NUCLEAR WASTE & ELECTRICITY RATES

April 2017

In the shadow of a bright nuclear presence

Abstract

Nuclear energy accounts for about 60% of Ontario's electricity. It is promoted as clean and efficient. Not so much in the limelight is the large amount of radioactive waste and the billions of dollars it costs ratepayers and taxpayers.

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<u>The views expressed in this paper are strictly those of the author</u>

MAIN POINTS

The main points of this paper are:

- The purpose of this paper is to increase awareness of nuclear waste produced from nuclear power, in particular the cost and how it's paid for.

- Ontario is highly dependent on nuclear power to generate about 60% of the Province's electricity. It is promoted as clean and efficient. Less featured is the large amount of nuclear waste that must be safely managed in perpetuity. Of prime concern is highly radioactive used nuclear fuel - about 2.3 million bundles owned by Ontario Power Generation (OPG) and increasing year over year.

- Nuclear waste is a multi-generational, multi-dimensional, and multi-billion dollar problem. It poses political, social, scientific, technical, safety, environmental, and financial challenges unlike any other.

- Responsibilities for managing radioactive waste are dispersed among many players and costs spread out for payment over many years – making accountability and transparency difficult to achieve. The total collective cost for dealing with nuclear waste in Canada is an unknown quantum.

- Costs for managing nuclear waste in Ontario are recovered in the price of electricity. Ratepayers pay almost all Ontario Power Generation expenditures associated with nuclear waste liabilities/costs – about $5 billion over thirteen years.

- There are significant costs looming on the horizon for the permanent storage of used nuclear fuel in a proposed deep geological repository likely in Ontario – costing an estimated $18.3 billion to $28.4 billion (2015 $). This translates to $1,310 to $2,033 per man, woman and child living in Ontario.

- There is a potential funding gap and deferment of costs to future generations of about $7.9 billion relative to estimated total costs for permanently placing used nuclear fuel in a deep geological repository.

- Nuclear power generation appears not all that profitable for Ontario Power Generation – losing $47 million over two years compared to a profit from hydroelectricity of $1,152 million.

- The time is opportune to more openly integrate planning for nuclear waste into long-term energy planning for Ontario.

EXECUTIVE SUMMARY

The prime purpose of this paper is to increase awareness of the nuclear waste produced from nuclear generated electricity and the financial cost of managing the waste. This paper and others addressing Ontario's electricity system can be found at www.breckenhill.com/BreckenhillBlog.php.

Nuclear energy currently accounts for about 60% of Ontario's electricity. While it is promoted as clean and efficient for producing electricity, nuclear waste is far from that.

Nuclear waste is virtually timeless and potentially dangerous of course if not well managed. It is a multi-generational and multi-dimensional problem costing billions and with costs spread out for payment over decades. Disposal of nuclear waste is like no other and cannot be project managed in conventional ways. It is a risk to be managed in perpetuity.

Radioactive waste management involves many players including federal and provincial governments, resource industries, electricity generating companies and others. The collective cost to taxpayers and electricity customers for dealing with the waste is an unknown quantum since responsibilities and costs are parsed between various players. In such a structure and context, accountability and transparency for nuclear waste management is difficult to achieve.

Ontario Power Generation (OPG) expenditures for managing nuclear waste are recovered from hydro customers. This includes "interim" storage of low-level and intermediate-level radioactive waste and used nuclear fuel bundles (high-level waste) on station sites. Hydro consumers have also been covering expenditures into segregated funds for the long-term management of nuclear waste – one for used nuclear fuel and a second for decommissioning of nuclear reactors and long-term management of low & intermediate level waste. The expenditures covered by ratepayers is about $2.7 billion over the past eight years and $2.3 billion for the next five years assuming the Ontario Energy Board approves a recent OPG payments application.

The dye is long cast for the use of CANDU nuclear generated electricity in Ontario and eventual permanent safekeeping of nuclear waste, in particular highly radioactive used nuclear fuel. The system continues accumulating large amounts of used nuclear fuel – some 90,000 bundles a year – adding to the existing Canadian inventory of about 2.6 million bundles – about 90% of which belongs to Ontario.

There are significant costs looming on the horizon. This for the long-term placement of nuclear waste into two proposed deep geologic repositories in Ontario – one for low and intermediate-level radioactive waste and a second for used nuclear fuel (high-level radioactive waste). Both are significant, but a deep geologic repository (DGR) for used nuclear fuel is the more significant because it is dealing with high-level radioactive waste.

Created in 2002, the Nuclear Waste Management Organization (NWMO) has been slowly and thoughtfully working for 10 years toward establishing a DGR likely in Ontario to permanently store used nuclear fuel from all of Canada – this being the Adaptive Phased Management strategy adopted by the federal government in 2007. OPG is the main player in NWMO. The project is estimated to cost between $18.3 billion and $28.4 billion (in 2015 $) including the transportation and safekeeping in a DGR of between 3.6 million and 7.2 million used nuclear fuel bundles – 90% or more from OPG. This translates to $1,310 to $2,033 per man, woman and child living in Ontario. Construction is expected to start around the year 2033 and take ten years to complete.

