Nuclear Fuel Waste Projections in Canada – 2013 Update

NWMO TR-2013-11 **December 2013**

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ABSTRACT

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Abstract

This report updates the 2012 Nuclear Fuel Waste Projections report [Garamszeghy, 2012], summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2013 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. The report focuses on power reactors, but also includes prototype, demonstration and research reactor fuel wastes held by AECL which are included in the NWMO mandate.

As of June 30, 2013, a total of approximately 2.42 million used CANDU fuel bundles (approx 48,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 76,000 bundles from the 2012 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 3.4 to 5.2 million used CANDU fuel bundles (69,000 t-HM to 104,000 t-HM), depending upon decisions to refurbish 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 refurbishment), while the upper end assumes that most reactors are refurbished and life extended for an additional 25 EFPY of operation. This represents a slight increase in the low scenario forecasts from the 2012 report due to the refurbishment and re-start of Bruce A1, Bruce A2 and Point Lepreau.

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 4.4 million bundles. For design and safety assessment purposes, the NWMO has conservatively assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet.

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 a formal licence application has already been submitted are eventually constructed (i.e. at Darlington), 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 2012 report.

When 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.

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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. The NWMO continually monitors new developments to be prepared to assume its legal responsibility to manage used nuclear fuel in light of these evolving energy developments.

In recent years, interest in new nuclear generation has increased. New Brunswick, Ontario, Saskatchewan, and even Alberta (heretofore a "non-nuclear" province) have considered adding new nuclear capacity to their energy mix. In Ontario, OPG has recently received a Site Preparation Licence from the Canadian Nuclear Safety Commission (CNSC) for the construction of new nuclear at Darlington. In its application, in addition to CANDU reactor designs, consideration is also being given to introducing light water reactors, a technology used elsewhere in the world that produces used nuclear fuel with characteristics different from those which Canadian nuclear operators now manage.

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 nuclear operators in conjunction with government and the regulators. It is important that the NWMO recognize these uncertainties and put in place an active process for ongoing monitoring and review of new developments so that it can plan for the long-term management of used fuel arising from such decisions.

As energy policy decisions are taken that substantially affect the volumes 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. As part of continuing engagement of Canadians, the NWMO will be discussing with interested individuals and organizations how changing conditions, such as new-build, different fuel types or advanced fuel cycles should be addressed. The NWMO will continually review, adjust and validate implementation plans as appropriate against the changing external environment.

1.2 PURPOSE

The NWMO has made a commitment to publish information on current and future potential inventories of used fuel volumes and types on an annual basis [NWMO, 2013]. This document is the fifth such annual report and provides an update to the 2012 version [Garamszeghy, 2012].

1.3 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2013 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. The report focuses on power reactors, but also includes information on prototype, demonstration and research reactor fuel wastes held by AECL.

1.4 CHANGES SINCE THE 2012 REPORT

The primary changes to the Canadian nuclear landscape since the 2012 report are:

a) The shutdown of the Gentilly 2 reactor on December 28, 2012 and subsequent defueling of the reactor in 2013;

b) The successful refurbishment and re-start of Bruce A1 and A2 and Point Lepreau.

c) The receipt of new bids from Candu Inc and Westinghouse to OPG for the Darlington New Nuclear Project; and

d) 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 projected used fuel inventory are:

a) An increase in the total amount of used fuel currently in storage from June 30, 2012 to June 30, 2013.

	June 30, 2012	June 30, 2013	Net change	
Wet storage	1,532,211	1,513,805	-18,406	bundles
Dry storage	815,841	910,083	94,242	bundles
TOTAL	**2,348,052**	**2,423,888**	**75,836**	**bundles**

b) No significant change in the overall projected future total number of used fuel bundles produced by the existing reactor fleet for the reference scenario (4.4 million bundles) and the high scenario (5.2 million bundles). An increase in the projected future total number of used fuel bundles for the low scenario (3.4 million bundles from 3.0 million previously) due to the refurbishment, restart and inclusion of extended reactor operation in the low scenario for Bruce A1, Bruce A2 and Point Lepreau.

Additional considerations include

a) The indefinite postponement by the Government of Ontario to build new reactors at Darlington will affect the likelihood and timing of any used fuel from new build 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, 2013. 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.

