Nuclear Fuel Waste Projections in Canada – 2017 Update

NWMO-TR-2017-14 December 2017

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ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2017 Update**
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Abstract
This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2017 and forecasts the potential future arisings 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, 2017, a total of approximately 2.8 million used CANDU fuel bundles (approx. 55,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 90,000 bundles from the 2016 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 ranges from about 3.5 to 5.4 million used CANDU fuel bundles (approx. 70,000 t-HM to 108,000 t-HM), depending upon future decisions to life-extend the current reactors. The lower end is based on an average of 25 effective full power years (EFPY) of operation for each reactor (i.e. no additional refurbishment beyond what has already been completed), while the upper end assumes that most reactors are refurbished and life extended for an additional 25 EFPY of operation. The upper end is based on the plans to refurbish and life-extend all Darlington and Bruce reactors.

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. If all of the units where formal licensing has already been initiated are eventually constructed (i.e. at Darlington, which was granted a site preparation licence by the Canadian Nuclear Safety Commission in 2012), the total additional quantity of used fuel from these reactors could be up to approximately 1.6 million CANDU fuel bundles (30,000 t-HM), or 10,800 PWR fuel assemblies (5,820 t-HM). This total is unchanged from the 2016 report. Assuming 4 new CANDUs, the total number of CANDU fuel bundles could be 7.0 million.

When reactor refurbishments are completed and/or decisions on future reactor refurbishment, new nuclear build or advanced fuel cycle technologies are made by the nuclear utilities in Canada, any resulting changes in forecasted 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) has a legal obligation to manage all of Canada's used nuclear fuel – that which exists now and that which will be produced in the future [Canada, 2002]. The NWMO continually monitors new developments to be prepared to assume its legal responsibility to manage used nuclear fuel.

Decisions on new nuclear reactors, advanced fuel cycles or other changes in energy choices will not be made by the NWMO. They will be taken by the utilities in conjunction with government and regulators. However, it is important that NWMO is prepared for these potential changes in technologies 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, 2015, 2016].

As energy policy decisions are taken that substantially affect the amount and/or types of used fuel that the NWMO must manage, the ongoing engagement of Canadians on the social, ethical and technical appropriateness of the long-term management plans for these materials must be provided for. The NWMO will continually review, adjust and validate implementation plans as appropriate against the changing external environment.

As part of this process, the NWMO annually publishes the current and future potential inventories of used fuel amounts and types. This document provides an update to the 2016 version [Garamszeghy, 2016].

1.2 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2016 and forecasts the potential future arisings 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 AECL.

1.3 CHANGES SINCE THE 2016 REPORT

The primary changes to the Canadian nuclear landscape since the 2016 report are:

a) The defueling and start of refurbishment of Darlington Unit 2 [Ontario, 2016];
b) The plan by Canadian Nuclear Laboratories (CNL) to partner with small modular reactor vendors to promote the development and demonstration of small modular reactors (SMRs) in Canada; and
c) An increase in the total amount of used fuel currently in storage, due to another year of reactor operation.

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, 2016 to June 30, 2017.

	June 30, 2016	June 30, 2017	Net change	
Wet storage	1,477,471	1,465,360	-12,111	bundles*
Dry storage	1,203,354	1,305,558	102,204	bundles
TOTAL	**2,680,825**	**2,770,918**	**90,093**	**bundles**

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

b) No significant change in the overall projected future total number of used fuel bundles produced by the existing reactor fleet for the low scenario (3.5 million bundles), reference scenario (5.2 million bundles) or high scenario (5.4 million bundles).

Additional considerations include

a) The indefinite postponement by the Government of Ontario to build new power reactors will affect the likelihood or timing of any used fuel from new-build reactors.

b) The possibility of introducing small modular reactors will affect the nature of the used nuclear fuel.

c) Introduction of new fuel types into the current power reactors, notably the 37M regular and long fuel bundles in the Bruce and Darlington reactors, will affect the future quantities of fuel types from existing reactors.

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, 2017. 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 (see note 3).

Assuming a rounded average of 20 kg heavy metals in a fuel bundle, 2.8 million bundles is equivalent to approximately 55,000 tonnes of heavy metal (t-HM). Further details on the existing reactors can be found in Appendix A and fuel types in Appendix C.

