Nuclear Fuel Waste Projections in Canada – 2022 Update

NWMO-TR-2022-17 **November 2022**

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ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2022 Update**
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Abstract

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2022 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, 2022, a total of approximately 3.2 million used CANDU fuel bundles (about 61,130 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of about 84,193 bundles since the 2021 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 5.5 million used CANDU fuel bundles (approximately 106,100 t-HM). The projection is based on the published plans to refurbish and life extension for all Darlington and Bruce reactors, as well as continued operation of Pickering A until 2024 and Pickering B until September 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. The impacts of any future decisions on reactor refurbishment, new nuclear build or advanced fuel cycle technologies made by the nuclear utilities in Canada on projected inventory of nuclear fuel waste will be incorporated into future updates of this report.

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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 (Gobien and Ion 2021). This document provides an update as of June 2022.

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 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 2022).

1.2 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2022 and forecasts the potential future nuclear fuel waste from the existing reactor fleet as well as from proposed new reactors. The report focuses on power reactors, but also includes information on prototype, demonstration and research reactor fuel wastes held by Atomic Energy of Canada Limited (AECL).

1.3 CHANGES SINCE THE 2021 REPORT

The primary changes to the Canadian nuclear landscape since the 2021 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 continues with reassembly of the 480 fuel channels being completed in July 2022 (OPG 2022a). Unit 3 was shut down in July 2020, its refurbishment started in September 2020, and its refurbishment is expected to be complete in Q1 of 2024 (OPG 2021a).

c) Darlington Unit 1 was removed from operation in February 2022 to initiate refurbishment. Refurbishment of Unit 1 is expected to be completed by Q2 of 2025 (OPG 2022b).

d) Bruce Power continues the major component replacement at Unit 6 with replacement of the eight steam generators completed in December 2021 (Bruce Power 2021). Unit 6 refurbishment was initiated in January 2020 and is expected to be complete in Q4 of 2023.

e) Pickering B Units 5-8 will operate until September 2026, extended from the end of 2025 (Ontario 2022).

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, 2021 to June 30, 2022.

	June 30, 2021	June 30, 2022	Net change	
Wet storage	1,428,645	1,418,651	-9,994	bundles*
Dry storage	1,677,763	1,771,950	94,187	bundles
TOTAL	**3,106,408**	**3,190,601**	**84,193**	**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 changes to the overall projected future total number of used fuel bundles (see Section 2.2). The forecast presented in this report is most similar to the high scenarios from the previous versions of this report.

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, 2022. 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, 2022 there are approximately 3.2 million bundles in wet or dry storage. This is equivalent to approximately 61,130 tonnes of heavy metal (t-HM). Further details on the existing reactors can be found in Appendix A and fuel types in Appendix B.

Table 1: Summary of Nuclear Fuel Waste in Canada as of June 30, 2022

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)	Current Status
Bruce A	OPG[(1)]	338,982	270,720	**609,702**	- 4 units operational
Bruce B	OPG[(1)]	341,618	449,654	**791,272**	- 3 units operational, - 1 unit undergoing refurbishment.
Darlington	OPG	313,530	315,173	**628,703**	- 2 units operational, - 2 units undergoing refurbishment.
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	385,045	443,524	**828,569**	- 2 units operational, 2 units non-operational since 1997 (permanently shut down 2005)
Pickering B	OPG				- 4 units operational
Point Lepreau	NBPN	39,476	126,898	**166,374**	- operational
Whiteshell	AECL	0	2,301	**2,301**	- permanently shut down 1985; see Note (2).
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 (3)
	Total	**1,418,651**	**1,771,950**	**3,190,601**	

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) This value includes UO_2 and uranium carbide bundles from the WR-1 reactor, 360 natural UO_2 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.
3) 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 deep geological repository and have therefore been excluded at this time.

Figure 1 summarizes the history of wet and dry storage of used fuel in Canada to the end of June 2022. 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.