As of 31 December 2015, OPG had $8.6 billion in a segregated fund (Used Fuel Fund – UFF) for the long-term management of used nuclear fuel. As of 2015, there was approximately a $7.9 billion gap between the UFF and the total estimated costs for the disposal of used nuclear fuel into a DGR. Deferred to future ratepayers are costs for constructing a DGR and safely transporting used nuclear fuel to it.

At this time, OPG indicates the costs now incurred for the Adaptive Phased Management/DGR project for used nuclear fuel translates to only about 0.1 cents per kilowatt hour of electricity. But the total bill is yet to come. Ontario continues building up the inventory of used nuclear fuel and downstream costs for its long-term disposal.

Meanwhile, nuclear power generation appears not all that profitable for OPG. It reportedly lost $47 million over 2014 and 2015 for nuclear generation and nuclear waste business segments as compared to a net income of $1,152 million from hydroelectricity.

Lastly, the time is opportune to explicitly integrate long-term management of nuclear waste into long-term energy planning for Ontario.

INTRODUCTION & CONTEXT

For the first time in Ontario's history, in February 2017 the cost of electricity was polled as the number one public policy issue – ahead of the economy and health care. As I worked on this paper on March 2, 2017 the Ontario government announced a 17% reduction in electricity rates on top of the previously announced 8% relieve on the HST for a total 25% reduction. The $25 billion cost for the rate reduction is apparently made possible by renegotiating OPG's rates such that OPG is financing the rate reduction and will eventually be repaid by consumers in paying more for electricity down the road. Some call this "snowplowing".

This paper focusses on one aspect of a very complex electricity system in Ontario – nuclear waste and its cost. Of particular concern is spent nuclear fuel. When the term "nuclear waste" is used in this paper it means all three of high-level (used/spent nuclear fuel), intermediate-level and low-level radioactive waste. This is the standard categorization of nuclear waste.

This paper does not address the human health and environmental risks arising from the mining and processing of uranium into nuclear fuel or other product or the exposure to radioactive material/particles. There are many books and papers on this. Suffice it to say they are considerable and require specialized skill and technology for risk managing them, especially used nuclear fuel containing highly radioactive elements.

Ontario is heavily dependent on nuclear power and committed to it. Prior decisions regarding nuclear power are pushing electricity rates upwards as witnessed by the recent Ontario Power Generation (OPG) application to the Ontario Energy Board (OEB) to cover the $12.3 billion cost to refurbish the Darlington nuclear generating station and extend its service life another 30 years. As announced by the Liberal Government in December 2015, previous plans to refurbish 6 of 8

Bruce nuclear reactors starting in 2016 (15 year project costing $13 billion) has been delayed until 2020. Bruce reactors are owned by OPG and leased to Bruce Power.

Also before the OEB is an OPG application for payment of $307 million to cover the incremental enabling costs to extend the service life of the Pickering station (six operating 540 MW reactors) beyond 2020 up to 2024 as approved by the Provincial government in January 2016. A business case was made showing economic benefits for Ontario including job preservation. In addition to economic benefit, it is a convincing case in OPG having more time to shut down Pickering, providing back up while Darlington is refurbished, and avoiding need to construct and operate gas-fired replacement capacity and resulting CO_2 emissions.

I may look further into what alternatives were considered to Pickering extension such as importing hydroelectricity from Quebec or Manitoba rather than producing additional surplus electricity from extending Pickering. An interesting questing too is what happens after Pickering is closed in 2024. Topic for another day.

BACKGROUND

In accordance with the "polluter pay" principle, waste producers and owners are responsible for the funding, organization, management and operation of disposal and other facilities required for their waste.

That said, in the end analysis it is the taxpayer and/or the hydro customer paying the bill for radioactive waste. As users of nuclear generated electricity are we not collectively the "polluter"? We probably do not think of this – at least I did not until doing the work for this paper. Am reminded that electricity is an essential public service and the use of nuclear power is a matter of public policy with an implicit social contract binding on multiple generations.

