Nuclear Fuel Waste Projections in Canada – 2020 Update

NWMO-TR-2020-06 October 2020

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Nuclear Waste Management Organization

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ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2020 Update**
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Abstract

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2020 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, 2020, a total of approximately 3.0 million used CANDU fuel bundles (about 58,200 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of about 90,250 bundles since the 2019 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 106,500 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 2025.

Used fuel produced by potential new-build reactors will depend on the size and type of reactor and number of units deployed. New-build plans are at various stages of development and the decisions about whether to proceed with individual projects, reactor technology and number of units have not yet been made.

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.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

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 (Gobien and Ion 2019). This document provides an update as of June 2020.

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 2019).

1.2 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2020 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 2019 REPORT

The primary changes to the Canadian nuclear landscape since the 2019 report are:

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

b) The plan to safely extend the life of the Pickering A Units 1 and 4 to 2024 and Pickering B Units 5 to 8 to 2025 (Ontario 2020).

c) Darlington Unit 2 returned to service in June 2020 (OPG 2020a). Darlington Unit 3 was shut down in July 2020, and its refurbishment started in September 2020, with a slight delay due in response to COVID-19 (OPG 2020b).

d) Bruce Power initiated the major component replacement at Unit 6 in January 2020. (Bruce Power 2020a). In August 2020, Bruce Power and Cameco launched the Centre for Next Generation Nuclear Technologies and support innovation and isotope production (Bruce Power 2020b).

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, 2019 to June 30, 2020.

	June 30, 2019	June 30, 2020	Net change	
Wet storage	1,448,284	1,444,092	-4,192	bundles*
Dry storage	1,486,638	1,581,081	94,443	bundles
TOTAL	**2,934,922**	**3,025,173**	**90,251**	**bundles**

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

b) A small increase in the overall projected future total number of used fuel bundles produced by the existing reactors to align with the current refurbishment and operational plans (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, 2020. 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) or non-CANDU-like research fuels.

As of June 30, 2020 there are approximately 3.0 million bundles in wet or dry storage. This is equivalent to approximately 58,200 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, 2020

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)	Current Status
Bruce A	OPG[1]	343,579	227,712	571,291	- 4 units operational
Bruce B	OPG[1]	349,396	406,646	756,042	- 3 units operational, 1 unit undergoing refurbishment. See Note (2).
Darlington	OPG	313,853	271,015	584,868	- 3 units operational, 1 unit undergoing refurbishment. See Note (2).
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	3,865	126,060	129,925	- permanently shut down 2012
Pickering A	OPG	396,935	395,494	792,429	- 2 units operational, 2 units non-operational since 1997 (permanently shut down 2005)
Pickering B	OPG				- 4 units operational
Point Lepreau	NBPN	36,464	121,498	157,962	- operational
Whiteshell	AECL	0	2,301	2,301	- permanently shut down 1985. See Note (3).
Chalk River	AECL	0	4,886	4,886	- mostly fuel from NPD (permanently shut down 1987) with small amounts from other Canadian reactors and research activities
		Note (4)	Note (4)	Note (4)	- currently under assessment
	Total	**1,444,092**	**1,581,081**	**3,025,173**	

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 B and Darlington are currently undergoing refurbishment, unit-by-unit. The Bruce B first unit (Unit 6) was shut down in Jan 2020 and refurbishment is expected to be complete in Dec 2023. The Darlington first unit (Unit 2) refurbishment was completed in Jun 2020, and the refurbishment of its second unit (Unit 3) started in Sep 2020.
3) 360 bundles of Whiteshell fuel are standard CANDU bundles (from the Douglas Point reactor). The remaining bundles are various research, prototype and test fuel bundles, similar in size and shape to standard CANDU bundles, mainly from the research/prototype WR-1 reactor.
4) AECL also owns some components of research and development fuels such as fuel elements, fuel pellets and fuel debris in storage at Chalk River. While the total mass of these components is small compared to the overall quantity of CANDU fuel, their varied composition, storage form, dimensions, etc. requires special consideration for future handling. There are also small quantities (a few kg) of non-CANDU research reactor fuel.

Figure 1 summarizes the history of wet and dry storage of used fuel in Canada to the end of June 2020. 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.

