

Nuclear Fuel Waste Projections in Canada – 2012 Update

NWMO TR-2012-13

December 2012

M. Garamszeghy

Nuclear Waste Management Organization

nwmo

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MANAGEMENT
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ABSTRACT

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Abstract

Since the Nuclear Waste Management Organization submitted its Final Study in 2005, there have been a number of completed and planned nuclear refurbishments as well as proposed new-build initiatives which could extend the projected end of nuclear reactor operation in Canada from about 2034 to about 2085 or beyond.

The important technical features of these recent nuclear initiatives include:

- The amount of used nuclear fuel produced in Canada; and
- The type of used nuclear fuel produced in Canada;

This report updates the 2011 report [Garamszeghy, 2011] and summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2012 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.

As of June 30, 2012, a total of approximately 2.35 million used CANDU fuel bundles (approx 46,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 74,000 bundles from the 2011 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 3.0 to 5.2 million used CANDU fuel bundles (61,000 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 decrease in the forecasts from the 2011 report due to the decision to shutdown the Gentilly-2 reactor at the end of 2012.

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 constructed, 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 2011 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.

TABLE OF CONTENTS

Page

| | |
|--|-----------|
| ABSTRACT | v |
| 1. INTRODUCTION..... | 1 |
| 1.1 BACKGROUND..... | 1 |
| 1.2 PURPOSE..... | 1 |
| 1.3 SCOPE..... | 1 |
| 1.4 CHANGES SINCE THE 2011 REPORT | 2 |
| 2. INVENTORY FROM EXISTING REACTORS..... | 3 |
| 2.1 CURRENT INVENTORIES | 3 |
| 2.2 FUTURE FORECASTS..... | 4 |
| 3. INVENTORY FROM POTENTIAL NEW-BUILD REACTORS..... | 5 |
| 3.1 PROJECTS CURRENTLY UNDERGOING REGULATORY APPROVALS..... | 5 |
| 3.1.1 ONTARIO POWER GENERATION..... | 5 |
| 3.2 ADDITIONAL PROJECTS IN PRELIMINARY DISCUSSION OR RECENT CONSIDERATION | 6 |
| 3.3 SUMMARY OF NUCLEAR FUEL CHARACTERISTICS FROM NEW-BUILD REACTORS | 7 |
| 4. SUMMARY OF PROJECTED USED FUEL INVENTORY | 10 |
| REFERENCES | 12 |
| APPENDIX A: SUMMARY OF EXISTING CANADIAN REACTORS | 15 |
| APPENDIX B: USED FUEL WASTE FORECAST DETAILS FOR EXISTING REACTORS..... | 19 |
| APPENDIX C: DESCRIPTION OF FUEL TYPES | 21 |
| C.1 FUELS FROM EXISTING REACTORS | 21 |
| C.2 FUELS FROM POTENTIAL NEW-BUILD REACTORS | 25 |

LIST OF TABLES

| | Page |
|---|------|
| TABLE 1: Summary of Nuclear Fuel Waste in Canada as of June 30, 2012 | 3 |
| TABLE 2: Summary of Projected Nuclear Fuel Waste from Existing Reactors | 4 |
| TABLE 3: Summary of Proposed New Reactors..... | 5 |
| TABLE 4: Summary of Fuel Types for Proposed New Reactors | 8 |
| TABLE 5: Summary of Potential Fuel Arisings from New Reactors at Darlington | 9 |
| TABLE A1: Nuclear Power Reactors | 15 |
| TABLE A2: Prototype and Demonstration Power Reactors..... | 16 |
| TABLE A3: Research Reactors..... | 17 |
| TABLE B1: Detailed Used Fuel Forecasts for Existing Reactors | 20 |

LIST OF FIGURES

| | Page |
|---|------|
| FIGURE 1: Summary of Projected Used Fuel Inventory..... | 10 |
| FIGURE A-1: Current Nuclear Fuel Waste Storage Locations in Canada..... | 16 |

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, 2012]. This document is the fifth such annual report and provides an update to the 2011 version [Garamszeghy, 2011].

