuel is in dry storage on site.
Hamilton, Ontario				
McMaster University	5	1959	U_3Si-Al fuel pins	MTR Pool type reactor; Operating.
Kingston, Ontario				
Royal Military College	0.02	1985	UO_2 fuel pins	SLOWPOKE-2 reactor; Operating.
Montreal, Quebec				
Ecole Polytechnique	0.02	1976	UO_2 fuel pins	SLOWPOKE-2 reactor; Operating.

Note: the SLOWPOKE reactors can operate on one fuel charge for 20 to 40 years. Other former research reactors include the 2 MW(th) SLOWPOKE Demonstration Reactor at Whiteshell, the low power PTR and ZEEP reactors at Chalk River, and shut down / decommissioned SLOWPOKE reactors at University of Toronto, Dalhousie University, Nordion Kanata, University of Alberta and University of Saskatoon. Used fuel from these shut down research reactors is stored at the Chalk River site, Whiteshell site or has been returned to the country of origin.

Table B4: Summary of Dry Storage Facilities for Used Nuclear Fuel

Facility	Owner	Technology	Fuel Type	Year In-service
Chalk River	AECL	AECL Concrete Canister/Silo	CANDU & CANDU-like (mainly 19 element)	1992
Darlington Waste Management Facility (DWMF)	OPG	OPG Dry Storage Container (DSC)	CANDU (37 element)	2008
Douglas Point Waste Management Facility	AECL	AECL Concrete Canister/Silo	CANDU (19 element)	1987
Gentilly 1	AECL	AECL Concrete Canister/Silo	CANDU-BLW (18 element)	1984
Gentilly 2	HQ	AECL CANSTOR/MACSTOR modular concrete vault	CANDU (37 element)	1995
Pickering Waste Management Facility (PWMF)	OPG	OPG Dry Storage Container (DSC)	CANDU (28 element)	1996
Point Lepreau	NBPN	AECL Concrete Canister/Silo	CANDU (37 element)	1990
Western (Bruce) Waste Management Facility (WWMF)	OPG	OPG Dry Storage Container (DSC)	CANDU (37 element)	2003
Whiteshell	AECL	AECL Concrete Canister/Silo	CANDU & CANDU-like (various sizes)	1977