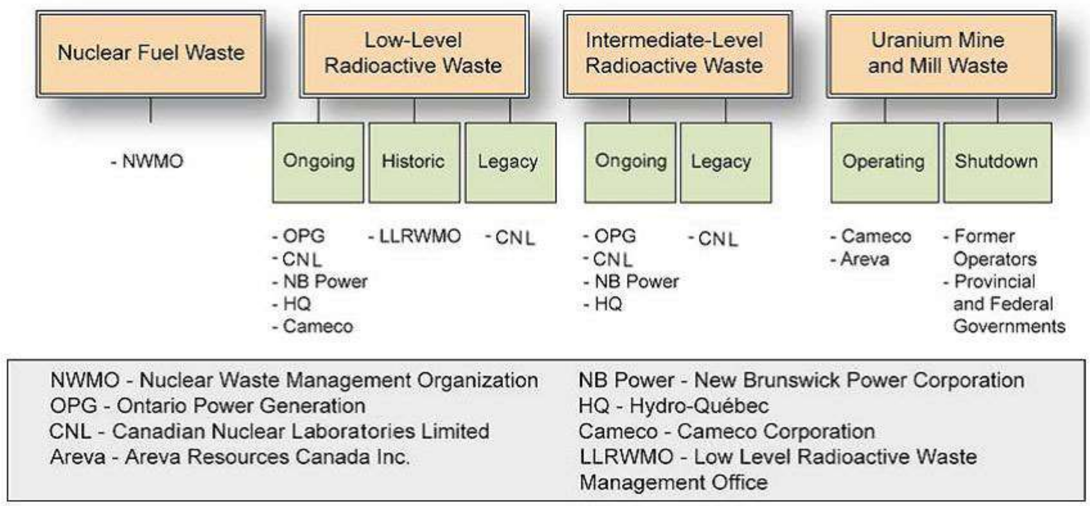
The Canadian Nuclear Safety Commission (CNSC) policy framework recognizes that long-term management arrangements may be different for various categories of radioactive waste, such as used nuclear fuel (high-level radioactive waste), low-level and intermediate-level waste, and uranium mining and milling waste.

The CNSC has licensed 20 radioactive management facilities in Canada – 15 in Ontario, 2 in Quebec (Chantilly reactors 1 & 2), one in New Brunswick (Point Lepreau), one in Manitoba (Whiteshell Laboratories, Pinewa), and one in Alberta (University of Alberta, Edmonton). In addition, there are several closed and decommissioned uranium mines also managed under CNSC licenses.

CNSC also conducts nuclear station site inspections – but not as well as it might in terms of documentation to support planning decisions - this according to the October 2016 Report of the Commissioner of Environment & Sustainable Development for Canada.

ORGANIZATIONS RESPONSIBLE FOR MANAGING RADIOACTIVE WASTE

The organizations responsible for long-term management of radioactive waste in Canada are shown in this figure as per the CNSC:



This chart is useful to show how many players there are, but not completely accurate. Under nuclear fuel waste, NWMO is not solely responsible when OPG, HQ, NB Power and AECL have responsibility for the safe storage of nuclear waste on station sites and are also the four main players in NWMO.

RADIOACTIVE WASTE INVENTORY

Canada has been operating nuclear facilities for almost fifty years and has accumulated a significant amount of nuclear waste from mining uranium, processing it and running nuclear reactors to produce electricity or in the making of other products such as medical isotopes. The amount of waste is large as indicated by the radioactive waste inventory shown in Table 1.

Table 1: Canada's radioactive waste inventory

Radioactive waste category	Waste inventory to end 2011	Waste inventory to end 2050
High-level (used nuclear fuel)	9,075 cubic metres	20,000 cubic metres
Intermediate-level	32,906 cubic metres	67,000 cubic metres
Low-level	2,338,000 cubic metres	2,594,000 cubic metres
Uranium mill tailings	214,000,000 tonnes	Not available
Source: Inventory of Radioactive Waste in Canada, Low-level Radioactive Waste Management Office of Natural Resources Canada, March 2012 – data collection by Statistics Canada.		

As seen in Table 1, six years ago high-level and intermediate-level radioactive waste was projected to double over 39 years. A more current inventory of used nuclear fuel (also called spent nuclear fuel) is provided later (see Table 2).

High-level waste in the form of used nuclear fuel is currently stored on station sites – most of which is in Ontario. Also stored on station sites or nearby facilities are low-level and intermediate-level waste (L&ILW). Responsibility for all stored nuclear waste in Ontario rests with Ontario Power Generation (OPG) which owns the Pickering, Darlington and Bruce nuclear power stations. The Bruce station is leased by OPG to Bruce Power.

FEDERALLY MANAGED RADIOACTIVE WASTE

There are also abandoned uranium mines and mill processing sites that fall under the historic/legacy responsibility of the federal government. These became the responsibility of the federal government when resource operators closed operations. These are included in the Federal Contaminated Sites Inventory that federal tax dollars are paying for and are part of the total $13.3 billion environmental liability of the Government of Canada (source: Public Accounts of Canada - Audited Consolidated Statement of Financial Position as at March 31, 2016).

The $13.3 billion federal environmental liability (estimated costs to contain/remediate) is a composite figure made up of many different things. Drilling down, included in that figure is a liability of $6.3 billion for 6,739 variously contaminated sites and then included in that figure is $1.1 billion for five sites associated with former nuclear operations, e.g. low-level radioactive waste, radioactive isotopes. The remediation cost/liability of individual sites is not made public.