Table 1: Summary of Nuclear Fuel Waste in Canada as of June 30, 2017

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)	Current Status
Bruce A	OPG[2]	331,866	182,784	514,650	- 4 units operational
Bruce B	OPG[2]	352,952	329,462	682,414	- 4 units operational
Darlington	OPG	324,146	208,442	532,588	- 4 units operational. See Note (4).
Douglas Point	AECL	0	22,256	22,256	- permanently shut down 1984
Gentilly 1	AECL	0	3,213	3,213	- permanently shut down 1978
Gentilly 2	HQ	17,965	111,960	129,925	- permanently shut down 2012
Pickering A	OPG	399,703	337,114	736,817	- 2 units operational, 2 units non-operational since 1997 (permanently shut down 2005)
Pickering B	OPG				- 4 units operational
Point Lepreau	NBPN	38,728	103,138	141,866	- operational
Whiteshell	AECL	0	2,268	2,268	- permanently shut down 1985. See Note (1).
Chalk River	AECL	0	4,921	4,921	- mostly fuel from NPD (permanently shut down 1987) with small amounts from other Canadian reactors and research activities.
Chalk River	AECL	Note (3)	Note (3)	Note (3)	- currently under assessment
	TOTAL	***1,465,360***	***1,305,558***	***2,770,918***	

Notes:

AECL = Atomic Energy of Canada Limited HQ = Hydro-Québec

NBPN = New Brunswick Power Nuclear OPG = Ontario Power Generation Inc.

(1) 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.

(2) Bruce reactors are leased to Bruce Power for operation. However, OPG is responsible for the used fuel that is produced.

(3) AECL also owns some ~22,000 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 fuel associated with several research reactors in Canada.

(4) Darlington is currently undergoing refurbishment, unit-by-unit. The first unit (Unit 2) was shut down for refurbishment in mid-October 2016.

Figure 1 summarizes the history of wet and dry storage of used fuel in Canada to the end of 2016. Initially, all fuel was wet-stored in the station used fuel storage bays. Dry storage was initiated in the 1970s on a small scale 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.

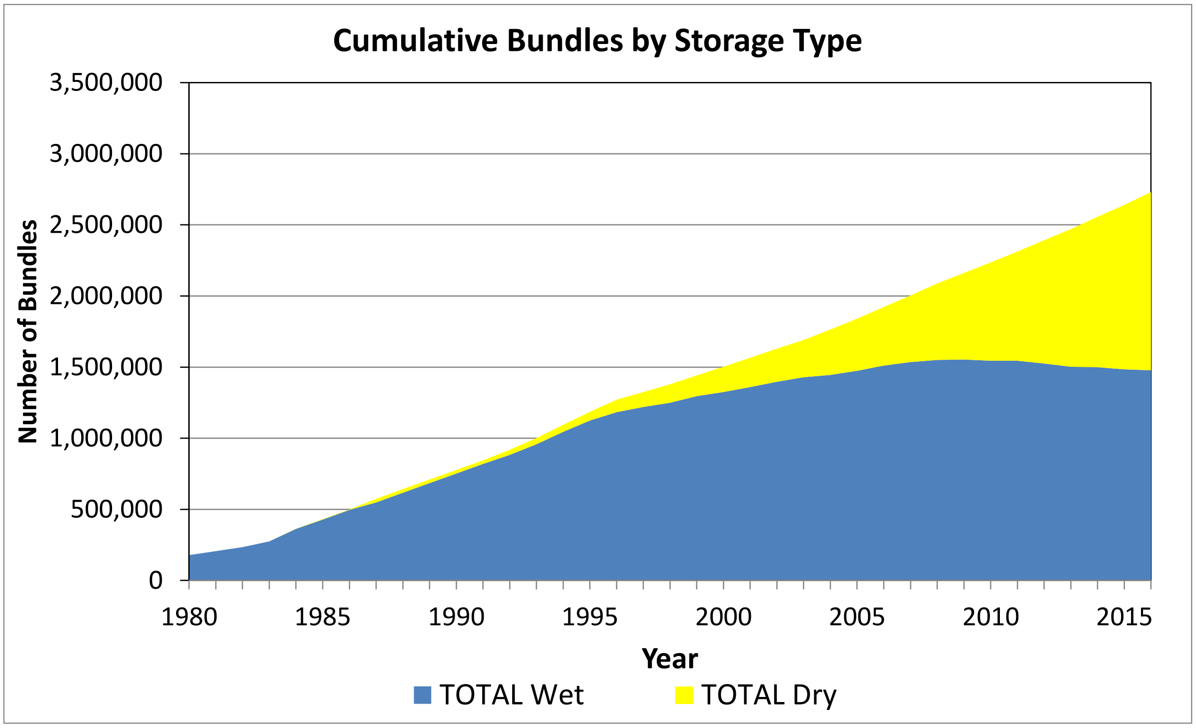

Figure 1: Summary of Used Fuel Wet and Dry Storage History

2.2 FUTURE FORECASTS

Forecasts of future nuclear fuel waste arisings are given in Table 2. Three scenarios are provided in the estimates:

a) **Low:** the reactors are shut down at the end of the projected life of the fuel channels (i.e. nominal 25 effective full power years (EFPY) of operation), with existing completed refurbishments and some planned life extension maintenance activities. Under this scenario, Darlington, Bruce A Units 3 and 4 as well as Bruce B will not be refurbished. Pickering reactors will begin to shut down in 2018.