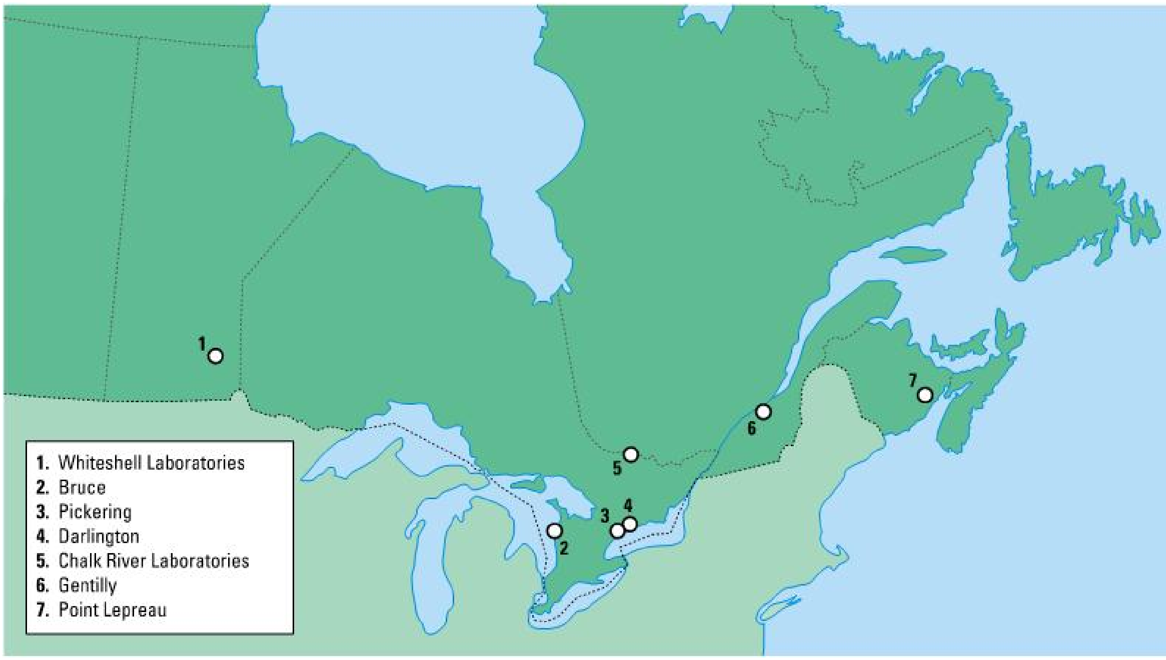


Figure B1: Current Nuclear Fuel Waste Major Storage Location in Canada

APPENDIX C: DESCRIPTION OF FUEL TYPES

Table C1 summarizes the inventory of the various fuel types in Canada as of June 2023.

Section C.1 details the physical characteristics and usage of the fuels in operating reactors. Section C.2 details the physical characteristics and usage of the fuels in demonstration and prototype reactors. Section C.3 details the physical characteristics and usage of the fuels in projects undergoing regulatory review. Note that these are fuel characteristics, the fuel wastes accepted for disposal may be different.

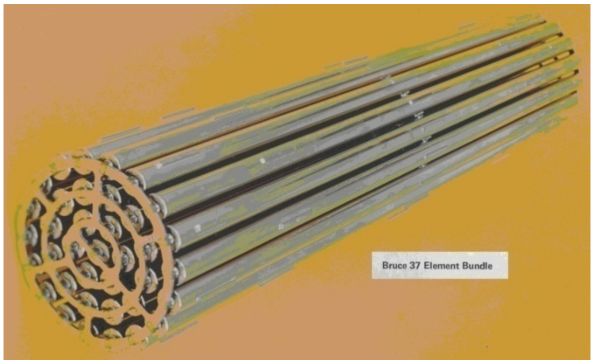
Note that the physical characteristics of the fuels described in this appendix are intended to be nominal and other sources may quote different numbers.

Table C1: Summary of Inventory by Bundle Type (June 2023)

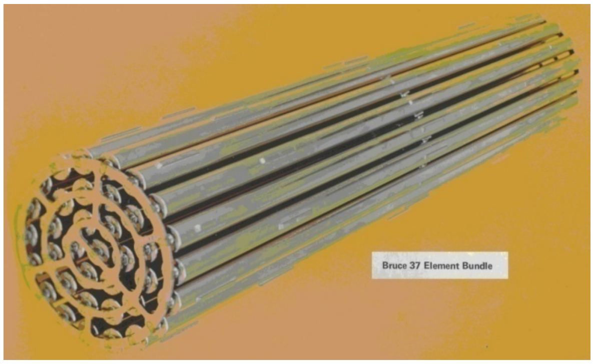
CANDU Bundle Type	Where Used	Wet Storage (# bundles)	Dry Storage (# bundles)	Total (# bundles)
18 Element	Gentilly 1	-	3,213	3,213
7 Element / 19 Element	NPD, Douglas Point	-	27,446	27,446
28 Element	Pickering	376,162	469,327	845,489
37R	Bruce, Darlington, Gentilly 2, Pt Lepreau	419,331	1,211,777	1,631,108
37R Long	Bruce, Darlington	87,890	154,980	242,870
37M	Bruce, Darlington	396,701	-	396,701
37M Long	Bruce, Darlington	115,044	-	115,044
43 Element LVRF	Bruce	24	-	24
Other	AECL (various)	-	5,397	5,397
	Total	**1,395,152**	**1,872,140**	**3,267,292**