The main federally managed legacy site for radiation waste is the Port Hope Area of Ontario including the Welcome Waste Management Facility. Here, Natural Resources Canada is the custodian responsible for some 2 million cubic metres of low-level waste radium 226, uranium and arsenic contaminants. As of 2011, this site had a liability cost then of $1.1 billion (source: Commissioner of the Environment & Sustainable Development for Canada - 2011 Report on Federal Contaminated Sites).

As far as I know, there is no singular figure for what it is collectively costing taxpayers and/or “hydro” consumers in the “Toto” to deal with radioactive waste in Canada. Costs are divided among jurisdictions and among various entities. Whatever the number is, it would be in the many billions of dollars.

NUCLEAR FUEL WASTE

The prime interest of this paper is high-level radioactive waste in the form of used nuclear fuel. Intermediate level waste would include materials that have come into contact with nuclear reactors such as used reactor components, ion exchange resins, filters, pressure tubes, and other structural materials. Low level consists of materials used in station operations such as tools, mops, and protective clothing.

Nuclear waste, especially used nuclear fuel, can remain radioactive for thousands of years. The responsibility to safeguard used nuclear fuel and the cost for managing it remain for as long as there are people living in Ontario and long after we may someday cease nuclear generated electricity as happened in Quebec and Germany.

CANDU used nuclear fuel is what nuclear fuel becomes after it is used in a reactor – when it can no longer efficiently heat water to steam. It looks exactly like the fuel that was loaded into the reactor - assemblies of metal rods enclosing stacked-up ceramic pellets of uranium dioxide. But since nuclear reaction has occurred, the contents aren't quite the same since the elements have changed.

CANDU fuel bundle. Source: [Nuclear Waste Management Organization]

Such high-level radioactive waste is the major issue arising from the use of nuclear reactors to generate electricity. Highly radioactive fission products and transuranic elements are produced from uranium and plutonium during reactor operations and are contained within the used fuel.

Transuranic elements are the chemical elements with atomic numbers greater than 92 (the atomic number of uranium). There are 26 such elements discovered or pending confirmation as made possible by synthesis through nuclear reactors. Two of the elements (93-neptunium and 94-plutonium) exist in nature but only in trace amounts. All transuranic elements are unstable and decay radioactively, with half-lives that range from tens of millions of years to fractions of a second.

Of particular concern in nuclear waste management are two long-lived fission products, Technetium-99 (half-life 220,000 years) and Iodine-129 (half-life 15.7 million years), which dominate spent fuel radioactivity after a few thousand years. There are other radionuclides of concern to the environment and human health. Apparently the strongest known "nuclear poison" is fission product Xenon-135 with a half-life of 9.1 hours. It is the complex mixture of radionuclides with different chemistries and radioactivity that makes handling of nuclear waste and dealing with nuclear fallout particularly problematic.

Ontario is the primary user of nuclear energy in Canada generating electricity from 18 operational reactor units. It is noted that Quebec has opted out of generating nuclear electricity having shut down the Gentilly 2 reactor in 2012. New Brunswick is the only other province providing electrical power by one reactor at Point Lepreau.

Pickering: 3,100 MW

Darlington: 3,500 MW

Bruce Power: 6,400 MW

As a result, Ontario is the primary producer of nuclear fuel waste in Canada – accounting for about 90%. Over time this proportion will increase since all other reactor units are now permanently shut down (Quebec & AECL) except for one unit in New Brunswick (Point Lepreau).

A more up to date inventory and projection of nuclear fuel waste is provided by the Nuclear Waste Management Organization (NWMO) in its December 2015 update report:

- As of June 30, 2015, approximately 2.6 million used CANDU fuel bundles (approx. 52,000 tonnes of heavy metal (t-HM)) were in storage (wet and dry) at the reactor sites, an increase of approximately 88,000 bundles from the 2014.

- 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 million to 5.2 million used CANDU fuel bundles (approx. 69,000 t-HM to 103,000 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 additional refurbishment beyond what has already been completed as of 2015), while the upper end assumes that most reactors are refurbished and life extended for an additional 25 EFPY of operation.

- Based on currently announced (to 2015) 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 assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet.

Each nuclear generating station has capacity in its wet bays to store used fuel corresponding to approximately 15 to 20 years of operation. After sufficient cooling off, used fuel is transferred to above ground concrete canisters (dry storage) also stored at each nuclear station site. The question is where to from there.

A nuclear fuel bundle is about the size of a fireplace log and weighs about 24 kilograms. As stated on its website, NWMO indicates that if stacked end-to-end like cordwood, the 2.6 million bundles would fit into a space the size of seven hockey rinks, from the ice surface to the top of the boards. At the end of the planned operation of Canada's existing nuclear reactors, the number of used fuel bundles could total about 5.2 million.