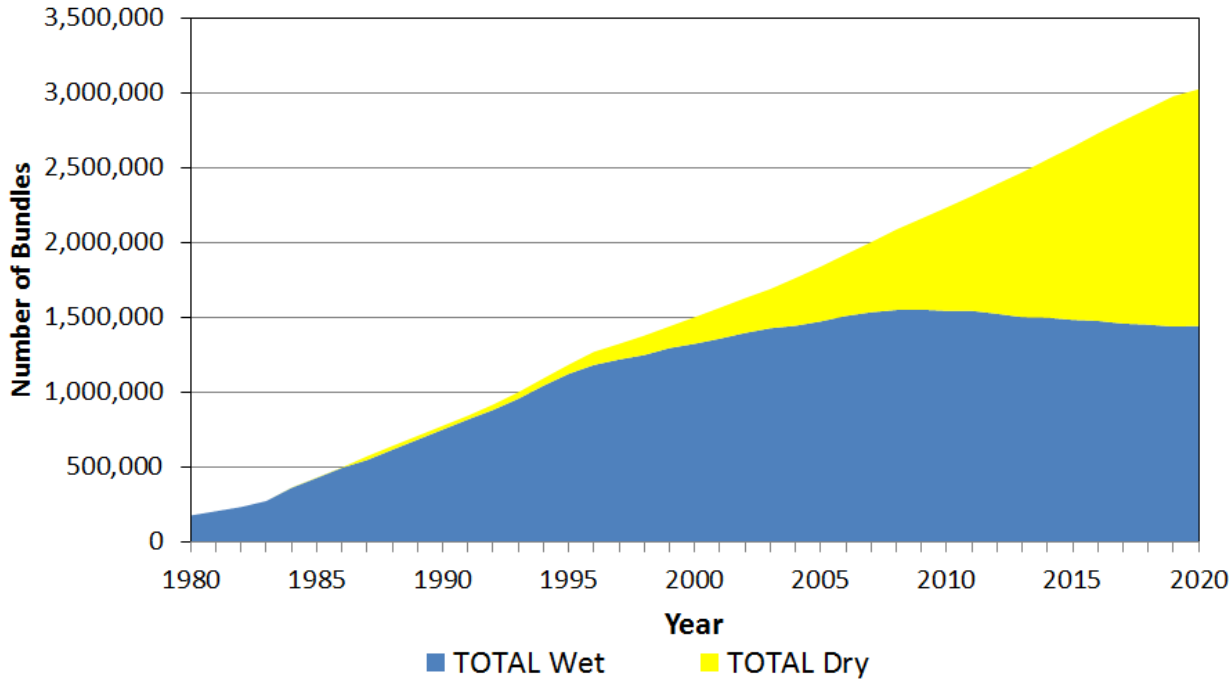


Figure 1: Summary of Used Fuel Wet and Dry Storage History

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. All reactors in the existing fleet are assumed to be refurbished, except those already shut down or where there is a firm decision not to refurbish, and will be operated in accordance with current plans (Ontario 2020, OPG 2020c, 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 where a definite decision has been made not to refurbish will operate to the end of their current announced service life only (i.e., Pickering A Units 1 and 4 will run until 2024 and Pickering B Units 5–8 will run until 2025).
   - Reactors that have been refurbished (Bruce A Units 1 and 2 and Point Lepreau) and reactors that will be refurbished (Darlington, 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).

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 2020 actuals) + (number of years from June 2020 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 was high by about +6,200 to +8,000 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 about 100,000-160,000 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.

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).

   Assuming 1,000 MWe of new reactors operating for 30 years, could result in an additional 100,000-200,000 equivalent CANDU bundles, based on a simple correlation of electric power to CANDU bundles on a thermal power basis.

In summary, the approximate 5.5 million 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), -0.10 to -0.16 million bundles (based on conservatism in projection), +0.1 to +0.2 million equivalent CANDU bundles (for a modest operation of new reactors), and about -0.05 million bundles (for mid-year end-of-life shutdown vs assumed end-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 2020 (# bundles)	Typical Annual Production (bundles/a)	Refurbishment Schedule (Start-End)[8]	Forecast[6] Shutdown[9]	Forecast[6] (# bundles)
Bruce A	1	1977	571,291	20,500[2]	Complete	2043	1,233,000
	2	1977			Complete	2043	
	3	1978			01/2023 – 06/2026	2061	
	4	1979			01/2025 – 12/2027	2062	
Bruce B	5	1985	756,042	23,500[2]	07/2026 – 06/2029	2062	1,693,000
	6	1984			01/2020 – 12/2023	2058	
	7	1986			07/2028 – 06/2031	2063	
	8	1987			07/2030 – 06/2033	2063	
Darlington	1	1992	584,868	22,000[2]	01/2022 – 06/2025	2053	1,271,000
	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	792,429	7,200[4]	Complete	2024	932,000
	2	1971			-	2005	
	3	1972			-	2005	
	4	1973			Complete	2024	
Pickering B	5	1983		14,500[2]	-	2025	
	6	1984			-	2025	
	7	1985			-	2025	
	8	1986			-	2025	
Point Lepreau	1	1983	157,962	4,800	Complete	2040	261,000
Whiteshell	-	1965	2,301	0[3]	-	1985	2,301
Chalk River/ NPD/other	-	-	4,886	0[5]	-	-	4,886
Total (bundles)			**3,025,173**	**92,500**			**5,553,000 (See Note 1)**
(t-HM)[7]			**58,210**	**1,780**			**106,500**