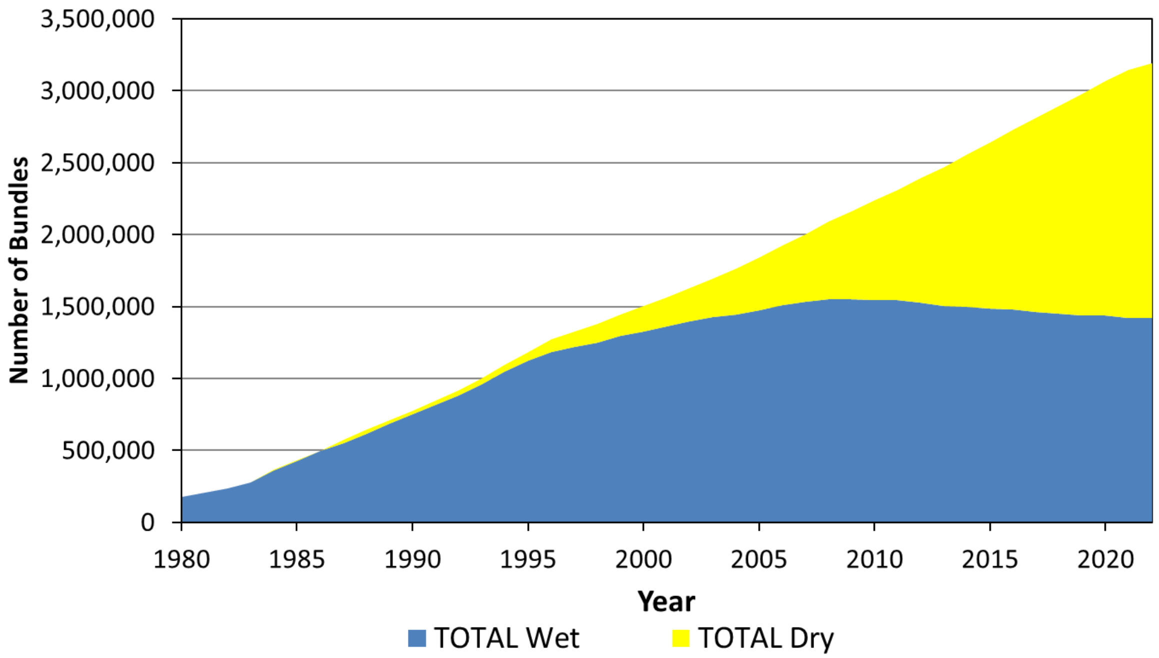


Figure 1: Summary of Used Fuel Wet and Dry Storage History

2.2 PROJECTED NUCLEAR FUEL WASTE

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

This estimate is based on the latest published plans for refurbishment and life extension for the current reactor fleet, uses conservative assumptions, and includes a number of uncertainties, as described below.

The current projection in Table 2 is based on the following:

1. Only existing CANDU stations are included in the 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 Unit 2 and Point Lepreau) and reactors that will be refurbished (Darlington Units 1, 3 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 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 2022 actuals) + (number of years from June 2022 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 9,500 bundles/year. Projected over the next 30 years, and applying the 5-year average on a station by station basis, this could indicate the current total is high by up to 200,000 bundles.

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

    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.

[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.

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.

7. Current projection does not include new reactors, such as small modular reactors (SMRs).

In summary, the approximate 5.5 million used fuel bundles forecast represents the best estimate based on current plans. Its associated uncertainty could include +/- 0.28 million bundles (based on 3-year early or delayed shutdown of all current units), up to -0.2 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.

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

Location	Unit	Startup	Total to June 2022 (# bundles)	Typical Annual Production (bundles/a)	Refurbishment Schedule (Start-End)(8)	Forecast(6)	
						Shutdown(9)	(# bundles)
Bruce A	1	1977	609,702	20,500(2)	Complete	2043	1,230,000
	2	1977			Complete	2043	
	3	1978			01/2023 – 06/2026	2061	
	4	1979			01/2025 – 12/2027	2062	
Bruce B	5	1985	791,272	23,500(2)	07/2026 – 06/2029	2062	1,687,000
	6	1984			01/2020 – 12/2023	2058	
	7	1986			07/2028 – 06/2031	2063	
	8	1987			07/2030 – 06/2033	2063	
Darlington	1	1992	628,703	22,000(2)	01/2022 – 06/2025	2053	1,279,000
	2	1990			Complete	2049	
	3	1993			09/2020 – 03/2024	2052	
	4	1993			07/2023 – 12/2026	2055	
Douglas Point	-	1968	22,256	0(3)	-	1984	22,256
Gentilly 1	-	1972	3,213	0(3)	-	1977	3,213
Gentilly 2	-	1983	129,925	0(3)	-	2012	129,925
Pickering A	1	1971	828,569	7,200(4)	Complete	2024	936,000
	2	1971			-	2005	
	3	1972			-	2005	
	4	1973			Complete	2024	
Pickering B	5	1983		14,500(2)	-	2026	
	6	1984			-	2026	
	7	1985			-	2026	
	8	1986			-	2026	
Point Lepreau	1	1983	166,374	4,800	Complete	2040	260,000
Whiteshell	-	1965	2,301	0(3)	-	1985	2,301
Chalk River/ NPD/other	-	-	~8,286	0(5)	-	-	~8,286
Total (bundles)			**3,190,601**	**92,500**			**5,557,071(1)**
(t-HM)(7)			**61,130**	**1,770**			**106,100**