1.3 SCOPE

This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2012 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 2011 REPORT

The primary changes to the Canadian nuclear landscape since the 2011 report are:

- a) The restart of Bruce A units 1 and 2 and Pt Lepreau reactors after refurbishment activities;
- b) The planned shutdown of the Gentilly 2 reactor on December 28, 2012;
- c) The issuance of a Nuclear Power Reactor Site Preparation Licence by the CNSC to OPG for the Darlington New Nuclear Project; and
- d) An increase in the amount of used fuel currently in wet and dry 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, 2011 to June 30, 2012.

| | June 30, 2011 | June 30, 2012 | Net change | |
|--------------|----------------------|----------------------|-------------------|----------------|
| Wet storage | 1,545,642 | 1,532,211 | -13,431 | bundles |
| Dry storage | 728,231 | 815,841 | 87,610 | bundles |
| TOTAL | 2,273,873 | 2,348,052 | 74,179 | bundles |

- 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 forecast (3.0 million bundles), and a slight decrease in projected total for the reference scenario (4.6 million bundles down to 4.4 million) and for the high scenario (5.3 million bundles down to 5.2 million) due to the planned shutdown of the Gentilly 2 reactor at the end of 2012.

Additional considerations include the sale of AECL reactor division to a private company (Candu Inc), which may affect the future development and commercialization of reactors in Canada.

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, 2012. 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, 2012

| Location | Waste Owner | Wet Storage (# bundles) | Dry Storage (# bundles) | TOTAL (# bundles) | Current Status |
|------------------|--------------------|-------------------------|-------------------------|------------------------|--|
| Bruce A | OPG ⁽²⁾ | 355,061 | 74,112 | 429,173 | - 4 units operational |
| Bruce B | OPG ⁽²⁾ | 356,318 | 210,806 | 567,124 ⁽⁵⁾ | - 4 units operational |
| Darlington | OPG | 336,233 | 86,745 | 422,978 ⁽⁶⁾ | - 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 | 36,933 | 87,120 | 124,053 | - See Note (4). |
| Pickering A | OPG | 406,908 | 243,435 | 650,343 | - 2 units operational, 2 units permanently shut down |
| Pickering B | OPG | | | | - 4 units operational |
| Point Lepreau | NBPN | 40,758 | 81,000 | 121,758 | - operational |
| AECL Whiteshell | AECL | 0 | 2,268 | 2,268 | - permanently shut down. See Note (1). |
| AECL Chalk River | AECL | 0 | 4,886 | 4,886 | - mostly fuel from NPD (permanently shut down) and with small amounts from other CANDU reactors. See Note (3). |
| TOTAL | | 1,532,211 | 815,841 | 2,348,052 | Total of: - 19 units in operation - 7 units shut down |

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) Hydro Québec announced on Oct 3, 2012 that Gentilly 2 would be permanently shut down on December 28, 2012. [Hydro Québec, 2012]

(5) Total includes approx 96,000 “long bundles”.

(6) Total includes approx 115,000 “long bundles”.

Assuming a rounded average of 20 kg heavy metals in a fuel bundle, 2.3 million bundles is equivalent to approximately 46,000 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 of operation, with 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 effective full power years. Pickering reactors will be run until 2019 [OPG, 2010] and Gentilly-2 until 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 2012 (# bundles) | Typical Annual Production (# bundles) | Low Scenario (# bundles) | Reference Scenario (# bundles) | High Scenario (# bundles) |
|--------------------------------------|-------------|-----------------------------|---------------------------------------|--------------------------|--------------------------------|---------------------------|
| Bruce A | OPG | 429,173 | 20,500 ⁽¹⁾ | 527,000 | 1,157,000 ⁽⁴⁾ | 1,157,000 ⁽⁴⁾ |
| Bruce B | OPG | 567,124 | 23,500 ⁽¹⁾ | 767,000 | 767,000 | 1,496,000 |
| Darlington | OPG | 422,978 | 22,000 ⁽¹⁾ | 632,000 | 1,292,000 | 1,292,000 |
| 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 | 124,053 | 4,500 | 130,200 | 130,200 ⁽⁸⁾ | 130,200 ⁽⁸⁾ |
| Pickering A | OPG | 650,343 | 7,200 ⁽³⁾ | 792,000 | 792,000 ⁽⁵⁾ | 792,000 ⁽⁵⁾ |
| Pickering B | OPG | | 14,500 ⁽¹⁾ | | | |
| Point Lepreau | NBPN | 121,758 | 4,500 | 121,758 | 260,000 ⁽⁷⁾ | 260,000 ⁽⁷⁾ |
| AECL Whiteshell | AECL | 2,268 | 0 ⁽²⁾ | 2,268 | 2,268 | 2,268 |
| AECL Chalk River | AECL | 4,886 | 0 ⁽⁶⁾ | 4,886 | 4,886 | 4,886 |
| TOTAL (bundles)⁽⁹⁾ | | 2,348,052 | 96,700 | 3,003,000 | 4,431,000 | 5,160,000 |
| (t-HM)⁽¹⁰⁾ | | 46,000 | 1,940 | 61,000 | 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 2019 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) In October 2012, Hydro Québec announced Gentilly-2 will be permanently shut down on Dec 28, 2012.
- 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 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 |
|--|---------------------|--|--|--|
| <i>Projects currently undergoing regulatory approvals</i> | | | | |
| 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 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].