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.

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 the projects rests entirely with the proponent.

3.1 PROJECTS WHICH HAVE RECEIVED OR CURRENTLY UNDERGOING REGULATORY APPROVALS

3.1.1 Ontario Power Generation

OPG currently holds a 10-year 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. In June 2020, OPG has submitted an application to renew the licence for a new 10-year term, to maintain the option for future nuclear generating capacity at the site (OPG 2020d).

To date, OPG has not selected a reactor technology for the new build at Darlington. In its original application (OPG 2007, 2009), OPG considered four “Generation III+” reactor types, designed to operate for 60 years:

a) ***CANDU ACR 1000 (Advanced CANDU reactor)***, a 1085 MW(e) net heavy water moderated, light water cooled pressure tube reactor. Four ACR 1000 reactors would result in a total production of approximately 770,400 used fuel bundles (12,480 t-HM) over 60 years.

b) ***CANDU EC-6 (Enhanced CANDU 600 reactor)***, a 686 MW(e) net heavy water reactor, similar to the existing CANDU 600 reactors at Gentilly-2 and Point Lepreau. Four EC-6 reactors would result in a total production of approximately 1,572,000 used fuel bundles (30,000 t-HM) over 60 years.

c) ***Westinghouse AP1000***, a 1037 MW(e) net pressurized light water reactor (PWR). Four AP1000 reactors result in a total production of approximately 10,800 PWR fuel assemblies (5,820 t-HM) over 60 years.

d) ***AREVA EPR (Evolutionary Power Reactor)***, a 1580 MW(e) net PWR. Three EPR reactors would result in a total production of approximately 9,900 PWR fuel assemblies (5,220 t-HM) over 60 years.

The EC-6 uses standard CANDU fuel, with options for advanced fuel types (SEU, MOX, etc.). The other three reactor types operate with enriched uranium fuel. The ACR 1000 fuel is similar in size and shape to existing CANDU fuel bundles. The AP1000 and EPR fuel assemblies are considerably different from the CANDU fuels in terms of size and mass, but are very similar to conventional pressurized light water reactor fuels used in many other countries around the world. Further details on fuel types and potential inventories of fuel wastes are included in Appendix C.

The province, through its Infrastructure Ontario program, would select the preferred vendor. The selection process is currently suspended, however, the Ontario Government has stated that new nuclear remains an option for the future (Ontario 2017).

3.1.2 Global First Power

Global First Power, Ultra Safe Nuclear Corporation, and OPG propose to construct and operate a 5 MWe “Micro Modular Reactor” (MMR) plant on Atomic Energy of Canada Limited’s property at the Chalk River Laboratories.

In December 2018, the CNSC completed Phase 1 of the pre-licensing review of the MMR (CNSC 2019a). 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 small modular reactor project at the Chalk River Laboratories (CNSC 2019b). 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 2020a).

At this stage there is limited information about the MMR fuel and its fuel waste characteristics. The MMR has a 30 year operation life (Global First Power 2019b) and quantities of potential fuel wastes are unknown at this time. The MMR fuel is substantially different than CANDU fuel. The fuel contains low-enriched uranium and is manufactured with Triple Coated Isotopic (TRISO) fuel particles.

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

Feasibility studies and public discussions by provincial governments and potential proponents have been previously conducted for other new reactors in Ontario (Bruce Power 2008a, 2008b, 2009a), Alberta (Bruce Power 2009b), Saskatchewan (Saskatchewan 2011) and New Brunswick (MZConsulting 2008).