b) **Reference:** based on announced life plans for the reactor fleet (i.e. refurbishment or not). Under this scenario, Darlington, Bruce A Units 3 and 4 and Bruce B will be refurbished. Bruce A Units 1 and 2 as well as Point Lepreau have already been refurbished and will operate until the new pressure tubes have accumulated 25 EFPY. Pickering reactors will be run until 2020.

c) **High:** Darlington, Bruce A Units 3 and 4 and Bruce B are all refurbished with a new set of pressure tubes and other major components, then operated for a further nominal 25 to 30 EFPY (i.e. to the end of the period covered under current environmental assessments and/or operating agreements). Bruce A Units 1 and 2 as well as Point Lepreau have already been refurbished and will operate until the new pressure tubes have accumulated 25 EFPY. Pickering A reactors will be run until 2022 and Pickering B until 2024.

Pickering units 2 and 3 as well as Gentilly-2 are permanently shut down and will not be restarted under any of the scenarios.

Note that these scenarios are constructed for NWMO planning purposes only to provide a range of possible fuel arisings and may differ from the official business plans and operational assumptions of the reactor operators. Operation of the reactors, including whether or not to refurbish or life extend, are subject to future business planning decisions of the individual reactor operators. Forecasts are expressed in terms of number of used CANDU fuel bundles and are rounded to nearest thousand bundles. Detailed planning dates for each scenario and reactor are provided in Appendix B.

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

Location	Waste Owner	Total June 2017 (# bundles)	Typical Annual Production (# bundles)	Low Scenario (# bundles)	Reference Scenario (# bundles)	High Scenario (# bundles)
Bruce A	OPG	514,650	20,500 (1)	833,000	1,153,000 (4)	1,204,000 (4)
Bruce B	OPG	682,414	23,500 (1)	877,000	1,605,000	1,664,000
Darlington	OPG	532,588	22,000 (1)	577,000	1,259,000	1,259,000
Douglas Point	AECL	22,256	0 (2)	22,256	22,256	22,256
Gentilly 1	AECL	3,213	0 (2)	3,213	3,213	3,213
Gentilly 2	HQ	129,925	0 (2)	129,925	129,925	129,925
Pickering A	OPG	736,817	7,200 (3)	781,000 (5)	781,000 (5)	864,000
Pickering B	OPG		14,500 (1)			
Point Lepreau	NBPN	141,866	4,800	260,000	260,000	260,000
Whiteshell	AECL	2,268	0 (2)	2,268	2,268	2,268
Chalk River	AECL	4,921	0 (6)	4,921	4,921	4,921
TOTAL (bundles)(7)		**2,770,918**	**92,500**	**3,491,000**	**5,221,000**	**5,414,000**
(t-HM)(8)		***55,000***	***1,850***	***70,000***	***104,000***	***108,000***

Notes:

1) Based on 4 reactors operating.
2) Reactor is permanently shut down and not producing any more fuel.
3) Based on 2 reactors operating.
4) All units at Bruce A are assumed to be refurbished (refurbishment completed for 2 units in 2012).
5) Pickering reactors assumed to be operated until 2020 only.
6) 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.
7) Totals may not add exactly due to rounding to nearest 1,000 bundles for future forecasts.
8) "tonnes of heavy metals" (t-HM) includes uranium and all of the transuranic isotopes produced in the reactor as part of the nuclear reactions via various neutron activation and radioactive decay processes, based on an average of 20 kg per bundle.

3. INVENTORY FROM POTENTIAL NEW REACTORS

There are two categories of proposed new reactor projects:

a) projects which have received or are currently undergoing regulatory approvals; and

b) 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. In addition, the technologies for each project have not yet been selected. Until such decisions have been made by the proponents, the forecast regarding types and amounts of fuel resulting from new-build projects is speculative.

Table 3: Summary of Proposed New Reactors

Proponent	Location	In-service timing	Reactor Type(s)	Status
Projects currently undergoing regulatory approvals				
OPG	Darlington, Ontario	Originally planned first unit 2018. Due to the current suspension of the procurement process, the first unit would not likely be operational until the mid to late 2020s.	4 x EC-6 or 4 x AP1000 or	Selected as site for first 2 reactors by Ontario Government. Procurement process currently suspended.