TABLE 1: Summary of Nuclear Fuel Waste in Canada as of June 30, 2013

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)	Current Status
Bruce A	OPG(2)	341,331	97,536	438,867	- 4 units operational
Bruce B	OPG(2)	351,746	236,534	588,280(4)	- 4 units operational
Darlington	OPG	338,510	106,711	445,221(5)	- 4 units operational
Douglas Point	AECL	0	22,256	22,256	- permanently shut down
Gentilly 1	AECL	0	3,213	3,213	- permanently shut down
Gentilly 2	HQ	35,173	93,060	128,233	- permanently shut down end of 2012, defueling completed in Q3 2013
Pickering A	OPG	406,315	261,324	667,639	- 2 units operational, 2 units permanently shut down
Pickering B	OPG				- 4 units operational
Point Lepreau	NBPN	40,730	82,260	122,990	- operational
AECL Whiteshell	AECL	0	2,268	2,268	- permanently shut down. See Note (1).
AECL Chalk River	AECL	0	4,921	4,921	- mostly fuel from NPD (permanently shut down) and with small amounts from other CANDU reactors. See Note (3).
	TOTAL	***1,513,805***	***910,083***	***2,423,888***	Total of: - 19 units in operation - 7 units shut down (including prototype and demonstration reactors)

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. The remaining bundles are various research, prototype and test fuel bundles, similar in size and shape to standard CANDU bundles.

(2) Bruce reactors are leased to Bruce Power for operation.

(3) In addition to the totals shown in Table 1, AECL also has 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 storage form, dimensions, etc. requires special consideration for future handling.

(4) Total includes approx 96,000 "long bundles".

(5) Total includes approx 115,000 "long bundles".

Assuming a rounded average of 20 kg heavy metals in a fuel bundle, 2.4 million bundles is equivalent to approximately 48,000 tonnes of heavy metal (t-HM). Further details on the existing reactors can be found in Appendix A and fuel types in Appendix C.

2.2 FUTURE FORECASTS

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

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.

b) **Reference:** Based on announced life plans for the reactor fleet (i.e. refurbishment or not).

c) **High:** most of the reactors are refurbished with a new set of pressure tubes and other major components, then operated for a further nominal 25 EFPY. Pickering reactors will be run until 2020 [OPG, 2010]. Gentilly-2 was permanently shut down at the end of 2012.

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. Details are provided in Appendix B.

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

Location	Waste Owner	Total June 2013 (# bundles)	Typical Annual Production (# bundles)	Low Scenario (# bundles)	Reference Scenario (# bundles)	High Scenario (# bundles)
Bruce A	OPG	438,867	20,500 (1)	824,000	1,147,000 (4)	1,147,000 (4)
Bruce B	OPG	588,280	23,500 (1)	765,000	765,000	1,494,000
Darlington	OPG	445,221	22,000 (1)	633,000	1,293,000	1,293,000
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	128,233	0 (2)	129,925	129,925 (8)	129,925 (8)
Pickering A	OPG	667,639	7,200 (3)	798,000	809,000 (5)	809,000 (5)
Pickering B	OPG		14,500 (1)			
Point Lepreau	NBPN	121,758	4,500	260,000	260,000 (7)	260,000 (7)
AECL Whiteshell	AECL	2,268	0 (2)	2,268	2,268	2,268
AECL Chalk River	AECL	4,921	0 (6)	4,886	4,886	4,886
TOTAL (bundles)(9)		**2,423,888**	**92,200**	**3,443,000**	**4,437,000**	**5,166,000**
(t-HM)(10)		***48,000***	***1,850***	***69,000***	***89,000***	***104,000***

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. AECL Chalk River does not produce any power reactor CANDU used fuel bundles.
7) Point Lepreau has completed refurbishment and re-started in 2012.
8) Gentilly-2 was permanently shut down on Dec 28, 2012. Final amount, includes remaining fuel in-core.
9) Totals may not add exactly due to rounding to nearest 1,000 bundles for future forecasts.
10) “tonnes of heavy metals” (t-HM) includes uranium and all of the transuranics isotopes produced in the reactor as part of the nuclear reactions via various neutron activation and decay processes.

3. INVENTORY FROM POTENTIAL NEW-BUILD 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)

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 highly 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 (see note 1)	4 x EC-6 or 4 x AP1000 or (see note 2)	Selected as site for first 2 reactors by Ontario Government EIS report & updated application for a site preparation licence was submitted Sept 30, 2009 for 4 reactor types. [OPG, 2009] Joint Panel Review public hearing conducted in 2011 and report issued on EIS, Aug 2011 [JRP, 2011]. Site Preparation Licence issued Aug 2012 [CNSC, 2012] EC-6 and AP1000 under detailed consideration [OPG, 2012].