C.1 FUELS FROM OPERATING REACTORS

<table>
<tr><th colspan="2">28 element CANDU bundle</th></tr>
<tr><td rowspan="5">
</td><td>Physical dimensions:
102.5 mm OD x 497.1 mm OL</td></tr>
<tr><td>Mass:
20.1 kg U (22.8 kg as UO_2)
2.0 kg Zircaloy (e.g., cladding, spacers)
24.8 kg total bundle weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of natural UO_2</td></tr>
<tr><td>Typical burnup:
8,300 MW day / tonne U
(200 MWh/kg U)</td></tr>
<tr><td>Cladding material:
Zircaloy-4</td></tr>
<tr><td colspan="2">Construction:
- Bundle is composed of 28 elements (fuel pins), arranged in 3 concentric rings with 4 elements in the inner most ring, 8 elements in the second ring and 16 elements in the outer ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.</td></tr>
<tr><td colspan="2">Comments:
- Used in Pickering A and B reactors</td></tr>
</table>

<table>
<tr><th colspan="2">37 element CANDU standard length bundle</th></tr>
<tr><td rowspan="5">
</td><td>Physical dimensions:
102.5 mm OD x 495 mm OL</td></tr>
<tr><td>Mass:
19.2 kg U (21.7 kg as UO_2)
2.2 kg Zircaloy (e.g., cladding, spacers)
24.0 kg total bundle weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of natural UO_2</td></tr>
<tr><td>Typical burnup:
8,300 MW day / tonne U
(200 MWh/kg U)</td></tr>
<tr><td>Cladding material:
Zircaloy-4</td></tr>
<tr><td colspan="2">Construction:
- Bundle is composed of 37 elements (fuel pins), arranged in 4 concentric rings with 1 element in the inner most central ring, 6 elements in the second ring, 12 elements in the third ring and 18 elements in the outer ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.</td></tr>
<tr><td colspan="2">Comments:
- Used in Bruce A and B, Darlington, Gentilly-2, Point Lepreau and EC-6 reactors (Gentilly-2 and Point Lepreau have minor construction differences on the end plates and spacers compared to the Bruce and Darlington designs).
- Two variants, designated 37R (regular) and 37M (modified), have slightly different center pin configurations and uranium masses (19.2 kg U for 37R vs 19.1 kg U for 37M). 37M is presently in use in Bruce and Darlington stations replacing prior 37R.</td></tr>
</table>

37 element CANDU long bundle



Physical dimensions:
102.5 mm OD x 508 mm OL

Mass:
19.7 kg U (22.3 kg as UO_2)
2.24 kg Zircaloy (e.g., cladding, spacers)
24.6 kg total bundle weight

Fissionable material:
Sintered pellets of natural UO_2

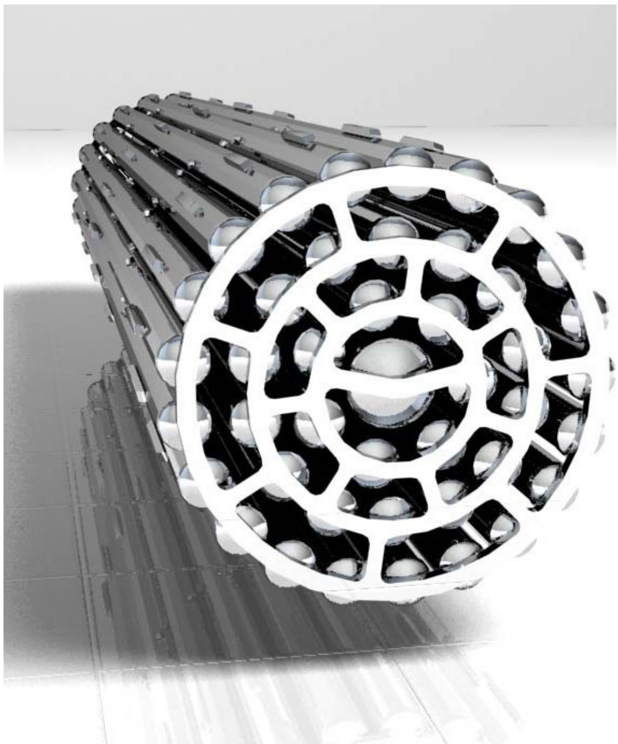
Typical burnup:
8,300 MW day / tonne U
(200 MWh/kg U)