Table 2 following indicates where the 2.6 million bundles are now located. The bulk of them (90% or about 2.3 million bundles) belong to Ontario Power Generation (OPG).

Table 2: Used nuclear fuel waste in Canada as at June 30, 2015

Owner	Location	Total bundles	Status
Ontario Power Generation - OPG	Bruce A	476,454	4 units operational. Reactors are leased to Bruce Power for operation.
OPG	Bruce B	636,392	4 units operational.
OPG	Darlington	489,696	4 units operational.
OPG	Pickering A & B	701,417	Pickering A has 2 units operational, 2 units permanently shut down. Pickering B has 4 units operational.
Hydro Quebec	Gentilly 2	129,941	Permanently shut down end of 2012.
Atomic Energy of Canada Ltd.*	Gentilly 1	3,213	Permanently shut down.
AECL	Douglas Point	22,256	Permanently shut down.
AECL	Whiteshell	2,268	Permanently shut down.
AECL	Chalk River	4,921	Mostly fuel from nuclear power demonstration (permanently shut down) and with small amounts from other CNADU reactors.
New Brunswick Power Nuclear	Point Lepreau	132,430	Operational
TOTAL CANADA		2,598,988	19 reactor units operational. 7 units shut down including prototype and demonstration reactors.

Source: Page 77 of NWMO 2015 Annual Report. *Update: AECL still exists as a holding shell but its operations are now known as Canadian Nuclear Laboratories.

For those interested, I have added **Attachment A** outlining how nuclear fuel is made. Basically, this requires uranium to be extracted from the rock in which it is found, then enriched in the uranium-235 isotope, before being made into pellets that are loaded into assemblies of nuclear fuel rods. The attachment also includes a schematic of a CANDU nuclear reactor. CANDU stands for Canada Deuterium Uranium, because it was invented in Canada, uses deuterium oxide (also known as heavy water) as a moderator, and uranium as a fuel.

Attachment B provides information about uranium mining in Canada. It has a long history and Canada remains prominent in the world's mining of uranium all of which is now in northern Saskatchewan. It produces its own set of waste in the form of tailings placed in "ponds".

Attachment C gives an overview of repositories in other countries. This shows that Canada is not alone in the challenge of long-term management of nuclear waste.

LONG-TERM NUCLEAR WASTE MANAGEMENT

Study and research into what to do with nuclear waste has been going on for many years and in many countries. See Attachment C.

There is no ideal solution for nuclear waste. Deep geologic repositories (DGRs) are commonly an option in national planning for the long-term management of nuclear waste. The consensus among experts is that DGRs are the preferred option for permanent safekeeping rather than above ground. It is just a matter of where, when and how to build them.

As mentioned earlier, nuclear waste is currently stored on site at stations on an "interim" basis. In this case "interim" means about five decades. This is in the process of slowly changing.

There are two separate long-term radioactive waste management initiatives underway in Canada that may result in deep geological repositories. One deals with used nuclear fuel rods and the second with other waste classified as low-level and intermediate-level (L&ILW):

1. **The Nuclear Waste Management Organization (NWMO) Adaptive Phased Management (APM) project** seeks to find a solution for the long-term management of **used nuclear fuel** (**high-level waste**) – a solution that is socially acceptable, technically sound, environmentally responsible and economically feasible to Canadians.
2. **The Ontario Power Generation Deep Geologic Repository** focuses on the disposal of **low and intermediate-level radioactive wastes** at the Bruce Site in Tiverton, Ontario. The repository will also hold waste produced from the continued operation of the Bruce, Pickering and Darlington nuclear power plants.

The NWMO APM project is the more significant of the two in as much as it deals with highly radioactive waste in the form of used nuclear fuel.

NUCLEAR WASTE MANAGEMENT ORGANIZATION PROJECT

The **Nuclear Waste Management Organization** (NWMO) was formed in 2002 as a not-for-profit corporation. The four founding members and contributors to NWMO are Ontario Power Generation (OPG), Hydro Quebec, New Brunswick Power Corporation, and Atomic Energy of Canada Limited (AECL). As at December 31, 2015 NWMO had assets totalling $49 million made up mostly of deferred pension assets of $37 million. Its annual revenue is about $66 million from member contributions.

NWMO is implementing Adaptive Phased Management (APM), Canada's strategic plan for the long-term management of used nuclear fuel. The APM was adopted by the Federal Government in June 2007 after considering NWMO proposals made in November 2005. The APM approach involves centralized containment and isolation of used nuclear fuel in a deep geological repository (DGR) constructed within a suitable host rock formation such as crystalline or sedimentary rock.

The APM also includes a used fuel transportation system to safely move used fuel from reactor sites in Ontario, Quebec and New Brunswick (thousands of kilometres by road) to a proposed repository site likely somewhere in Ontario. The DPR site selection process has been underway for several years. A site has not been selected as yet but is anticipated by 2023. There are several communities interested and being considered.