3.1 PROJECTS CURRENTLY UNDERGOING REGULATORY APPROVALS

3.1.1 Ontario Power Generation

In 2009, OPG submitted an Environmental Impact Statement (EIS) and supporting documentation for building up to 4 new reactors at its Darlington site, in Clarington just east of Toronto [OPG, 2007]. The Darlington site had been selected by the Government of Ontario to host the first two new-build reactors in the province, with an original reference in service date of 2018. If the project goes ahead, the first unit is not likely to be in-service until the mid to late 2020s due to subsequent suspension of the procurement process. The EIS was based on the maximum physical capacity of the site to allow for possible future expansion. A Joint Panel Review was completed in 2011, including public hearings. In August 2011, the Joint Review Panel issued its report on the environmental assessment (EA) with a conclusion that “the project is not likely to cause significant adverse environmental effects, provided the mitigation measures proposed and commitments made by OPG during the review, and the Panel’s recommendations are implemented” [JRP, 2011]. A Site Preparation Licence was granted by the CNSC on August 2012 [CNSC, 2012]. In May 2014, a group of non-governmental organizations had the approval overturned in a court challenge [Federal Court of Canada, 2014]. This ruling was subsequently overturned itself by a Federal Court of Appeal ruling in Sept 2015 which restored the original approval [Federal Court of Appeal, 2015]. The procurement process is currently suspended. However, the Ontario Government has stated that new nuclear remains an option for the future [Ontario, 2013].

Four reactor types were considered in the EIS submission:

a) ***CANDU ACR 1000 (Advanced CANDU reactor)***, which is a 1085 MW(e) net heavy water moderated, light water cooled pressure tube reactor. Up to 4 ACR 1000 reactors would be built on the site in two twin unit pairs. This would result in a total lifetime production of approximately 770,400 used fuel bundles (12,480 t-HM) over 60 years.

b) ***CANDU EC-6 (Enhanced CANDU 600 reactor)***, which is a 686 MW(e) net heavy water reactor, similar to the existing CANDU 600 reactors at Gentilly-2, Point Lepreau and elsewhere in the world. Up to 4 EC-6 reactors would be built on the site in two twin unit pairs. This would result in a total lifetime production of approximately 1,572,000 used fuel bundles (30,000 t-HM) over 60 years.

c) ***Westinghouse AP1000***, which is a 1037 MW(e) net pressurized light water reactor (PWR). Up to 4 AP1000 reactors would be built on the site, which would result in a total lifetime production of approximately 10,800 PWR fuel assemblies (5,820 t-HM) over 60 years.

d) ***AREVA EPR (Evolutionary Power Reactor)***, which is a 1580 MW(e) net PWR. Up to 3 EPR reactors would be built on the site, which would result in a total lifetime production of approximately 9,900 PWR fuel assemblies (5,220 t-HM) over 60 years.

All four reactor designs are considered to be “Generation III+”, and are designed to operate for 60 years. The province, through its Infrastructure Ontario program, will be selecting the preferred vendor. This selection process was suspended in 2009 [Infrastructure Ontario, 2009]. In 2012, OPG announced that they had contracted with Candu Inc. and Westinghouse to prepare detailed cost estimates for implementing the EC-6 and the AP1000, respectively, at the Darlington site [OPG, 2012]. The Nuclear Power Reactor Site Preparation Licence issued by the CNSC to OPG has a validity of 10 years [CNSC, 2012]. This timeframe allows a reactor vendor to be chosen prior to commencing the site preparation work. However, in 2013, the procurement process was again suspended [CTV, 2013].

For the purposes of forecasts in this report only, it is assumed that the project will eventually proceed in some form and the first unit is assumed to be in operation in 2027, with three additional units after that at one year intervals. Any actual decision to proceed with the project and its timing will be made by the Province of Ontario.

The EC-6 uses standard CANDU fuel, with options for advanced fuel types (SEU, MOX, etc.). As described below in Section 3.3 (with further details in Appendix C), 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.

3.2 ADDITIONAL PROJECTS IN RECENT CONSIDERATION

Feasibility studies and public discussions by provincial governments and potential proponents have been previously conducted for other new reactors in Ontario [Bruce Power, 2008a, 2008c, 2009a], Alberta [Bruce Power, 2009b], Saskatchewan [Saskatchewan, 2011] and New Brunswick [MZConsulting, 2008], [AREVA, 2010].

Other proposals include the introduction of small modular reactors (SMRs) of up to a few tens 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.

There are currently no active environmental assessments or licence applications underway for any of these projects or proposals. However, the CNSC has completed a Phase 1 pre-licensing review of a Canadian designed molten salt cooled SMR [Terrestrial Energy, 2016], [CNSC, 2017]. Two other SMR types currently undergoing a CNSC Phase 1 assessment are a lead-cooled reactor and a gas-cooled reactor. Several other vendors have indicated that they will be submitting pre-licensing review applications in the near future, including sodium-cooled, gas-cooled and molten salt designs [CNSC, 2017]. In addition, Canadian Nuclear Laboratories (CNL) is also seeking to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada [CNL, 2017].

The NWMO will continue to monitor the situation and will evaluate the implications and options for any new reactors as part of the review of the Adaptive Phased Management approach.

3.3 SUMMARY OF NUCLEAR FUEL CHARACTERISTICS FROM NEW REACTORS

Table 4 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. Further details can be found in Appendix C. The data have been extracted from references [Bruce Power, 2008a], [Bruce Power, 2008c], [IAEA, 2004] and [JRP, 2011].