Cladding material:
Zircaloy-4

Construction:
- Bundle is composed of 37 elements (fuel pins), arranged in 4 concentric rings with 1 element in the inner most central ring, 6 elements in the second ring, 12 elements in the third ring and 18 elements in the outer ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.

Comments:
- Similar to 37 element "standard" bundle, but is 13 mm longer.
- Used in Bruce B, and Darlington reactors.
- Two variants, designated 37R-long and 37M-long, have slightly different center pin configurations and uranium masses (19.7 kg U for 37R-long vs 19.6 kg U for 37M-long). 37M-long is presently in use in Bruce stations, replacing prior 37R-long.

43 element CANFLEX LVRF bundle



Physical dimensions:
102.5 mm OD x 495.3 mm OL

Mass:
18.5 kg U (21.0 kg as UO_2)
2.1 kg Zircaloy (e.g., cladding, spacers)
23.1 kg total bundle weight

Fissionable material:
Sintered pellets of UO_2
slightly enriched to 1.0% U-235

Typical burnup:
8,300 MW day / tonne U
(200 MWh/kg U)

Cladding material:
Zircaloy-4

Construction:

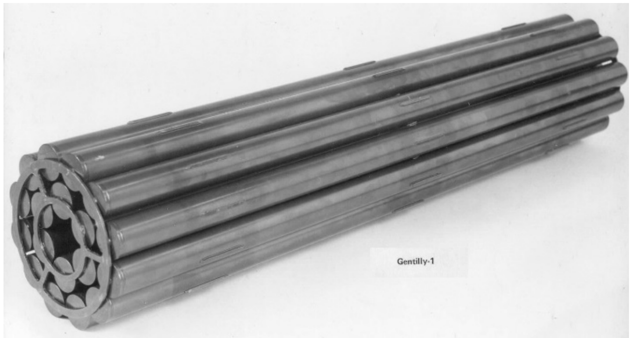
- Bundle is composed of 43 elements (fuel pins), arranged in 4 concentric rings with 1 element in the inner most central ring, 7 elements in the second ring, 14 elements in the third ring and 21 elements in the outer ring.
- The inner central element uses Dysprosium (an element that absorbs neutrons and reduces the bundle power maintaining a flat neutronic field profile across the bundle during operation).
- Diameter and composition of fuel pins vary by ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.

Comments:

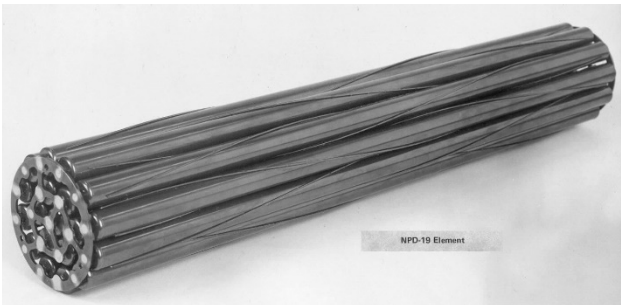
- Has been used in Bruce B reactors in limited quantities, option for use in EC-6 reactors