Other proposals include the introduction of SMRs of up to a few tens or hundreds of megawatts each 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). The reactors are based on a variety of non-CANDU technologies, including liquid metal 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 Roadmap report was published in November 2018, containing more than 50 recommendations in areas such as waste management, regulatory readiness and international engagement (SMR 2018). The Government of Canada will launch Canada’s SMR Action Plan in November 2020 (NRCan 2020).

The CNSC is currently undergoing a number of pre-licensing reviews for a variety of small modular reactor designs (CNSC 2020b).

Canadian Nuclear Laboratories (CNL) is looking to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada (CNL 2017). At present, four proponents are in various stages of CNL's review (CNL 2019). Global First Power has started 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 2020a), Ultra Safe Nuclear Corporation (CNL 2020b), New Brunswick Power (CNL 2020c), and Terrestrial Energy (CNL 2020d), to research SMR fuels and advance SMR technology in Canada.

Some utilities have continued to express interest in supporting the development of SMR technologies; for example, Global First Power, USNC and OPG formed joint venture to own, operate Micro Modular Reactor Project at Chalk River (Global First Power 2020) and Cameco and Bruce Power have launched a centre for the next generation of nuclear technologies (Bruce Power 2020b). OPG has recently announced the plan to advance the development of an SMR in Ontario and advance engineering and design work with three developers of grid-scale SMRs: GE Hitachi (GEH), Terrestrial Energy and X-energy (OPG 2020e). At the same time, GEH has entered into MoUs with five Canadian companies to set up a supply chain for its SMR (World Nuclear News 2020).

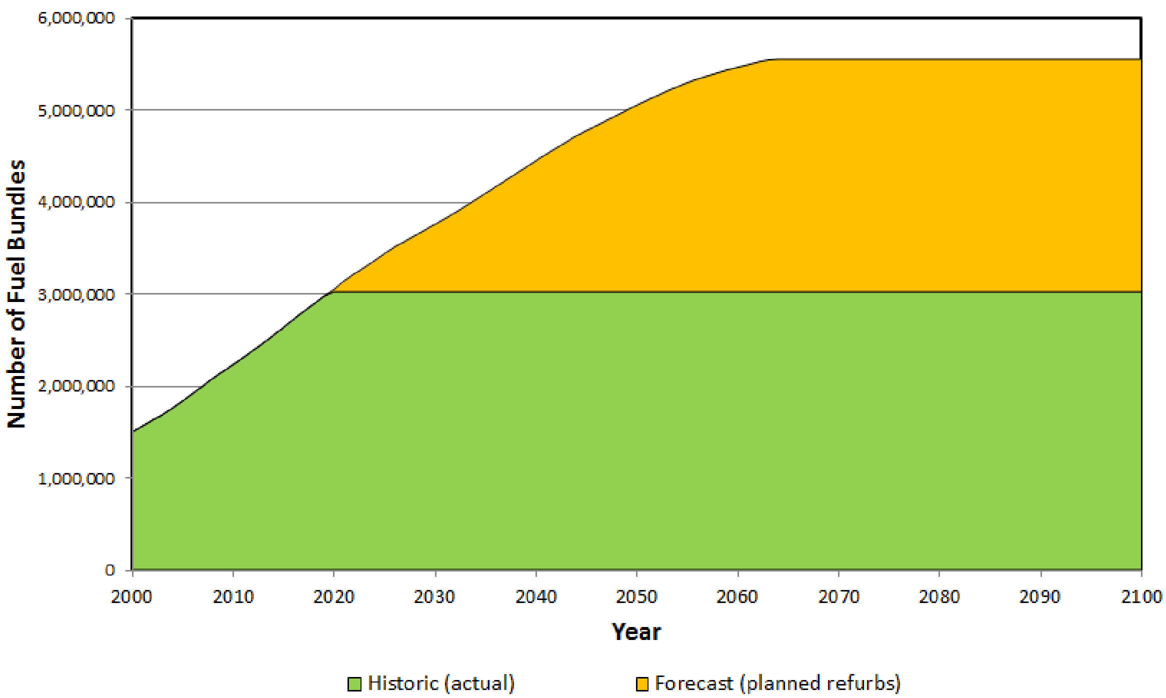
The NWMO will continue to monitor these developments and the implications of new reactors as part of its Adaptive Phased Management approach.

4. SUMMARY OF PROJECTED USED FUEL INVENTORY

As of June 30, 2020 there are approximately 3.0 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 about 5.5 million bundles (see Section 2.2 for details). The existing and projected inventory from current reactor operations, reactor refurbishment, developed in previous sections, is summarized in Figure 2.