Notes:

1) Due to the current stage of the reactor type selection process and the subsequent construction schedules, the first unit would not likely be operational until the mid to late 2020s.

2) The selection of reactor type for new-build in Ontario was to be made by Ontario Government (Infrastructure Ontario) in 2009. The procurement process was suspended in June 2009 until further notice [Infrastructure Ontario, 2009]. In June 2012, OPG issued contracts to Candu Inc and Westinghouse for more detailed cost estimates on the EC-6 and AP1000, respectively [OPG, 2012]. Procurement process was suspended again in October 2013 [CTV, 2013].

3.1 PROJECTS CURRENTLY UNDERGOING REGULATORY APPROVALS

3.1.1 ONTARIO POWER GENERATION

OPG is currently in the licensing process 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 Environmental Impact Statement (EIS), which was submitted in 2009, was based on the maximum physical capacity of the site to allow for possible future expansion. A Joint Panel

Review concluded 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 August 17, 2012 [CNSC, 2012], however, the procurement process is currently suspended.

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).

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).

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).

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).

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 June 2009 [Infrastructure Ontario, 2009]. In June 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 October 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 2025. Any decision to resurrect the project and proceed in the future 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 PRELIMINARY DISCUSSION OR 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]. However, there are currently no active environmental assessments or licence applications underway for any of these projects.

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-BUILD REACTORS

Table 4 presents a summary of the major characteristics and quantities of nuclear fuels that are used in the new-build reactor types 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.

These total projections have not changed from the previous forecasts. However, the sale of AECL to Candu Inc (a private company) in 2011 may affect the future development of reactor types in Canada (e.g. choice of EC-6 versus ACR).

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).

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 Power [MW(e)]	1085	686	1037	1580
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.
n/d = data not available

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 projected inventory from current reactor operations, reactor refurbishment, and potential new reactors, developed in Sections 2 and 3, is summarized in Figure 1.