C.2 FUELS FROM DEMONSTRATION AND PROTOTYPE REACTORS

<table>
<tr><th colspan="2">7 element CANDU bundle</th></tr>
<tr><td rowspan="5">
</td><td>Physical dimensions:
82.0 mm OD x 495.3 mm OL</td></tr>
<tr><td>Mass:
13.4 – 13.5 kg U (15.2 – 15.3 kg as UO_2)
1.4 – 1.5 kg Zircaloy (e.g., cladding)
16.7 kg total bundle weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of natural UO_2
Some low-enriched 7 element bundles exist at 1.4% wt ^{235}U and 2.5% wt ^{235}U enrichment</td></tr>
<tr><td>Typical burnup:
6474 MW day / tonne U
(156 MWh/kg U)</td></tr>
<tr><td>Cladding material:
Zircaloy-2
Nickel-free Zircaloy-2
Zircaloy-4</td></tr>
<tr><td colspan="2">Construction:
- Bundle is composed of 7 elements (fuel pins), arranged as 1 element surrounded by a ring of 6 elements.
- Construction included wire-wrap and split-spacer fuel elements; riveted or welded end plates (only one bundle model had riveted end plates, all others had welded end plates) and thin, medium and thick walled cladding</td></tr>
<tr><td colspan="2">Comments:
- Used in NPD</td></tr>
</table>

<table>
<tr><th colspan="2">18 element CANDU bundle</th></tr>
<tr><td rowspan="5">
</td><td>Physical dimensions:
102.4 mm OD x 500 mm OL</td></tr>
<tr><td>Mass:
20.7 kg U (23.5 kg as UO_2)
3.2 kg Zircaloy (e.g., cladding, spacers)
26.7 kg total bundle weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of natural UO_2</td></tr>
<tr><td>Typical burnup:
6972 MW day / tonne U
(168 MWh/kg U)</td></tr>
<tr><td>Cladding material:
Zircaloy-4</td></tr>
<tr><td colspan="2">Construction:
- Bundle is composed of 18 elements (fuel pins), arranged in 2 concentric rings with 6 elements in the inner most ring and 12 elements in the second ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.</td></tr>
<tr><td colspan="2">Comments:
- Used in Gentilly 1</td></tr>
</table>

19 element CANDU bundle



Physical dimensions:

82.0 mm OD x 495.3 mm OL

Mass:

12.1 – 13.4 kg U (13.7 – 15.2 kg as UO_2)

1.4 – 2.2 kg Zircaloy (e.g., cladding)

15.8 – 16.7 kg total bundle weight

Fissionable material:

Sintered pellets of natural UO_2

Some low-enriched 19 element bundles exists at up to 1.4% wt ^{235}U enrichment

Typical burnup:

6474 MW day / tonne U at NPD

7885 MW day / tonne U at Douglas Point

(156 MWh/kg U at NPD)

(190 MWh/kg U at Douglas Point)

Cladding material:

Zircaloy-4

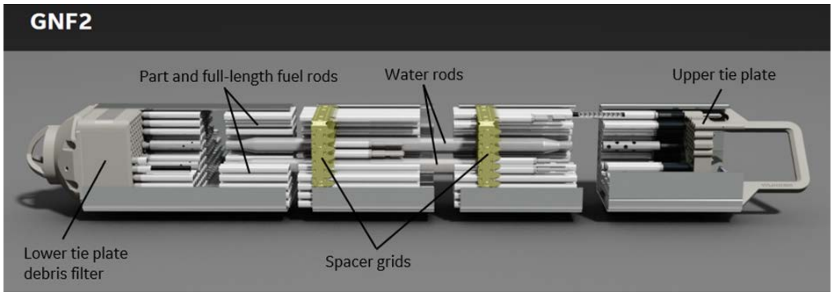
Construction:

- Bundle is composed of 19 elements (fuel pins), 1 element is surrounded by 2 concentric rings of fuel pins, 6 elements in the first ring and 12 elements in the outer ring.
- Originally produced as a wire-wrapped bundle this design was eventually replaced with split-spacer variation.