Notes:
1) This represents the best estimate based on current plans and includes conservative assumptions and uncertainties.
2) Based on 4 reactors operating.
3) Reactor is permanently shut down and not producing any more fuel.
4) Based on 2 reactors operating.
5) 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.
6) Totals may not add exactly due to rounding to nearest 1,000 bundles for future forecasts.
7) “tonnes of heavy metals” (t-HM) based on an average of bundle mass specific for each reactor type.
8) Assumes units under refurbishment do not produce fuel and annual fuel production rates are scaled accordingly.
9) Assumes units operate until December 31 of the shutdown year and the core is defueled in the following year, except for Pickering B which is assumed to operate until September 2026.

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.

These 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 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.

3.1 PROJECTS WHICH HAVE RECEIVED OR CURRENTLY UNDERGOING REGULATORY APPROVALS

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 2022c). By the end of 2022 OPG intends to begin 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 2022d).

The BWRX-300 is a light water reactor (LWR) 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 B.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 120,000 CANDU used fuel bundles.

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), Ultra Safe Nuclear Corporation (USNC), and OPG propose to construct and operate a 5 MWe (up to 15MWth) 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, Global First Power submitted to the CNSC an application to prepare site for a small modular reactor at the Chalk River Laboratories (Global First Power 2019a). In July 2019, the Federal government issued a Notice of Commencement of an environmental assessment for a SMR project at the Chalk River Laboratories (CNSC 2019). The regulatory review of this project continues; in September 2020, the CNSC has released the record of decision on the scope of the environmental assessment for Global First Power’s MMR (CNSC 2020). On May 6, 2021, the CNSC determined that GFP’s submissions to date were sufficient to begin technical review as a part of the licensing application process (Global First Power 2021).

The MMR is a high temperature gas-cooled reactor (HTGR) with an anticipated operational life of 20 years and a design approach with one single fuel loading at reactor start-up (Global First Power 2019b). At this stage there is limited information about the MMR fuel and its fuel waste characteristics. The fuel contains low-enriched uranium and is manufactured with Triple Coated Isotopic (TRISO) fuel particles. 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 over the reactor’s expected 20-year lifetime, it could result in an amount of used fuel that was equivalent to about 700 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.

3.2 POTENTIAL PROJECTS AND DEVELOPMENTS

Earlier feasibility studies and public discussions by provincial governments and potential proponents have been conducted for other new reactors in Ontario, Alberta, Saskatchewan and New Brunswick over several years. Other proposals include the introduction of SMRs of up to a few tens or hundreds of megawatts each for deployment in large established grids, small grids, in remote (i.e. off-grid) communities and resource extraction sites which currently rely on small-scale fossil fuel generating plants to provide heat and/or electricity (AECL 2012, HATCH 2016, SaskPower et al. 2021). The reactors are based on a variety of non-CANDU technologies, including liquid metal cooled, gas cooled, molten salt cooled and light water cooled.

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 November 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 December 2020 (NRCan 2020).

The CNSC continues pre-licensing reviews for a variety of small modular reactor designs (CNSC 2022).

A number of utilities have continued to express interest in supporting the development of SMR technologies. For example, Global First Power, USNC and OPG formed a joint venture to own and operate a Micro Modular Reactor Project at Chalk River (Global First Power 2020); Cameco and Bruce Power launched a centre for the next generation of nuclear technologies (Bruce Power 2020); and Cameco, GE Hitachi and Global Nuclear Fuel-Americas (GNF-A) have recently announced a memorandum of understanding (MoU) to explore collaboration to advance commercialization and deployment of BWRX-300 SMRs in Canada (World Nuclear News 2021). OPG has also announced plans to advance the development of an SMR in Ontario and advance engineering and design work with three developers of grid-scale SMRs: GEH, Terrestrial Energy and X-energy (OPG 2020). At the same time, GEH has entered into memorandums of understanding (MOUs) with five Canadian companies to set up a supply chain for its SMR (World Nuclear News 2020).