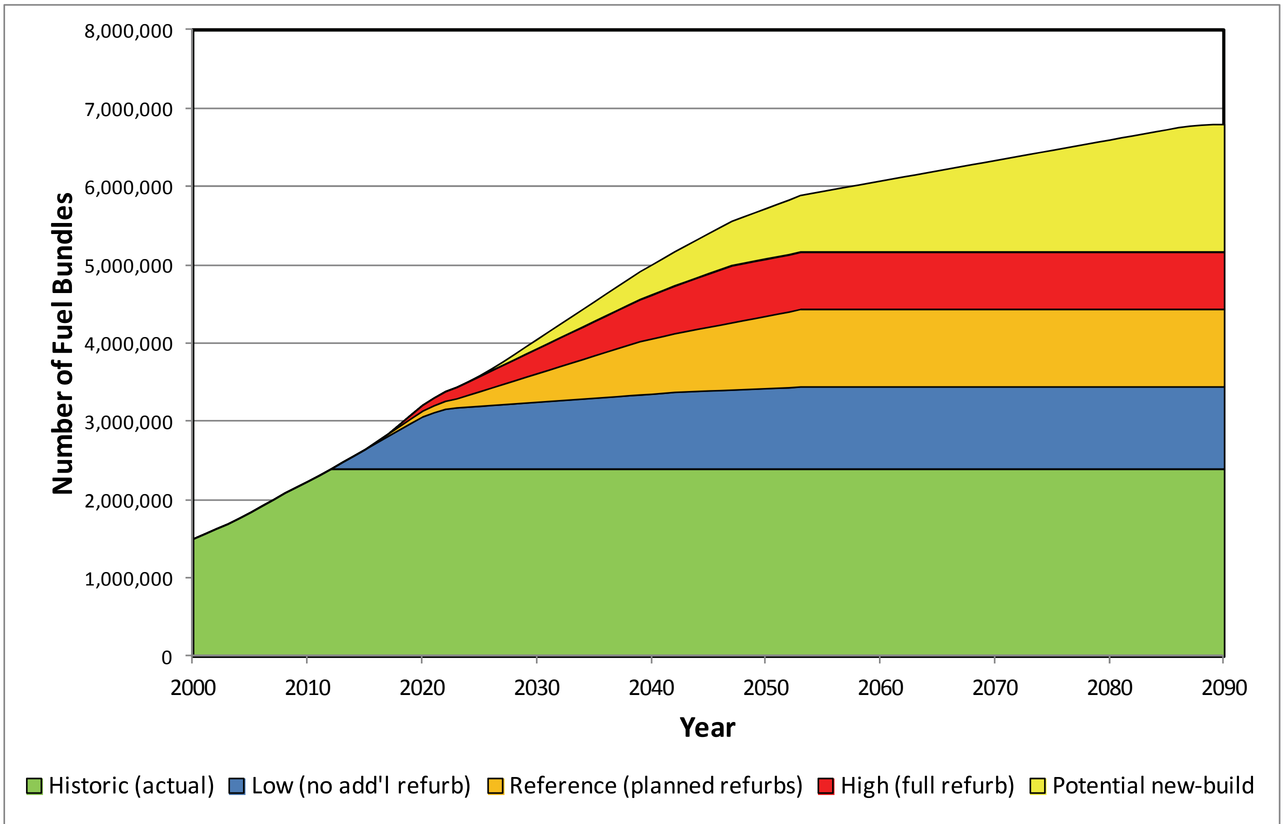

FIGURE 1: Summary of Projected Used Fuel Inventory

The "low forecast" (blue shaded area) represents the 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 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. This amounts to a total of approximately 3.4 million CANDU fuel bundles, of which 2.42 million bundles already exist in storage as of June 2013.

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. This amounts to an additional approximately 1.0 million CANDU fuel bundles, for a total of 4.4 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 and life extended for another nominal 25 effective full power years of operation (except Pickering, which is planned to be shut down by 2020 and Gentilly-2, which was permanently shut down at the end of 2012). This amounts to an additional approximately 0.8 million CANDU fuel bundles, for a total of 5.2 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 currently undergoing licensing at Darlington), amounting to approximately 1.6 million bundles over their projected 60 year operating life. This quantity and timing is highly 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.

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 4.4 million bundles (see Appendix B for details). For design and safety assessment purposes, the NWMO has conservatively assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet.

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, Table A-3), which are included within the NWMO’s mandate for implementing the APM program, if requested by the waste owner. 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 about 0.05% of the projected used fuel inventory). Note that these additional non-fuel wastes are not within the NWMO’s legislated mandate for used fuel waste.

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APPENDIX A: SUMMARY OF EXISTING CANADIAN REACTORS

TABLE A1: Nuclear Power Reactors

Location	Rating (MW(e) net)	Year In-service	Fuel Type*	Current Status
Bruce Nuclear Power Development, Ontario				
Bruce A – 1	750	1977	37 element CANDU 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 CANDU bundle; 37 element “long” bundle; (option for 43 element CANFLEX LVRF 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 CANDU bundle; 37 element “long” bundle	Operating
Darlington 2	881	1990		Operating
Darlington 3	881	1993		Operating
Darlington 4	881	1993		Operating
Gentilly, Quebec				
Gentilly 2	635	1983	37 element CANDU bundle	Permanently shut down in 2012
Pickering, Ontario				
Pickering A – 1	515	1971	28 element CANDU bundle	Operating
Pickering A – 2	515	1971		Permanently shut down in 2005
Pickering A – 3	515	1972		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 CANDU 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
Bruce Nuclear Power Development, Ontario				
Douglas Point (CANDU PHWR prototype)	206	1968	19 element CANDU bundle	Permanently shut down in 1984; All fuel currently 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 currently in dry storage on site
Rolphton, Ontario				
NPD (CANDU PHWR prototype)	22	1962	19 element CANDU bundle; various prototype fuel designs (e.g. 7 element bundle)	Permanently shut down in 1987; All fuel currently in dry storage at AECL Chalk River