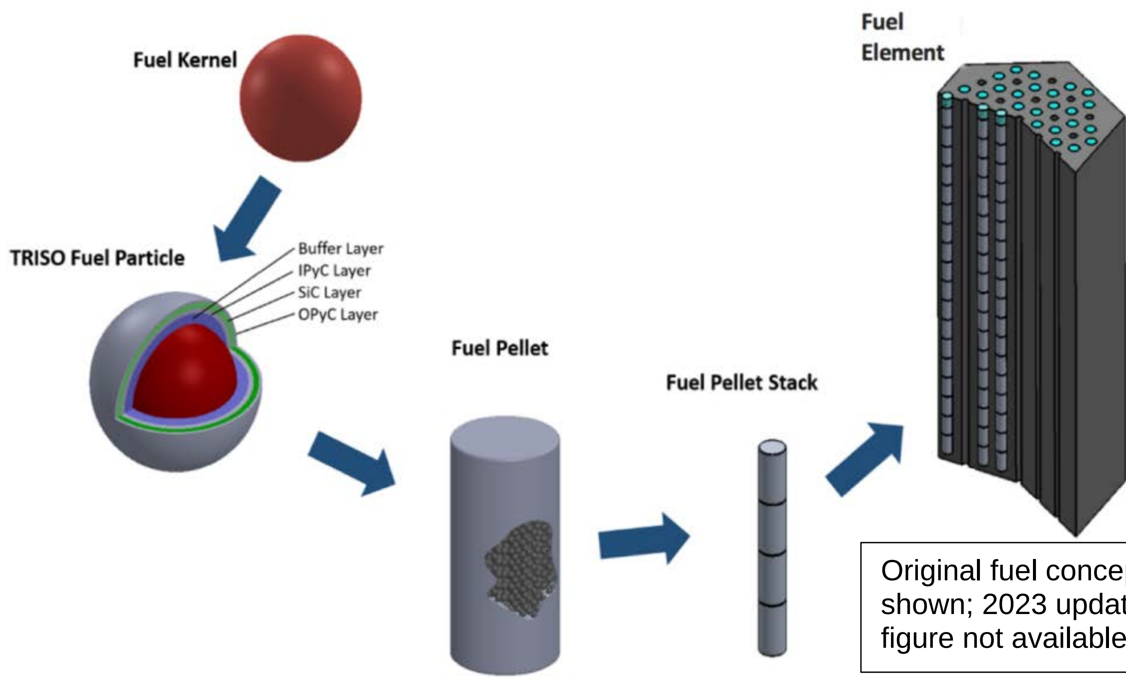
Comments:

- Used in NPD and Douglas Point

C.3 FUEL FROM PROJECTS UNDERGOING REGULATORY REVIEW

<table>
<tr><th colspan="2">GEH BWRX-300 fuel assembly [2]</th></tr>
<tr><td rowspan="6">
</td><td>Physical dimensions:
Up to 150 mm square x 4500 mm long</td></tr>
<tr><td>Mass:
186.5 kg U (211.6 kg as UO_2)
Up to 93.4 kg metals in cladding, tie plates, channels
Up to 305 kg total mass</td></tr>
<tr><td>Fissionable material:
Sintered pellets of UO_2
Batch average enrichment about 4% U-235</td></tr>
<tr><td>Typical burnup:
40,000-50,000
MW day/tonne U</td></tr>
<tr><td>Cladding material:
Zircaloy-2</td></tr>
<tr></tr>
<tr><td colspan="2">Construction:
- Global Nuclear Fuel GNF2 fuel design; same as in some operating BWRs.
- The GNF2 design contains a 10x10 array of 78 full-length fuel rods, 14 part-length rods, and two central water rods.</td></tr>
<tr><td colspan="2">Comments:
- To be used in new OPG Darlington site small modular reactor</td></tr>
</table>

[2] GE Hitachi Nuclear Energy, 2022. BWRX-300 General Description, 005N9751, Revision E, August 2023.