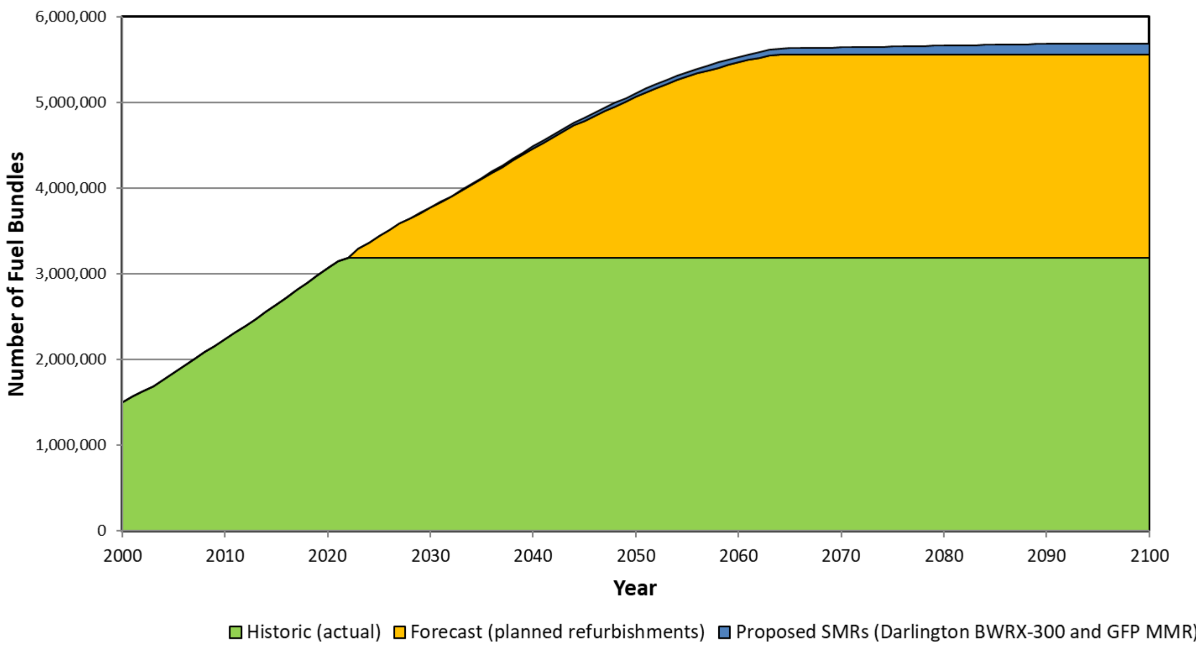
CNL looks to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada, and recently issued a call for proposals for the second round of its Canadian Nuclear Research Initiative program (CNL 2020b). At present, four proponents are in various stages of CNL's review (CNL 2022). Global First Power is in stage 3 for the proposed 5 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 2020c), Ultra Safe Nuclear Corporation (CNL 2020d), New Brunswick Power (CNL 2020e), and Terrestrial Energy (CNL 2020f), to research SMR fuels and advance SMR technology in Canada and has recently started fabrication of advanced SMR fuels (CNL 2021).

The NWMO will continue to monitor these developments and the implications of new reactors as part of its Adaptive Phased Management approach.

4. SUMMARY OF PROJECTED USED FUEL INVENTORY

As of June 30, 2022 there are approximately 3.2 million used fuel bundles in wet or dry storage. Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the current forecast projects a total of approximately 5.5 million bundles (see Section 2.2 for details). The existing and projected inventory from current reactor operations, reactor refurbishment and proposed SMRs, developed in previous sections, is summarized in Figure 2.

The approximately 5.5 million used fuel bundles forecast represents the best estimate based on current plans. Its associated uncertainty could include +/- 0.28 million bundles (based on 3-year early or delayed shutdown of all current units), up to -0.2 million bundles (based on conservatism in projection), -0.05 million bundles (for mid-year end-of-life shutdown vs assumed end-of-year shutdown), and approximately +0.12 million equivalent CANDU used fuel bundles from the proposed Darlington BWRX-300 and Chalk River GFP MMR projects.