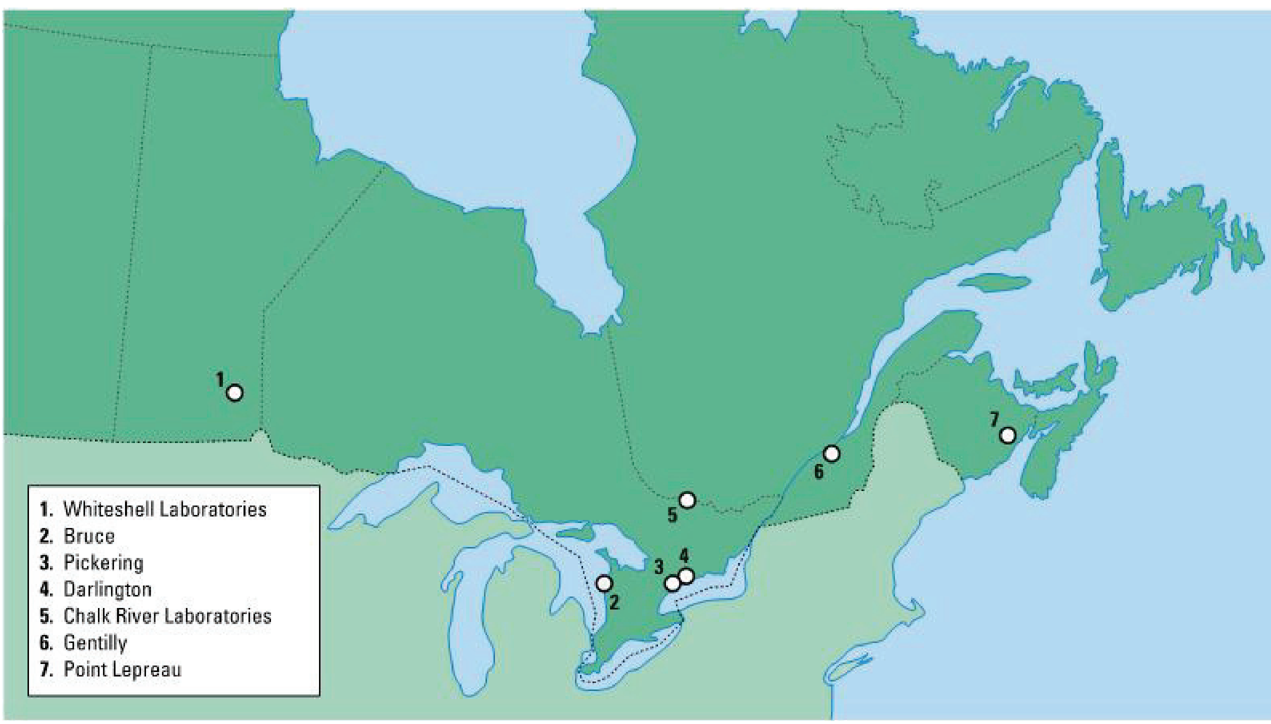


FIGURE A-1: Current Nuclear Fuel Waste Storage Locations in Canada

TABLE A3: Research Reactors

Location	Rating (MW(th))	Year In-service	Fuel Type	Comments
Hamilton, Ontario				
McMaster University	5	1959	(research)	MTR Pool type reactor
Kingston, Ontario				
Royal Military College	0.02	1985	(research)	(20 kW(th) SLOWPOKE 2)
Chalk River, Ontario				
NRU	135	1957	(research)	Operating
NRX	42	1947	(research)	Permanently shut down in 1992
MAPLE 1	10		-	Never fully commissioned
MAPLE 2	10		-	
ZED-2	250 W(th)	1960	(research)	Operating
Whiteshell, Manitoba				
WR-1 (organic cooled reactor prototype)	60 MW(th)	1965	various research and prototype fuel bundle designs (similar size and shape to standard CANDU bundles)	Permanently shut down in 1985; All fuel currently in dry storage on site
Montreal, Quebec				
Ecole polytechnique	0.02	1976	(research)	(20 kW(th) SLOWPOKE 2)
Halifax, Nova Scotia				
Dalhousie University	0.02	1976	(research)	(20 kW(th) SLOWPOKE 2, decommissioned 2011)
Edmonton, Alberta				
University of Alberta	0.02	1977	(research)	(20 kW(th) SLOWPOKE 2)
Saskatoon, Saskatchewan				
Saskatchewan Research Council	0.02	1981	(research)	(20 kW(th) SLOWPOKE 2)

Note: the SLOWPOKE reactors use U-235 enriched fuel and can operate on one fuel charge for 20 to 40 years. The total mass of U-235 fuel in a SLOWPOKE reactor core is about one kilogram. Other former research reactors include the 2 MW(th) Slowpoke Demonstration Reactor at Whiteshell, the low power PTR and ZEEP reactors at AECL Chalk River, and several shut down SLOWPOKE reactors at university sites. Used fuel from these shut down research reactors is stored at AECL Chalk River site, AECL Whiteshell site or has been returned to the country of origin (e.g. US).