No definitive decisions on new nuclear build have been made by the utilities in Canada, so they are not included in the current reference forecast.

The 5.5 million bundle forecast is a 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), -0.15 to -0.21 million bundles (based on conservatism in projection), +0.1 to +0.2 million equivalent CANDU bundles (for a modest operation of new SMRs), or about +1.6 million bundle-equivalents for 3-4 new large reactors at the Darlington site.



Notes:
1) The existing fuel (as of end of June 2020) 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

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 mentioned in the footnotes to Table 1, as well as used fuels from other Canadian research reactors (as listed in the Appendix A, Table A3), which are included within the NWMO's mandate for implementing the APM program, if requested by the waste owner. Some of these non-CANDU reactor fuels have been or will be returned to the country of origin, e.g. USA or France, under the terms of the original supply agreements or international agreements governing their usage.

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 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 (2020)
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	Operating
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 (2020)
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, UO_2, U_3Si-Al)	Permanently shut down on March 31, 2018. As of Jun 2020, half NRU fuel has been transferred to dry storage, with the remainder in wet storage pending transfer.
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; U-metal 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.
Edmonton, Alberta				
University of Alberta	0.02	1977	U-Al SLOWPOKE fuel pins	SLOWPOKE-2 reactor. Permanently shut down in 2017. Fuel was repatriated to US.
Saskatoon, Saskatchewan				
Saskatchewan Research Council	0.02	1981	U-Al SLOWPOKE fuel pins	SLOWPOKE-2 reactor. Permanently shut down in 2019. Fuel was repatriated to US.

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 and Nordion Kanata. 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 (e.g. US).

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

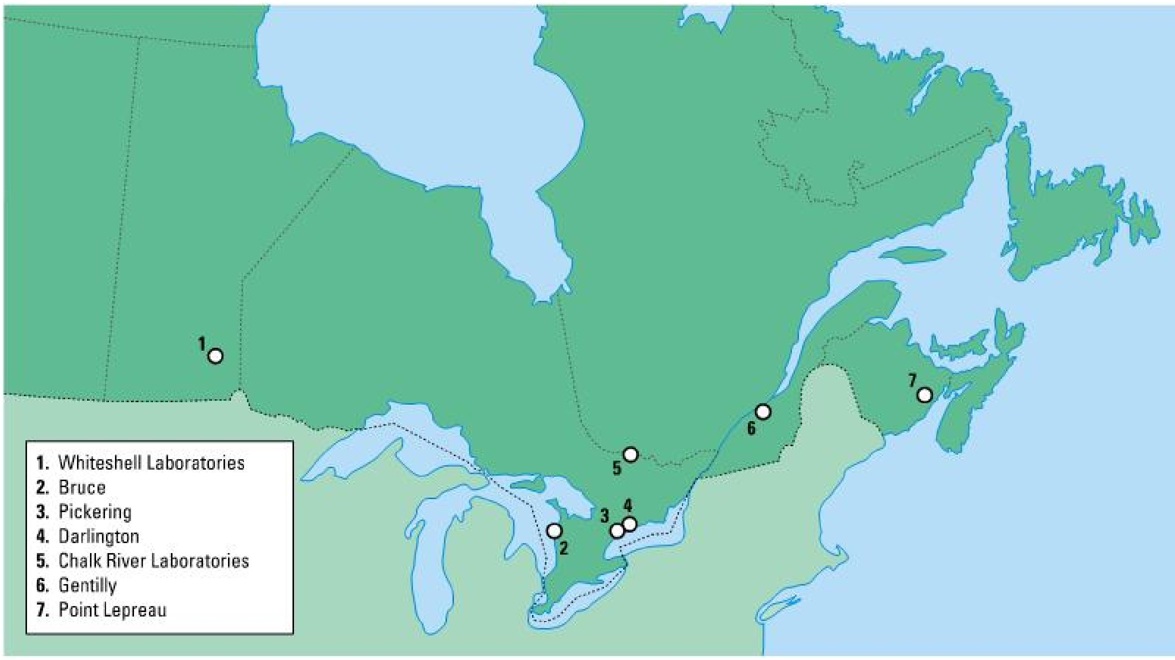


Figure A1: Current Nuclear Fuel Waste Major Storage Location in Canada

APPENDIX B: DESCRIPTION OF FUEL TYPES

Table B1 summarizes the inventory of the various bundles types in Canada as of June 2020.