Note that various other sources of data 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, etc.). 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 5 summarizes the total quantity of used fuel that might be produced for the proposed new-build reactors at Darlington. As mentioned above, 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.

Details of potential SMR fuels are not yet available. However, in all probability, they will be substantially different in design (physically, chemically and radiologically) from "conventional" CANDU fuels.

For NWMO planning purposes, a conservative, but reasonable, projection for new-build is based on four EC-6 reactors at Darlington. This is the only project that has currently received an initial regulatory approval (i.e. site preparation licence) and, of the technologies under consideration, the EC-6 reactor will produce the most used nuclear fuel over its lifetime for this project (1.6 million bundles for 4 reactors, compared to 0.8 million bundles for 4 ACR reactors). This total projection has not changed from the previous forecasts.

Table 4: 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	102.49 mm OD x 495.3 mm OL	102.49 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, 2008c], [IAEA, 2004] and [JRP, 2011]. Annual and lifetime data have been rounded.

Table 5: Summary of Potential Fuel Arisings from New Reactors at Darlington

Reactor	Darlington New Nuclear
Expected operation	2020s to 2080s
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

4. SUMMARY OF PROJECTED USED FUEL INVENTORY

The existing and projected inventory from current reactor operations, reactor refurbishment, and potential new reactors, developed in Sections 2 and 3, is summarized in Figure 2.

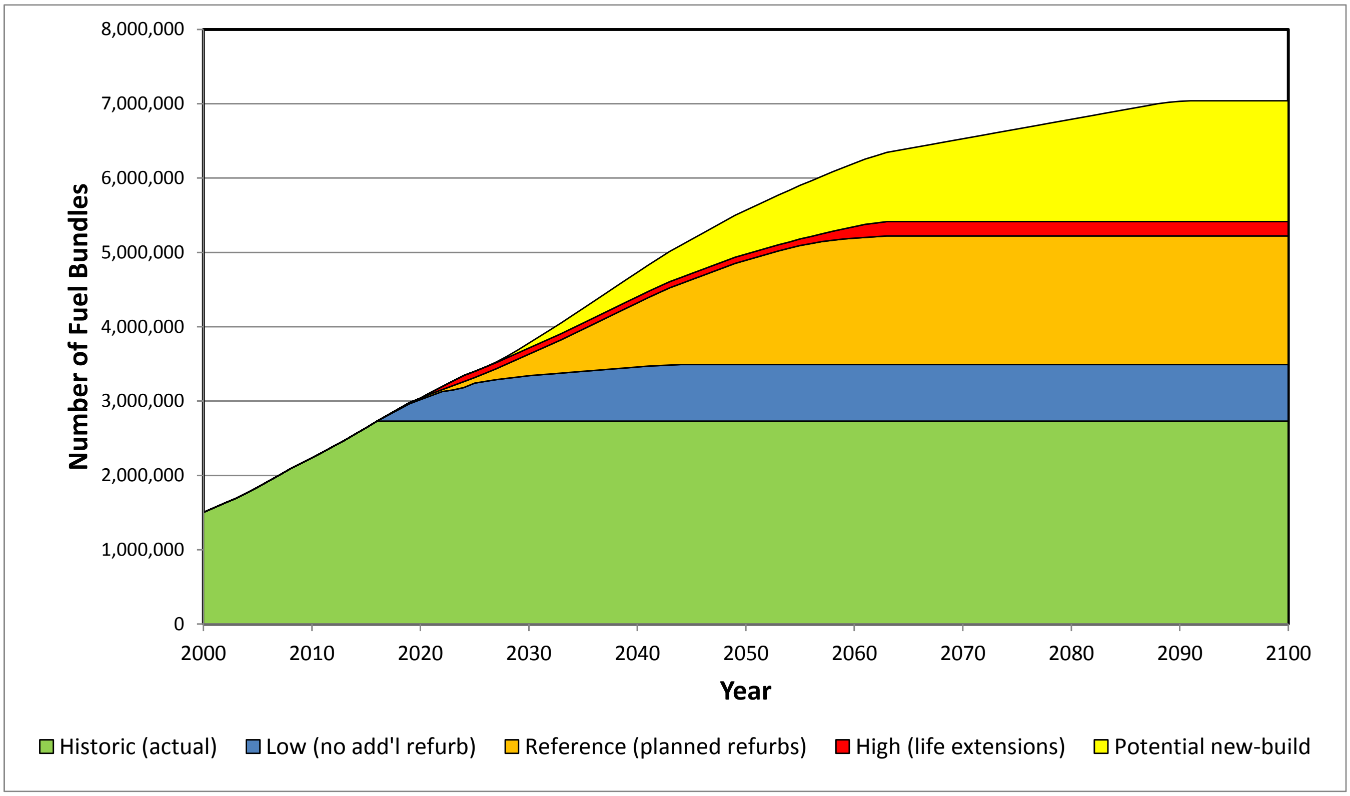

Figure 2: Summary of Projected Used Fuel Inventory

The currently existing fuel (as of end of June 2017) is shown in the green shaded area, totalling 2.8 million bundles.