APPENDIX B: USED FUEL WASTE FORECAST DETAILS FOR EXISTING REACTORS

Forecasts are based on:

Existing stations only (new build not considered).

[(June 2013 actuals) + (number of years from June 2013 to end-of-life) * (typical annual production of fuel bundles)] rounded to nearest 1000 bundles.

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 an assumed rounded bundle mass of 20 kg of heavy metals (e.g. uranium).

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

a) **"Low" scenario:**
   - the 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 do not restart; and
   - reactors that have been previously refurbished and are still operating, will operate to the end of their current expected or announced service life.

b) **"Reference" scenario:**
   - Based on currently announced life plans for the reactor fleet (i.e. refurbishment and life extension of all reactors except Gentilly 2, Pickering and Bruce B).

c) **"High" scenario:**
   - all reactors (except those mentioned below) are refurbished with a new set of pressure tubes and other major components, then operated for a further nominal 25 effective full power years (nominal 30 calendar years) to a total of 60 calendar years;
   - reactors that have been permanently shut down do not restart;
   - reactors that have been previously refurbished and are still operating, will operate to the end of their current expected service life only; and
   - reactors where a definite decision has been made not to refurbish (e.g. Gentilly 2, Pickering B), will operate to the end of their current announced service life only.

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 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 2013 (# 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 (~50 EFPY) End-of-life	High Scenario (~50 EFPY) (# bundles)
Bruce A	1	1977	438,867	20,500	2042	**824,000**	2042	**1,147,000**	2042	**1,147,000**
	2	1977			2043		2043		2043	
	3	1978			2022		2053		2053	
	4	1979			2022		2054		2054	
Bruce B	5	1985	588,280	23,500	2021	**765,000**	2021	**765,000**	2052	**1,494,000**
	6	1984			2021		2021		2052	
	7	1986			2021		2021		2052	
	8	1987			2021		2021		2052	
Darlington	1	1992	445,221	22,000	2022	**633,000**	2052	**1,293,000**	2052	**1,293,000**
	2	1990			2020		2050		2050	
	3	1993			2023		2053		2053	
	4	1993			2023		2053		2053	
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	128,233	**0**	**2012**	**129,925**	**2012**	**129,925**	**2012**	**129,925**
Pickering A	1	1971	667,639	7,200	2020	**798,000**	2020	**809,000**	2020	**809,000**
	2	1971			**2005**		**2005**		**2005**	
	3	1972			**2005**		**2005**		**2005**	
	4	1973			2020		2020		2020	
Pickering B	5	1983		14,500	2019		2020		2020	
	6	1984			2018		2020		2020	
	7	1985			2020		2020		2020	
	8	1986			2020		2020		2020	
Point Lepreau		1983	122,990	4,500	2041	**260,000**	2041	**260,000**	2041	**260,000**
AECL Whiteshell		1965	2,268	**0**	**1985**	**2,268**	**1985**	**2,268**	**1985**	**2,268**
AECL (NPD/other)			4,921	0		**4,921**		**4,921**		**4,921**
		TOTALS (bundles)	**2,423,888**	**92,200**		**3,443,000**		**4,437,000**		**5,166,000**
		(t-HM)	***48,000***	***1,850***		***69,000***		***89,000***		***104,000***

Reactor currently under refurbishment

Reactor permanently shut down

Reactor previously refurbished

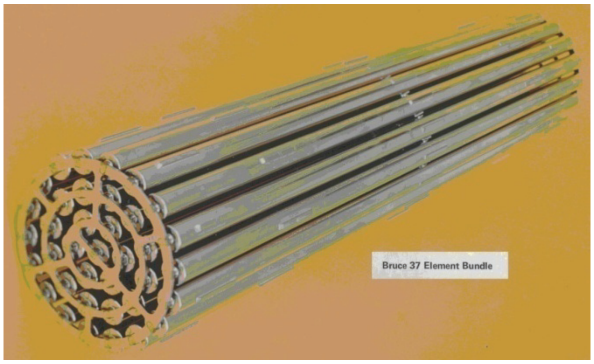
Note: forecasts are rounded to nearest 1,000 bundles or 1,000 t-HM

APPENDIX C: DESCRIPTION OF FUEL TYPES

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>Average 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" 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