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 has 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 (currently under review). 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 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].

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. 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 pressurized light water reactor. 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. However, 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.

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, 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 21,600 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 | Pressurized light water reactor |
| 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.

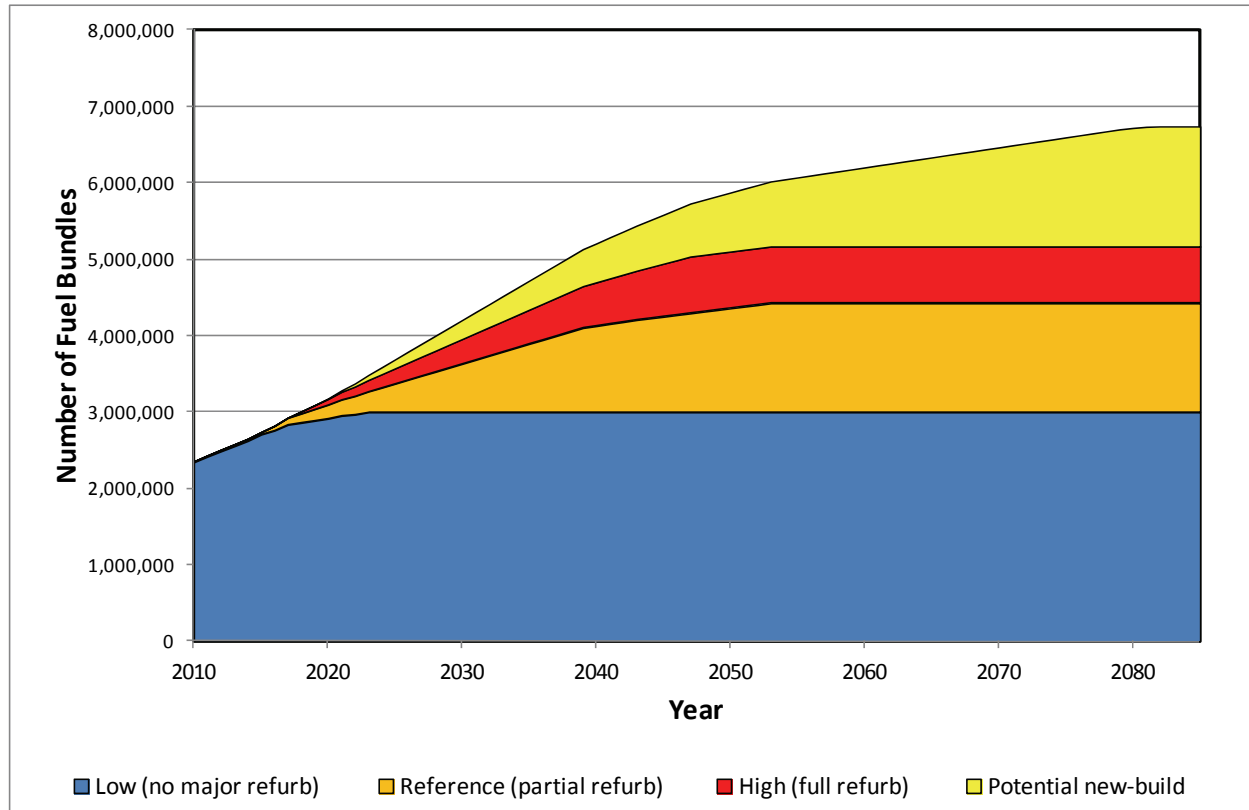


FIGURE 1: Summary of Projected Used Fuel Inventory

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), including currently planned life-extension activities, but prior to major refurbishment (e.g. large scale fuel channel replacement or steam generator replacement). This amounts to a total of approximately 3.0 million CANDU fuel bundles, of which 2.35 million bundles already exist in storage as of June 2012.

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 1.4 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 in 2019). 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.

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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 | Planned shut down as of Dec 28, 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).