The “**low forecast**” (blue shaded area) represents the forecast additional inventory from the existing Canadian fleet of reactors, up to the end of their initial operating period (nominal 25 effective full power years or announced shutdown dates), including currently executed life-extension activities, but prior to any additional major refurbishment (e.g. large scale fuel channel replacement and/or steam generator replacement). Previously refurbished and re-started reactors (Bruce A1, Bruce A2 and Point Lepreau) are assumed to operate for an additional nominal 25 effective full power years. Previously shut down reactors (Douglas Point, Gentilly 1 and 2, and Pickering 2 and 3) are assumed not to re-start. This amounts to an additional 0.7 million CANDU fuel bundles for a total of approximately 3.5 million CANDU fuel bundles.

The “**reference forecast**” (orange shaded area) represents the additional fuel bundles that would be generated if all of the currently announced refurbishment and life extension projects for the existing Canadian reactor fleet are implemented. The refurbishments are assumed to last for 3 to 4 years each (depending on the reactor and scope of the planned refurbishment for it), with the fuel removed from the core prior to refurbishment and not re-used. Previously shut down reactors (Douglas Point, Gentilly 1 and 2, and Pickering 2 and 3) are assumed not to restart. This amounts to an additional approximately 1.7 million CANDU fuel bundles, for a total of 5.2 million CANDU fuel bundles.

The “**high forecast**” (red shaded area) represents the additional used fuel bundles that would be generated if all of the existing Canadian reactor fleet is refurbished, similar to the reference scenario, and life extended for another 2-5 years beyond the reference scenario to cover the full period envisioned by current environmental assessments. This amounts to an additional approximately 0.2 million CANDU fuel bundles, for a total of 5.4 million CANDU fuel bundles.

Note that not all of the existing reactors may be refurbished and the decisions over whether or not to refurbish reactors will be taken by their owner/operators on a case-by-case basis over the next few years.

The “**potential new-build**” (yellow shaded area) represents the additional used fuel bundles that could be generated if four new EC-6 reactors are constructed (i.e. the four which have received a Site Preparation Licence at Darlington), amounting to approximately 1.6 million bundles over their projected 60 year operating life. This quantity and timing is speculative at this time, since decisions regarding potential new reactor numbers, types and in-service dates have not yet been taken. It will also depend on the operating history of the new reactors, such as capacity factors and achieved fuel burnup. Other potential future new reactors (including small modular reactors based on a variety of non-CANDU technologies, such as liquid metal cooled, molten salt cooled and light water cooled) are not included in the forecast at this time.

Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the current reference scenario projects a total of 5.2 million bundles (see Appendix B for details). For the purposes of developing overall APM program cost estimates, a range with a low of 3.6 million and a high of 7.2 million CANDU fuel bundles is used.

When definitive decisions on new nuclear build and reactor refurbishment are made by the nuclear utilities in Canada, any resulting changes in forecasted inventory of nuclear fuel waste will be incorporated into future updates of this report.

Note that in addition to the CANDU fuel bundles described above, there are (generally 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 power 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). Note that these additional 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

Table A1: Nuclear Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type*	Current Status (2017)
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		Operating
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		Undergoing refurbishment
Darlington 3	881	1993		Operating
Darlington 4	881	1993		Operating
Gentilly, Quebec				
Gentilly 2	635	1983	37 element bundle	Permanently shut down in 2012 All used fuel is in wet or dry storage on site.
Pickering, Ontario				
Pickering A – 1	515	1971	28 element bundle	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		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 C for description of fuel types

Table A2: Prototype and Demonstration Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type	Current Status (2017)
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 1978; 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)	Operating
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	20 kW(th) SLOWPOKE 2; Operating
Montreal, Quebec				
Ecole polytechnique	0.02	1976	UO_2 SLOWPOKE fuel pins	20 kW(th) SLOWPOKE 2; Operating
Edmonton, Alberta				
University of Alberta	0.02	1977	U-Al SLOWPOKE fuel pins	20 kW(th) SLOWPOKE 2; Operating
Saskatoon, Saskatchewan				
Saskatchewan Research Council	0.02	1981	U-Al SLOWPOKE fuel pins	20 kW(th) SLOWPOKE 2; 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 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