Notes:
1) The existing fuel (as of end of June 2022) is shown in the green shaded area.
2) The forecast (orange 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 proposed SMRs (blue shaded area) shows the estimated additional CANDU equivalent fuel bundles that could be generated from the Darlington BWRX-300 and Chalk River GFP MMR projects currently undergoing regulatory approvals.

Figure 2: Summary of Projected Used Fuel Inventory

Note that in addition to the CANDU fuel bundles described above, there are small quantities of other nuclear fuel waste, such as the AECL research fuels, pellets and elements, as well as used fuels from other Canadian research reactors (as listed in the Appendix A, Table A3). AECL have performed a mass-based estimate of the number of CANDU bundle equivalents for the majority of these fuels that are included in this inventory. The remaining inventory items will be assessed with respect to their suitability for disposal in the APM deep geological repository and have therefore been excluded at this time.

There are also other heat-generating radioactive wastes in Canada (such as cobalt-60 sources produced in Canadian CANDU reactors and used in industrial and therapeutic radiation devices), again in relatively small quantities (on the order of 1,000 to 2,000 fuel bundle equivalents, i.e. less than 0.1% of the projected used fuel inventory). These non-fuel, heat generating wastes are not within the NWMO’s legislated mandate for long-term management of nuclear fuel waste.

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APPENDIX A: SUMMARY OF EXISTING CANADIAN REACTORS & FUEL STORAGE

Appendix A presents a summary of commercial, demonstration and research reactors in Canada. Table A1 presents a summary of commercial power reactors in Canada and their status. Table A2 presents a summary of prototype and demonstration reactors in Canada and their status. Table A3 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 A4 presents a summary of dry storage facilities for used nuclear fuel and Figure A1 shows the location of the major storage locations in Canada.

Table A1: Nuclear Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type*	Current Status (2022)
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		Operating
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		Undergoing refurbishment
Darlington 4	881	1993		Operating
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 A2: Prototype and Demonstration Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type	Current Status (2022)
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 A3: 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. As of June 2022, 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; All 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 SLOWPOKE fuel pins	SLOWPOKE-2 reactor; Operating.
Montreal, Quebec				
Ecole polytechnique	0.02	1976	UO_2 SLOWPOKE 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 A4: 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

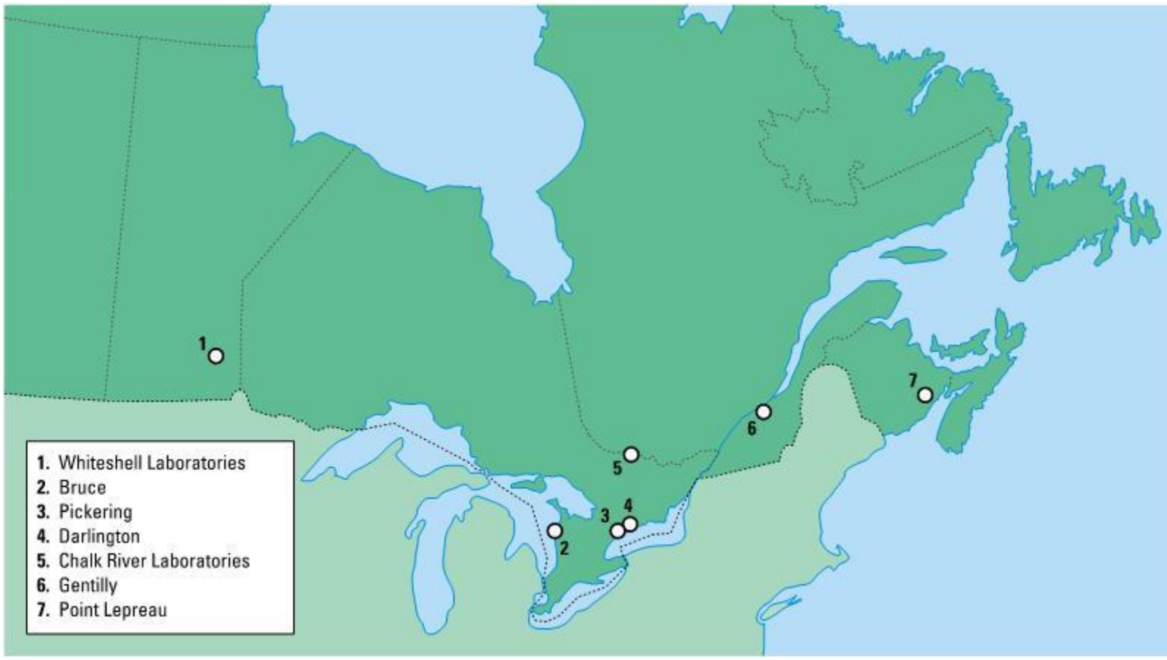


Figure A1: Current Nuclear Fuel Waste Major Storage Location in Canada

APPENDIX B: DESCRIPTION OF FUEL TYPES

Table B1 summarizes the inventory of the various bundles types in Canada as of June 2022.