$[(\text{June 2012 actuals}) + (\text{number of years from June 2012 to end-of-life}) * (\text{typical annual production of fuel bundles})]$ 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;
- reactors that have been previously refurbished and are still operating, will operate to the end of their current expected service life; and
- reactors which are currently undergoing refurbishment do not restart.

b) **“Reference” scenario:**

- Based on 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 2012 (# bundles) | Annual Production (# bundles) | Low Scenario (~25 EFY) | | Reference Scenario | | High Scenario (~50 EFY) | |
|-------------------------|------|---------|-----------------------------------|----------------------------------|------------------------|------------------|--------------------|------------------|-------------------------|------------------|
| | | | | | End-of-life | (# bundles) | End-of-life | (# bundles) | End-of-life | (# bundles) |
| Bruce A | 1 | 1977 | 429,173 | 20,500 | 1998 | 527,000 | 2042 | 1,157,000 | 2042 | 1,157,000 |
| | 2 | 1977 | | | 1998 | | 2043 | | 2043 | |
| | 3 | 1978 | | | 2022 | | 2053 | | 2053 | |
| | 4 | 1979 | | | 2022 | | 2054 | | 2054 | |
| Bruce B | 5 | 1985 | 567,124 | 23,500 | 2021 | 767,000 | 2021 | 767,000 | 2052 | 1,496,000 |
| | 6 | 1984 | | | 2021 | | 2021 | | 2052 | |
| | 7 | 1986 | | | 2021 | | 2021 | | 2052 | |
| | 8 | 1987 | | | 2021 | | 2021 | | 2052 | |
| Darlington | 1 | 1992 | 422,978 | 22,000 | 2022 | 632,000 | 2052 | 1,292,000 | 2052 | 1,292,000 |
| | 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 | 124,053 | 4,500 | 2012 | 130,200 | 2012 | 130,200 | 2012 | 130,200 |
| Pickering A | 1 | 1971 | 650,343 | 7,200 | 2019 | 792,000 | 2019 | 792,000 | 2019 | 792,000 |
| | 2 | 1971 | | | 2005 | | 2005 | | 2005 | |
| | 3 | 1972 | | | 2005 | | 2005 | | 2005 | |
| | 4 | 1973 | | | 2019 | | 2019 | | 2019 | |
| Pickering B | 5 | 1983 | | 14,500 | 2019 | | 2019 | | 2019 | |
| | 6 | 1984 | | | 2019 | | 2019 | | 2019 | |
| | 7 | 1985 | | | 2019 | | 2019 | | 2019 | |
| | 8 | 1986 | | | 2019 | | 2019 | | 2019 | |
| Point Lepreau | | 1983 | 121,758 | 4,500 | 2008 | 121,758 | 2041 | 260,000 | 2041 | 260,000 |
| AECL Whiteshell | | 1965 | 2,268 | 0 | 1985 | 2,268 | 1985 | 2,268 | 1985 | 2,268 |
| AECL (NPD/other) | | | 4,886 | 0 | | 4,886 | | 4,886 | | 4,886 |
| TOTALS (bundles) | | | 2,348,052 | 96,700 | | 3,003,000 | | 4,431,000 | | 5,160,000 |
| (t-HM) | | | 46,000 | 1,940 | | 61,000 | | 89,000 | | 104,000 |

Reactor currently under refurbishment


Reactor permanently shut down

Reactor previously refurbished

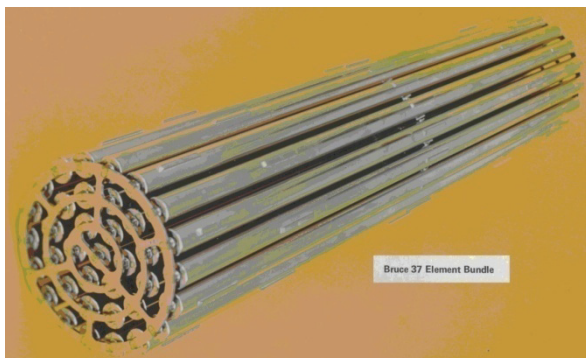
Note: forecasts are rounded to nearest 1,000 bundles
or 1,000 t-HM

APPENDIX C: DESCRIPTION OF FUEL TYPES

C.1 FUELS FROM EXISTING REACTORS

| 28 element CANDU bundle | |
|--|---|
|  | Physical dimensions: 102.5 mm OD x 497.1 mm OL |
| | Mass: 20.1 kg U (22.8 kg as UO_2) 2.0 kg Zircaloy in cladding, spacers, etc 24.8 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: <ul style="list-style-type: none"> - bundle is composed of 28 elements (fuel pins), arranged in 3 concentric rings with 4 elements in the inner most ring, 8 elements in the second ring and 16 elements in the outer ring - construction includes end plates, spacers and bearing pads to improve flow characteristics and maintain structural integrity | |
| Comments: <ul style="list-style-type: none"> - used in Pickering A and B reactors | |