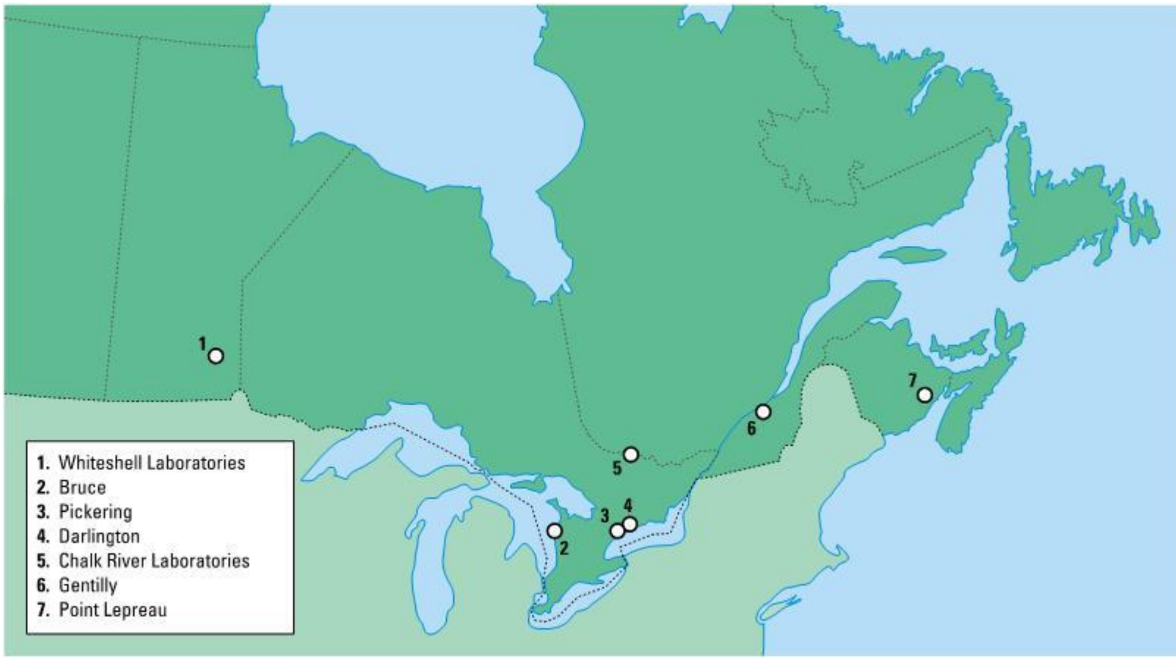

Figure A1: Current Nuclear Fuel Waste Major Storage Locations in Canada

APPENDIX B: USED FUEL WASTE FORECAST DETAILS FOR EXISTING REACTORS

Forecasts are based on:

- Existing stations only (new-build not considered).
- [(June 2017 actuals) + (number of years from June 2017 to end-of-life) * (typical annual production of fuel bundles)] rounded to nearest 1000 bundles.
- Fuel in reactor core is removed prior to a refurbishment and not re-used. No fuel is generated during the 36 to 48 month refurbishment period.
- End-of-life total includes final reactor core fuel.
- For multi-unit stations, the station total forecast is the sum of the above calculated on a unit-by-unit basis.
- Total mass of fuel is based on a rounded bundle mass of 20 kg of heavy metals (e.g. uranium).

End-of-life dates are determined from the following scenario details:

a) **"Low" scenario:**
- power reactors are shut down at the end of the projected life of the fuel channels (i.e. nominal 25 effective full power years (equivalent to nominal 30 calendar years) of operation);
- reactors that have been permanently shut down (Gentilly-2, Pickering Units 2 and 3) or are currently shut down for refurbishment (Darlington Unit 2) do not restart; and
- reactors that have been previously refurbished and are still operating, will operate to the end of their expected extended service life (Bruce Units 1 and 2; Point Lepreau).

b) **"Reference" scenario:**
- Based on currently announced life plans for the reactor fleet (i.e. refurbishment and life extension of all power reactors except Gentilly-2, and Pickering), with continued operation for a further nominal 25 effective full power years (nominal 30 calendar years) for a total of ~60 calendar years.
- reactors that have been permanently shut down do not restart (Gentilly-2, Pickering Units 2 and 3);
- reactors that have been previously refurbished and are still operating, will operate to the end of their expected extended service life (Bruce Units 1 and 2; Point Lepreau); and
- reactors where a definite decision has been made not to refurbish (Pickering B), will operate to the end of their current announced service life only.

c) **"High" scenario:**
- Similar to (b), except reactors are operated to end of the period included under current environmental assessments and/or operating agreements (i.e. 2 to 5 years longer than under (b) for Bruce A, Bruce B, Darlington and Pickering);

Note that forecasts are based on the above assumptions for NWMO planning purposes only and may differ from the business planning assumptions used by the reactor operators. In addition, as definitive decisions on refurbishment and service life are taken by the reactor operators, the "high" and "low" scenarios will merge into the "reference" scenario in the future.