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. 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 2020)

CANDU Bundle Type	Where Used	Wet Storage (# bundles)	Dry Storage (# bundles)	Total (# bundles)
18 Element	Gentilly 1, Whiteshell	-	4,417	4,417
7 Element / 19 Element	NPD, Douglas Point	-	26,296	26,296
28 Element	Pickering	396,935	395,494	792,429
37R	Bruce, Darlington, Gentilly 2, Pt Lepreau	574,468	1,050,430	1,624,898
37R Long	Bruce, Darlington	133,802	102,501	236,303
37M	Bruce, Darlington	254,124	-	254,124
37M Long	Bruce, Darlington	84,739	-	84,739
43 Element LVRF	Bruce	24	-	24
Other	AECL (various)	-	1,943	1,943
	Total	**1,444,092**	**1,581,081**	**3,025,173**

B.1 FUELS FROM OPERATING REACTORS

28 element CANDU bundle

Physical dimensions:
102.5 mm OD x 497.1 mm OL

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

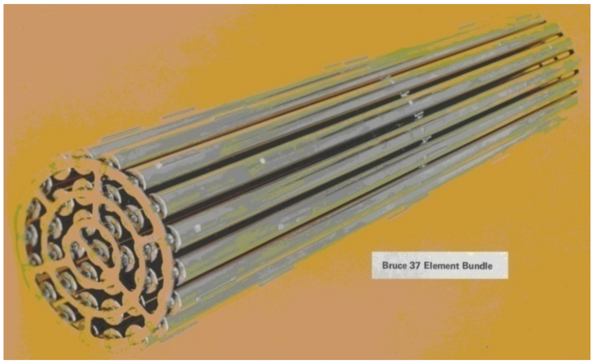
Fissionable material:
Sintered pellets of natural UO_2

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

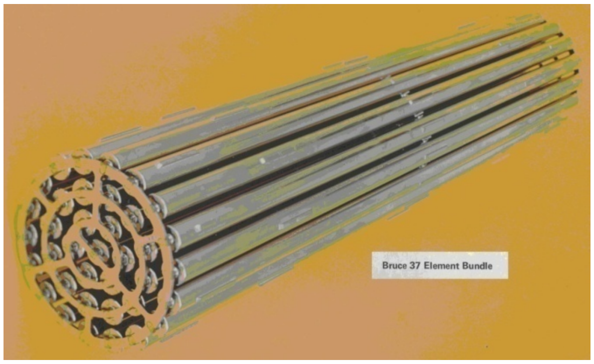
Cladding material:
Zircaloy-4

Construction:
- Bundle is composed of 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.

Comments:
- Used in Pickering A and B reactors

<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.

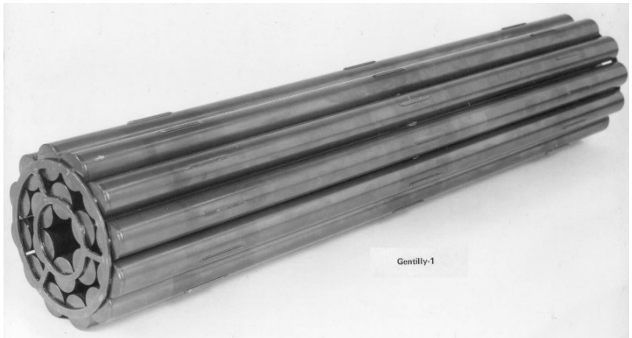
Comments:

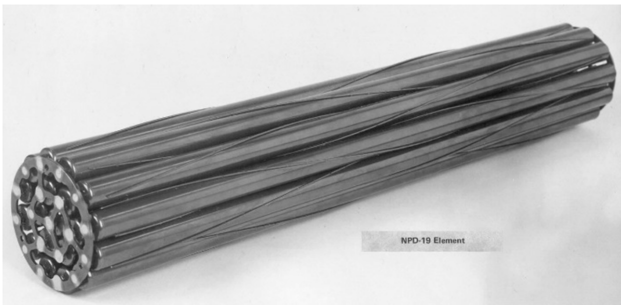
- Similar to 37 element "standard" bundle, but is 13 mm longer.
- Used in Bruce B, and Darlington reactors.
- Two variants, designated 37R-long and 37M-long, have slightly different center pin configurations and uranium masses (19.7 kg U for 37R-long vs 19.6 kg U for 37M-long). 37M-long is presently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