Section B.1 details the physical characteristics and usage of the bundles in operating reactors.

Section B.2 details the physical characteristics and usage of the bundles in demonstration and prototype reactors.

Section B.3 details the physical characteristics and usage of the bundles in proposed BWRX-300 SMR.

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

Table B1: Summary of Inventory by Bundle Type (June 2022)

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	385,045	443,524	828,569
37R	Bruce, Darlington, Gentilly 2, Pt Lepreau	472,589	1,154,219	1,626,808
37R Long	Bruce, Darlington	104,719	138,151	242,870
37M	Bruce, Darlington	346,099	-	346,099
37M Long	Bruce, Darlington	110,175	-	110,175
43 Element LVRF	Bruce	24	-	24
Other	AECL (various)	-	5,397	5,397
	Total	**1,418,651**	**1,771,950**	**3,190,601**

B.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:

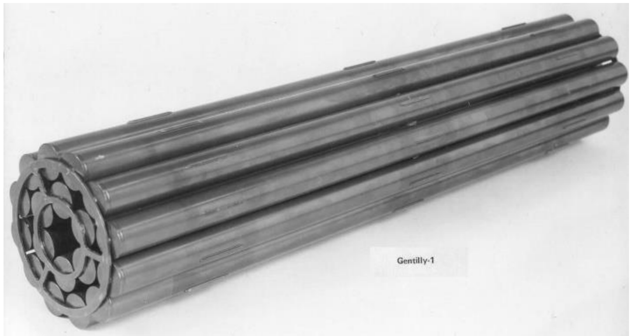
- Bundle is composed of 43 elements (fuel pins), arranged in 4 concentric rings with 1 element in the inner most central ring, 7 elements in the second ring, 14 elements in the third ring and 21 elements in the outer ring.
- The inner central element uses Dysprosium (an element that absorbs neutrons 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:

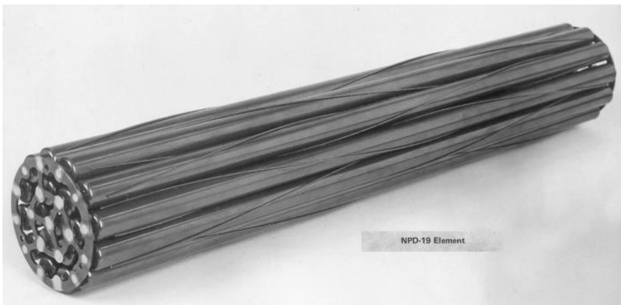
- Has been used in Bruce B reactors in limited quantities, option for use in EC-6 reactors

B.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 exists 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

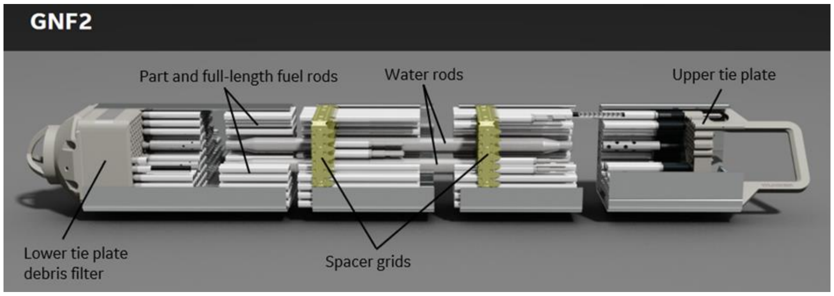
Typical burnup:
6474 MW day / tonne U at NPD
7885 MW day / tonne U at Douglas Point
(156 MWh/kg U at NPD)
(190 MWh/kg U at Douglas Point)

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

B.3 FUEL FROM PROPOSED GEH BWRX-300 REACTOR.

<table>
<tr><th colspan="2">GEH BWRX-300 fuel assembly</th></tr>
<tr><td rowspan="5">
</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><td colspan="2">Construction:
- Global Nuclear Fuel GNF2 fuel design; basically 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>