Table B1: Detailed Used Fuel Forecasts for Existing Reactors

Location	Unit	Startup	Total to June 2017 (# bundles)	Annual Production (# bundles)	Low Scenario (~25 EFPY) End-of-life	Low Scenario (~25 EFPY) (# bundles)	Reference Scenario End-of-life	Reference Scenario (# bundles)	High Scenario (~55 EFPY) End-of-life	High Scenario (~55 EFPY) (# bundles)
Bruce A	1	1977	514,650	20,500	2043	**833,000**	2043	**1,153,000**	2043	**1,204,000**
	2	1977			2043		2043		2043	
	3	1978			2022		2056		2061	
	4	1979			2024		2057		2062	
Bruce B	5	1985	682,414	23,500	2026	**877,000**	2059	**1,605,000**	2062	**1,664,000**
	6	1984			2019		2053		2058	
	7	1986			2028		2061		2063	
	8	1987			2030		2063		2063	
Darlington	1	1992	532,588	22,000	2021	**577,000**	2054	**1,259,000**	2054	**1,259,000**
	2	1990			2016		2049		2049	
	3	1993			2019		2052		2052	
	4	1993			2022		2055		2055	
Douglas Point		1968	22,256	**0**	**1984**	**22,256**	**1984**	**22,256**	**1984**	**22,256**
Gentilly 1		1972	3,213	**0**	**1978**	**3,213**	**1978**	**3,213**	**1978**	**3,213**
Gentilly 2		1983	129,925	**0**	**2012**	**129,925**	**2012**	**129,925**	**2012**	**129,925**
Pickering A	1	1971	736,817	7,200	2020	**781,000**	2020	**781,000**	2022	**864,000**
	2	1971			**2005**		**2005**		**2005**	
	3	1972			**2005**		**2005**		**2005**	
	4	1973			2020		2020		2022	
Pickering B	5	1983		14,500	2019		2019		2024	
	6	1984			2018		2018		2024	
	7	1985			2020		2020		2024	
	8	1986			2020		2020		2024	
Point Lepreau		1983	141,866	4,800	2041	**260,000**	2041	**260,000**	2041	**260,000**
Whiteshell		1965	2,268	**0**	**1985**	**2,268**	**1985**	**2,268**	**1985**	**2,268**
Chalk River/ NPD/other			4,921	0		**4,921**		**4,921**		**4,921**
TOTALS (bundles)			**2,770,918**	**92,500**		**3,491,000**		**5,221,000**		**5,414,000**
(t-HM)			***55,000***	***1,850***		***70,000***		***104,000***		***108,000***

Reactor currently under refurbishment

Reactor previously refurbished

Reactor permanently shut down

Note: forecasts are rounded to nearest 1,000 bundles or 1,000 t-HM

APPENDIX C: DESCRIPTION OF FUEL TYPES

Table C1: Summary of Inventory by Bundle Type (June 2017)

CANDU Bundle Type	Where Used	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)
18 Element	Gentilly 1, Whiteshell	-	4,417	4,417
19 Element	NPD, Douglas Point	-	26,296	26,296
28 Element	Pickering	399,703	337,114	736,817
37 R	Bruce, Darlington, Gentilly 2, Pt Lepreau	732,656	868,322	1,600,978
37 R Long	Bruce, Darlington	175,406	67,464	242,870
37 M	Bruce, Darlington	108,406	-	108,406
37 M Long	Bruce, Darlington	49,165	-	49,165
43 Element LVRF	Bruce	24	-	24
Other	AECL (various)	-	1,945	1,945
TOTAL		**1,465,360**	**1,305,558**	**2,770,918**

C.1 FUELS FROM EXISTING 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 in cladding, spacers, etc.
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>

37 element CANDU standard length bundle

Physical dimensions:
102.5 mm OD x 495 mm OL

Mass:
19.2 kg U (21.7 kg as UO_2)
2.2 kg Zircaloy in cladding, spacers, etc.
24.0 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:

- 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 starting to be used in Bruce and Darlington stations.

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 in cladding, spacers, etc.
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 starting to be used in Bruce stations.

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 in cladding, spacers, etc.
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 (a rare earth element that readily 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

Comments:
- has been used in Bruce B reactors in limited quantities, option for use in EC-6 reactors

C.2 FUELS FROM POTENTIAL NEW-BUILD REACTORS

43 element CANFLEX ACR bundle

Physical dimensions:
102.5 mm OD x 495.3 mm OL

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

Fissionable material:
Sintered pellets of UO_2
enriched to 2.5% U-235

Typical burnup:
20,000 MW day/ tonne 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
- 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

Comments:
- used in ACR-1000 reactors

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

EPR PWR fuel assembly

Physical dimensions:

214 mm square x 4805 mm OL

Mass:

527.5 kg U (598.0 kg as UO_2)

~182 kg other materials in cladding, spacers, etc.

780 kg total weight

Fissionable material:

Sintered pellets of UO_2

enriched up to 5% U-235

Typical burnup:

62,000 MWday/tonne U

Cladding material:

M5

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.

Comments:

- used in Areva EPR reactors