<table>
<tr><th colspan="2">43 element CANFLEX LVRF bundle</th></tr>
<tr><td rowspan="5"></td><td>Physical dimensions:
102.5 mm OD x 495.3 mm OL</td></tr>
<tr><td>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</td></tr>
<tr><td>Fissionable material:
Sintered pellets of UO_2
slightly enriched to 1.0% U-235</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 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 varies by ring.
- Construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity.</td></tr>
<tr><td colspan="2">Comments:
- Has been used in Bruce B reactors in limited quantities, option for use in EC-6 reactors</td></tr>
</table>

B.2 FUELS FROM DEMONSTRATION AND PROTOTYPE REACTORS

7 element CANDU bundle	
	**Physical dimensions:** 82.0 mm OD x 495.3 mm OL
	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
	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
	Typical burnup: 6474 MW day / tonne U (156 MWh/kg U)
	Cladding material: Zircaloy-2 Nickel-free Zircaloy-2 Zircaloy-4
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	
Comments: - Used in NPD	

<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>

<table>
<tr><th colspan="2">19 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:
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</td></tr>
<tr><td>Fissionable material:
Sintered pellets of natural UO_2
Some low-enriched 19 element bundles exists at up to 1.4% wt ^{235}U enrichment</td></tr>
<tr><td>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)</td></tr>
<tr><td>Cladding material:
Zircaloy-4</td></tr>
<tr><td colspan="2">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</td></tr>
<tr><td colspan="2">Comments:
- Used in NPD and Douglas Point</td></tr>
</table>

APPENDIX C: POTENTIAL NEW BUILD FUEL CHARACTERISTICS AND QUANTITIES

Table C1 presents a summary of the major characteristics and quantities of nuclear fuels that are used in the new reactors that have been proposed in various projects. The data have been extracted from references (Bruce Power 2008a, 2008b; IAEA 2004; JRP 2011).

Table C2 summarizes the total quantity of used fuel that might be produced for the proposed new-build reactors at Darlington. As mentioned in Section 3.1.1, until decisions on reactor types, number of units and operating conditions are taken by the proponents, these forecasts remain highly speculative.

The total additional quantity of used fuel from the Darlington New Nuclear Project could be up to 1.6 million CANDU fuel bundles (30,000 t-HM), or 10,800 PWR fuel assemblies, depending on the selected reactor type.

Section C.1 details the physical characteristics and usage of the bundles in potential new-build reactors. Note that other sources may quote different numbers for fuel properties and used fuel production rates. This is generally due to the preliminary nature of some of the designs combined with the various ways some of the reactors can be operated (e.g. enrichment level and burnup, assumed capacity factors, length of operating period between re-fuelling outages for light water reactors, conservative assumptions used for environmental assessment purposes). The quantities and characteristics used for forecasting in this report will be updated as reactor types are selected and their designs are further defined.

Table C1: Summary of Fuel Types for Proposed New Reactors

Parameter	ACR 1000	EC-6	AP1000	EPR
Reactor Type	Horizontal pressure tube, heavy water moderated, light water cooled	Horizontal pressure tube, heavy water moderated and cooled	Pressurized light water reactor (PWR)	Pressurized light water reactor (PWR)
Net / Gross Power [MW(e)]	1085 / 1165	686 / 745	1037 / 1117	1580 / 1770
Design Life	60 years	60 years	60 years	60 years
Fuel type	CANFLEX ACR fuel bundle	37 element CANDU bundle	Conventional 17x17 PWR fuel design	Conventional 17x17 PWR fuel design
Fueling method	On power	On power	Refueling shutdown every 12 to 24 months and replace portion of the core	Refueling shutdown every 12 to 24 months and replace portion of the core
Fuel enrichment	Up to 2.5% for equilibrium core	Natural U, with options for SEU (1.2%) and MOX	2.4-4.5% avg initial core 4.8% avg for reloads	Up to 5% for equilibrium core
Fuel dimensions	102.5 mm OD x 495.3 mm OL	102.5 mm OD x 495.3 mm OL	214 mm square x 4795 mm OL	214 mm square x 4805 mm OL
Fuel assembly U mass [kg initial U]	16.2	19.2	538.3	527.5
Fuel assembly total mass [kg]	21.5	24.0	789	780
# of fuel assemblies per core	6,240	4,560	157	241
Fuel load per core [kg initial U]	101,088	87,552	84,513	127,128
Annual used fuel production [t-HM/yr per reactor]	52	126	24	29
Annual used fuel production [number of fuel assemblies/yr per reactor]	3,210	6,550	45	55
Lifetime used fuel production [t-HM per reactor]	3,120	7,500	1,455	1,740
Lifetime used fuel production [number of fuel assemblies per reactor]	192,600	393,000	2,700	3,300

Note: Data extracted from references (Bruce Power 2008a; IAEA 2004; JRP 2011). Annual and lifetime data have been rounded.