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

Cladding material:
Zircaloy-4

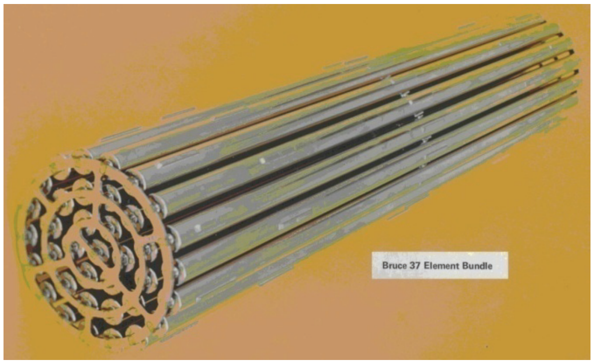
Construction:

- 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)

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

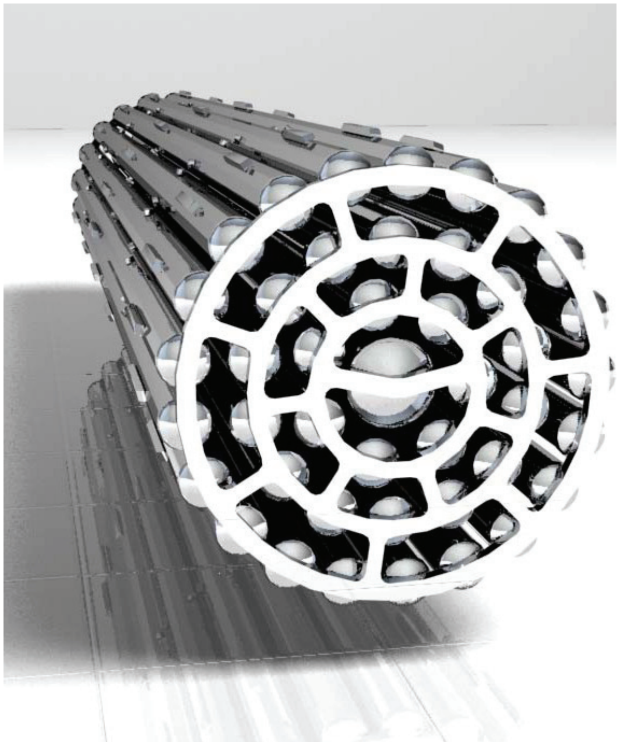
Fissionable material:
Sintered pellets of natural UO_2

Average 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

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
	Average burnup: 8,300 MW day / tonne U (200 MWh/kg U)
	Cladding material: Zircaloy-4

Construction:

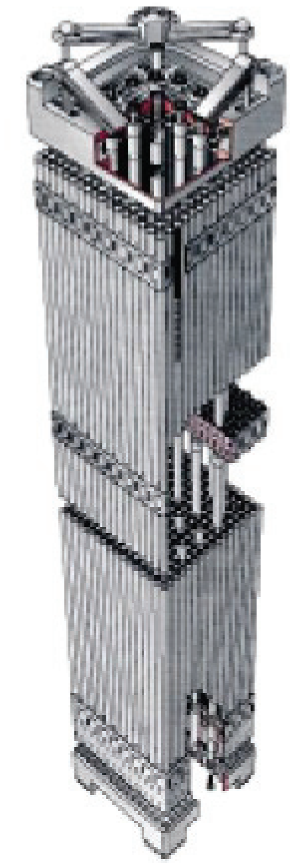
- bundle is composed of 43 elements (fuel pins), arranged in 4 concentric rings with 1 element in the inner most central ring, 7 elements in the second ring, 14 elements in the third ring and 21 elements in the outer ring
- the inner central element uses Dysprosium (a rare earth element that readily 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

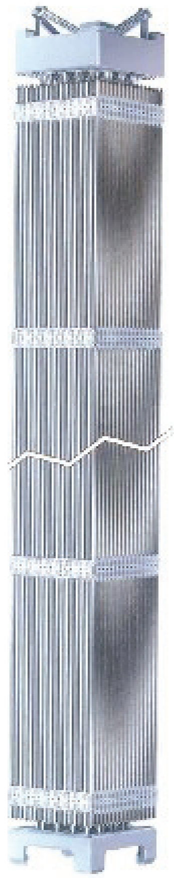
Comments:

- used in Bruce B reactors, option for use in EC-6 reactors

C.2 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>Average 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 **Average 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
	Average 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	