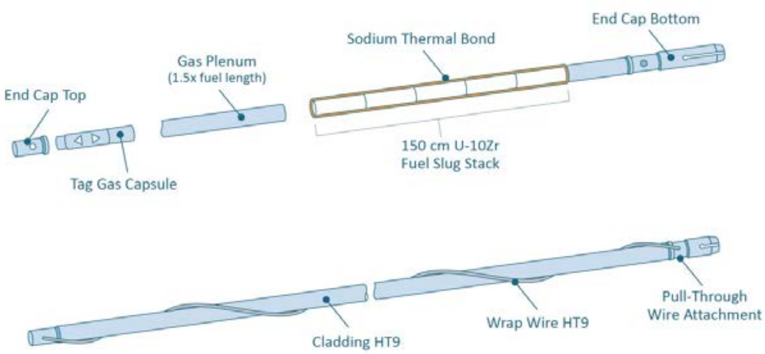
GFP USNC MMR fuel [3,4]
 Original fuel concept shown; 2023 update figure not available
Physical dimensions: TRISO fuel particles have a diameter of ~750-830 µm. The dimensions of the fuel pellets or elements are not yet available.
Fissionable material: TRISO fuel kernels can contain Uranium Carbide (UC_2) or Uranium oxide (UO_2) Enrichment range 9.9-19.75% U-235
Cladding material: TRISO fuel kernel particles are coated in several layers, including: - Buffer layer of porous PyC - IPyC layer - SiC layer - OPyC layer
Construction: - TRISO fuel particles are encased into a SiC matrix forming an FCM Fuel Pellet. - FCM Fuel pellets are stacked vertically in channels within hexagonal graphite blocks, forming a fuel element.
Comments: - Details on the irradiation characteristics and physical form of the fuel elements are not yet available.

[3]Global First Power, 2019. Project Description for the Micro Modular Reactor™ Project at Chalk River, CRP-LIC-01-001, Revision 2, 2019.

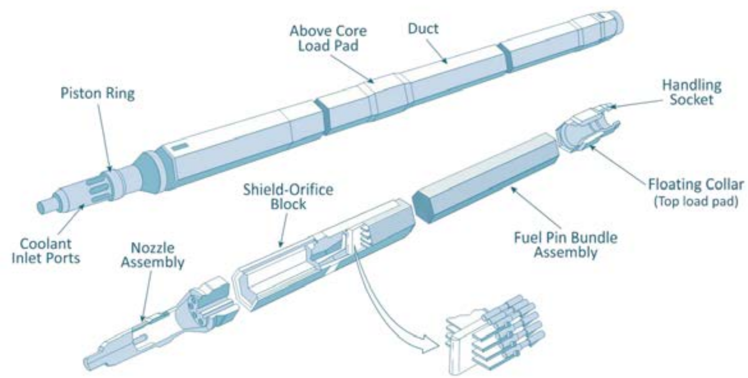
[4] Pacific Northwest National Laboratory, 2021. TRISO Fuel: Properties and Failure Modes, PNNL-31427, June 2021.

ARC-100 fuel [5]

Fuel pin:



Fuel assembly:



Physical dimensions:
Fuel pins are ~1 cm in diameter,
Total active fuel length is 150 cm (fuel slug stack)

The dimensions of the fuel assembly are not yet available

Mass:
~250 kg U per assembly

Fissionable material:
Metal fuel (Uranium with 10 wt% Zirconium alloy).
Enrichment of 10.9-15.5% U-235.
Average 13.1% U-235

Typical burnup:
77,000 MW day/tonne U

Cladding material:
Fuel pins are clad in HT-9 (heat-treated martensitic steel)

Construction:

- Details on the loading of the fuel pins into the fuel assembly are not currently available.

Comments:

- ARC-100 metallic fuel is based on the prototypical operations at EBR-II at Argonne National Laboratory.

[5] M. Manley, P. Thompson, B. Pilkington, 2023. Fuel Cycle for ARC-100 Commercial Demonstration at the Point Lepreau Nuclear Site in New Brunswick. Available from: https://www.arc-cleantech.com/technology (accessed November 2023)