For costing purposes, the repository is sited hypothetically in Ontario 1,000 km from all Ontario reactor sites as well as the Whiteshell operations (Ontario Power Generation Inc. & AECL), 1,500 km from the Gentilly facilities (Hydro Quebec & AECL) and 2,500 km from Point Lepreau (NBPN). All road transportation is assumed.

By design, NWMO has not prescribed deadlines for reaching each APM milestone. Timeline assumptions used for estimating costs were developed for planning purposes only. As the steward of the site selection process, the NWMO must take the time required to carefully assess sites and confirm a strong safety case. Communities and areas will also dictate the pace at which they are prepared to proceed.

Timelines for NWMO planning and cost estimation purposes are:

- The APM site selection process commenced with the issuance of the siting process document in May 2010. Initial screening and Phase 1 desktop Preliminary Assessments were the focus of the NWMO work program from 2010 to 2014.

- The Phase 2 Preliminary Assessments began in January 2014. Currently, the Phase 2 work program is assumed to be completed in 2022 with a single site selection in 2023.

- The detailed site characterization activities within the licensing phase is expected to take eight years to complete, resulting in the start of construction in 2033.

- With a 10-year construction period, the deep geological repository (DGR) is expected to be operational in 2043.

- Closure of the repository is indicated to be in the year 2160 – about 143 years from now.

Two used nuclear fuel (high-level waste) inventory scenarios are considered in NWMO cost analysis – revised APM reference lifecycle estimates:

1. The ***<u>base case</u>***, ***3.6 million used CANDU fuel bundles*** directed to the deep geological repository (DGR) over a 30-year placement period (out to around the year 2070), and

2. The ***<u>alternate case</u>***, which allows for potential refurbishment of existing plants and/or construction of new nuclear reactors, doubles the base case quantity to ***7.2 million used fuel bundles*** delivered to the DGR over a 60-year period.

NWMO's 2015 revised APM reference lifecycle cost estimate for the base case of 3.6 million used fuel bundles is $18,328 million (2015 $). The estimate for the alternate case of 7.2 million used fuel bundles is $28,429 million (2015 $).

This estimate translates to about $1,310 to $2,033 per man, woman and child living in Ontario.

Given the NWMO reported level of used nuclear fuel inventory of 2.6 million bundles and its projections for existing reactors to end of life cycle from 3.4 to 5.2 million bundles, it is likely that the base case scenario of 3.6 million bundles will be exceeded.

As at December 2015, a total of $3.7 billion (see Table 3 below) was set aside in trust accounts in relation to post-construction license costs of the DGR estimated at $5.8 billion. This is in addition to other segregated funds and financial guarantees the companies set aside for nuclear waste management and decommissioning of nuclear power plants (see next section). Funds are built up from annual contributions plus fund earnings.

Table 3: Trust funds pursuant to the *Nuclear Fuel Waste Act* (*NFWA*) – December 31, 2015

	Organization	Net Assets $ million	%
	Ontario *NFWA* Trust*	3,409	91.4
	Hydro Quebec	131	3.5
	New Brunswick Power Corporation	141	3.8
	Atomic Energy Canada Ltd. - AECL	48	1.3
	Total trust funds	3,729	100.0

Source: Audited Financial Statements for each Trust Fund

* Notes to the financial statements explain the Ontario *NFWA* Trust. The Province and OPG are the beneficiaries of the Trust. Notes state that the Trust forms part of the Used Fuel Segregated Fund (UFF) set up by OPG under the Ontario Nuclear Funds Agreement (ONFA) between the Province and OPG. In 2015 OPG contributed $188 million into the Trust fund.

Also included in the Notes is the following paragraph (underlining for emphasis):

> "The funds in the Trust will be used for the purpose of long-term management of nuclear used fuel waste. The primary objective of the Trust is to meet the payment obligations associated with the disposal costs associated with highly radioactive used nuclear fuel. These financial statements do not portray the funding requirements for the long-term management of nuclear fuel waste obligations".

This needs some explaining. It portrays a separation between payments into the Ontario NFWA Trust Fund to dispose waste on one hand and, on the other, what is required to fund future costs (obligations-liabilities) for the long-term management of nuclear fuel waste. As I interpret the paragraph, it is saying that the Trust financial statements present only half the story. They represent what has been paid into the Trust and earned by the Trust but not the corresponding obligation (liabilities-*costs*) for the long-term management of used nuclear fuel waste that the funds are intended to pay for. A reader might interpret them as equal, but this not necessarily so.

In fact, OPG has other funds set aside that together with the *NWFA* Trust Fund make up what is called the Used Fuel Fund for the long-term management of used nuclear fuel.