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

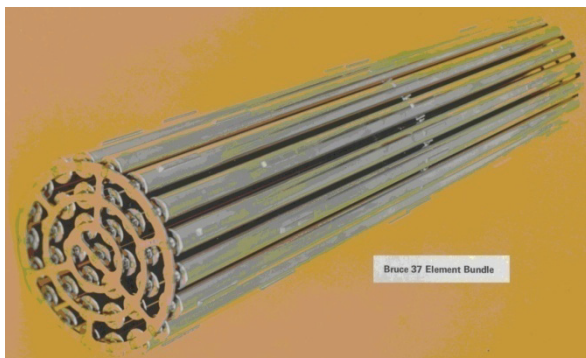
Construction:

- 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

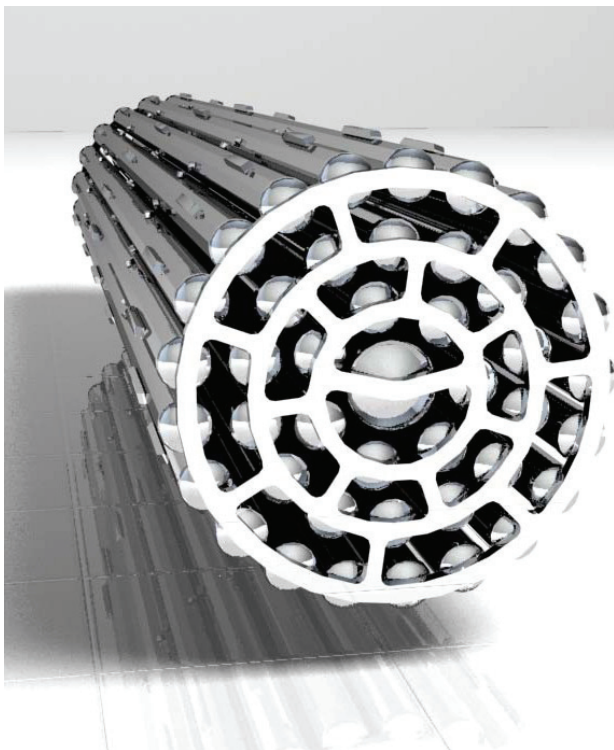
Construction:

- 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

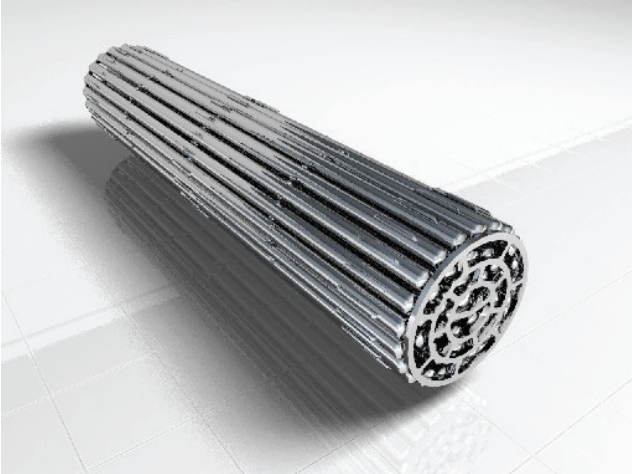
Construction:

- 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

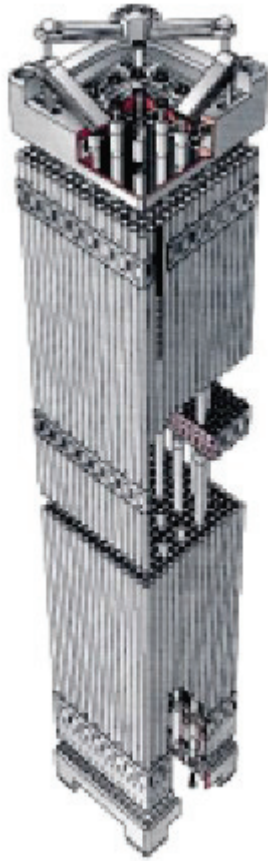
Comments:

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

C.2 FUELS FROM POTENTIAL NEW-BUILD REACTORS

| 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 |
| | Average burnup: 20,000 MW day/ tonne U |
| | Cladding material: Zircaloy-4 |
| Construction: <ul style="list-style-type: none"> - 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: <ul style="list-style-type: none"> - 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

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