Table C2: Summary of Potential Nuclear Fuel Waste from New Reactors at Darlington

Reactor	Darlington New Nuclear
Assumed operation	60 years
EC-6	
# of reactor units	4
Quantity of fuel (# bundles)	1,572,000
(t-HM)	30,000
AP 1000	
# of reactor units	4
Quantity of fuel (# assemblies)	10,800
(t-HM)	5,820

C.1 FUELS FROM POTENTIAL NEW-BUILD REACTORS

<table>
<tr><th colspan="2">43 element CANFLEX ACR bundle</th></tr>
<tr><td rowspan="5"></td><td>Physical dimensions:
102.5 mm OD x 495.3 mm OL</td></tr>
<tr><td>Mass:
16.2 kg U (18.4 kg as UO_2)
3.1 kg Zircaloy and other materials in cladding, spacers, etc.
21.5 kg total bundle weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of UO_2
enriched to 2.5% U-235</td></tr>
<tr><td>Typical burnup:
20,000 MW day/ tonne U</td></tr>
<tr><td>Cladding material:
Zircaloy-4</td></tr>
<tr><td colspan="2">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.
- Diameter and composition of fuel pins varies by 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 ACR-1000 reactors</td></tr>
</table>

AP1000 PWR fuel assembly

Physical dimensions:
214 mm square x 4795 mm OL

Mass:
538.3 kg U (613 kg as UO_2)
~176 kg ZIRLO and other materials in cladding, spacers, etc.
789 kg total weight

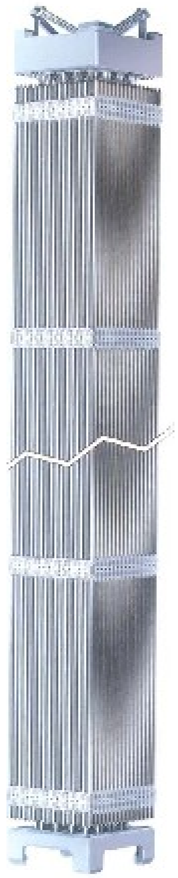
Fissionable material:
Sintered pellets of UO_2
enriched up to 5% U-235

Typical burnup:
60,000 MWday/tonne U

Cladding material:
ZIRLO

Construction:
- Each fuel assembly consists of 264 fuel rods, 24 guide thimbles, and 1 instrumentation tube arranged within a 17 x 17 matrix supporting structure. The instrumentation thimble is located in the center position and provides a channel for insertion of an in-core neutron detector, if the fuel assembly is located in an instrumented core position. The guide thimbles provide channels for insertion of either a rod cluster control assembly, a gray rod cluster assembly, a neutron source assembly, a burnable absorber assembly, or a thimble plug, depending on the position of the particular fuel assembly in the core.

Comments:
- Used in Westinghouse AP1000 reactors

<table>
<tr><th colspan="2">EPR PWR fuel assembly</th></tr>
<tr><td rowspan="5"></td><td>Physical dimensions:
214 mm square x 4805 mm OL</td></tr>
<tr><td>Mass:
527.5 kg U (598.0 kg as UO_2)
~182 kg other materials in cladding, spacers, etc.
780 kg total weight</td></tr>
<tr><td>Fissionable material:
Sintered pellets of UO_2
enriched up to 5% U-235</td></tr>
<tr><td>Typical burnup:
62,000 MWday/tonne U</td></tr>
<tr><td>Cladding material:
M5</td></tr>
<tr><td colspan="2">Construction:
- Each fuel assembly consists of 265 fuel rods and 24 guide thimbles which can either be used for control rods or for core instrumentation arranged within a 17 x 17 matrix supporting structure. The guide thimbles provide channels for insertion of either a rod cluster control assembly, a gray rod cluster assembly, a neutron source assembly, a burnable absorber assembly, a thimble plug or core instrumentation, depending on the position of the particular fuel assembly in the core.</td></tr>
<tr><td colspan="2">Comments:
- Used in Areva EPR reactors</td></tr>
</table>