It is worth mentioning that the *Nuclear Fuel Waste Act (NWFA)* is a federal act of 2002. It established a framework upon which the Federal Government (Governor in Council) could make decisions on the management of nuclear fuel waste. It allowed the creation of NWMO and requirement for trust funds, initial and subsequent contributions to trust funds, and for a study within three years by NWMO and what was to be included in such study setting out alternatives for management of nuclear fuel waste. As such, the *NFWA* does not establish funding formulas and what costs specifically are to be provided for. It sets out expectations that these will be done and requires Federal Minister of Natural Resources approval of the formula and annual deposits into trust funds.

ONTARIO POWER GENERATION CAPITAL PROJECTS

OPG has transported, processed and stored low and intermediate-level nuclear waste (L&ILW) for almost 50 years. OPG indicates it can continue to safely store this waste above ground, but has an obligation to future generations to dispose of this waste safely and responsibly where it cannot pose a threat to the public or the environment.

According to page 27 of OPG's 2015 Annual Report, one of its capital projects is a Deep Geologic Repository (DGR) for management of L&ILW. With the support of the Municipality of Kincardine (reportedly paid $35 million by OPG) and surrounding municipalities, OPG has proposed the construction and operation of a DGR on lands adjacent to the Western Waste Management Facility in Bruce County. The proposed DGR would isolate and contain the waste 680 meters underground in stable rock formations. More than 200,000 cubic meters of L&ILW is expected to be stored in the proposed DGR. The proposed location is convenient in not requiring long distance transportation of waste thus avoiding additional risk and costs.

OPG reports spending $7 million to December 2015 on the project with life-to-date expenditures of $186 million. As of 2015, design activities on the project had been suspended pending receipt of the site preparation and construction license. The license has not yet been issued pending federal approval of the environmental impact assessment. Also, OPG has applied to the CNSC for renewal of the operating license for its Western Waste Management Facility that expires on May 31, 2017.

As it happens, on April 1, 2017 CBC W5 aired a piece on this proposed DGR. It showed there are people both actively opposed and in favour of such a repository and that across Lake Huron there is US political opposition to a repository. Opponents ask why build a DGR for L&ILW on the shores of a lake that supplies fresh water for millions of people and not some other acceptable place inland? Despite all assurances – why take any risk at all with the Great Lakes? Not unreasonable.

OPG's main capital projects as of December 2015 were:

- The Darlington nuclear refurbishment project with year to date expenditures of $706 million, life-to-date expenditures of $2,166 million and with an approved budget of $12.8 billion. The last unit of four is scheduled to be completed by 2026. The CNSC has granted Darlington a 10 year operating license from January 2016 to November 2025.

- The Lower Mattagami River Hydroelectric Project costing $2.5 billion with all six new units placed in service by December 2014 ahead of schedule.

- In January 2016 the Ontario government approved OPG's plan to pursue continued operation of the Pickering Station beyond 2020 up to 2024. Two reactor units would be shut down in 2022 and the remaining four units would operate until 2024.

In relation to Darlington, OPG recently applied in February 2017 to the Ontario Energy Board (OEB) for a 69% increase in the amount it is paid for nuclear power over the next five years. This to help pay for the $12.8 billion cost to extend the life of the reactors by another 30 years. If approved by the OEB, it would reportedly increase a typical household electricity bill an average of $1.05 a month annually in each of the next five years, to $5.25 a month in 2022.

OPG is the only electricity generator that has to apply to the OEB for rate increases. All other suppliers have long-term contracts with the Province. Therein lies the difficulty in reducing consumer "hydro"* rates – they are essentially locked in unless contracts are broken or renegotiated or some other way is found. No easy task.

* The word "**hydro**" is a term from the "old days" of Ontario Hydro. Technically it is a term for electricity generated from water power i.e. hydroelectricity. It is still commonly used to refer to electricity which can be generated using water, nuclear, wind, solar, biomass etc. People talk about their "hydro" bill and not their nuclear electricity bill or their wind energy bill.

ONTARIO NUCLEAR FUNDS & LIABILITIES

There are two prime numbers on OPG's Balance Sheet with regard to nuclear fund assets and nuclear liabilities. The following is taken from OPG's Annual Report and Financial Statements for the year ending December 31, 2015.

Assets: Nuclear fixed asset removal and nuclear waste management funds $15,136 million.

In accordance with the current Ontario Nuclear Funding Agreement (ONFA) Reference Plan, OPG puts money into two segregated funds for discharging its obligation for nuclear decommissioning and long-term nuclear waste management. ONFA contribution requirements are calculated, at the station level, based on the difference between the station level ONFA lifecycle liabilities (in present value terms) and segregated fund balances, using the general principle that such differences are to be paid into funds over the remaining life of the stations.

The Decommissioning Segregated Fund (DF) was established to fund the future costs of nuclear fixed asset removal, long-term low-level and intermediate-level waste (L&ILW) management, and certain costs for used fuel storage incurred after stations are shut down. The Used Fuel Segregated Fund (UFF) was established to fund long-term nuclear used fuel management.

Liabilities: Fixed asset removal and nuclear waste management liabilities $20,169 million.

The following costs are recognized as a liability on OPG's consolidated balance sheet:

- The present value of the costs of **decommissioning the nuclear and thermal production facilities and other facilities** after the end of their useful lives.

- The present value of the **fixed cost portion of nuclear waste management programs** that are required based on the total volume of waste expected to be generated over the assumed lives of the stations.

- The present value of the **variable cost portion of nuclear waste management programs taking into account waste volumes generated to date**.

OPG's asset retirement obligation (ARO) was $20,169 million as at December 31, 2015. The obligation consists of fixed asset removal and nuclear waste management liabilities. The ARO is comprised of expected costs to be incurred up to and beyond termination of operations and the closure of nuclear and thermal generating plant facilities and other facilities. Costs will be incurred for activities such as preparation for safe storage, dismantlement, demolition and disposal of facilities and equipment, remediation and restoration of sites, and the ongoing and long-term management of nuclear used fuel bundles and L&ILW material.

Liabilities associated with nuclear comprise the most significant portion of the total obligation.

The obligation regarding nuclear was $19,792 million on a present value basis ($38,272 million on an undiscounted basis). This represents the estimated costs of closing the nuclear stations after the end of their service lives, which includes **preparation and placement of the stations into a safe state condition followed by an assumed 30-year safe store period prior to station dismantlement and site restoration**. Activities associated with the placement of the stations into a safe state condition include de-fueling and de-watering of the nuclear reactors.

The majority of the expenditures are expected to be reimbursed by OPG's Nuclear Funds as established by the ONFA. Under the ONFA, OPG was committed for $3.2 billion in fund contributions from 2016 to 2020 and thereafter. Contributions are based on the 2012 ONFA Reference Plan which was expected to be updated effective January 1, 2017.

At this point two things are noted:

- Contributions to segregated funds appear based on the life of nuclear stations and not the eventual long term placement of nuclear waste in facilities off station such as a deep geological repository which is well beyond the operating life of stations or an assumed 30 year store period prior to station dismantlement.

- As accounted for December 2015, there is a $4.7 billion difference between the total of nuclear liabilities ($19.8 billion) and nuclear liability fund assets ($15.1 billion). Table 4 provides a breakdown of an apparent gap/disparity between nuclear liabilities/cost and nuclear fund assets. Most of the difference relates to used nuclear fuel.

Table 4: OPG nuclear liabilities and nuclear fund assets as at December 31, 2015

Obligation	Liabilities $ million	Fund Assets $ million	Difference $ million
Nuclear used fuel waste management	12,793 (a)	8,587 (b)	4,206
Nuclear decommissioning and low & intermediate-level waste management	6,998	6,549	449
Total	19,791	15,136	4,655

Source: Data taken from note 8 to the Audited Consolidated Balance Sheet of OPG

(a) In 2015, a $2.3 billion adjustment increase was made to nuclear liabilities primarily on account of the planned refurbishment of Bruce reactor units as announced by the Province of Ontario in December 2015.

(b) According to notes to the separate audited financial statements of the Ontario NFWA Trust, the UFF $8,587 million would include the $3,409 million in the Ontario NFWA Trust (see Table 3).

Financial guarantees are also in play. It is the *Nuclear Safety and Control Act* (Canada) that requires OPG to have funds available to discharge the current nuclear decommissioning and nuclear waste management liabilities. As required by the terms of the Ontario Nuclear Funding Agreement (ONFA), the Province has provided a Provincial guarantee to the Canadian Nuclear Safety Commission (CNSC), on behalf of OPG, for any shortfall between the CNSC consolidated financial guarantee requirement and the value of the Nuclear Funds. The value of the Provincial Guarantee of $1,551 million is in effect through to the end of 2017. Based on this guarantee, OPG paid a guarantee fee of $8 million to the Province for each of 2014 and 2015.

THE ONTARIO NUCLEAR FUND AGREEMENT

The Ontario Nuclear Fund Agreement (ONFA) is a bilateral agreement between the Province and Ontario Power Generation (OPG). It is voluminous and complex. A November 2004 office consolidation of the April 1999 Agreement is 136 pages long.

The ONFA anticipates the possibility of deep geologic repositories for storing nuclear waste. This is evident from the definition of used fuel eligible costs. According to Article 3 of the ONFA, used fuel eligible costs are defined (in 3.1.1) to mean reasonable costs including disposal, deep geological disposal, storage … where such costs are in accordance with an Approved Reference Plan.

Direct costs relating to management of used fuel are defined to include many things such as studies, assessments, planning, research & development, making applications, providing public information, selecting-acquiring and maintaining one or more sites for repository, as well as all costs reasonably relating to:

- Construction of a repository
- Transporting used fuel to a repository
- Operating and maintaining any repository
- Handling containers
- Final closure and sealing of each repository
- Maintenance, insurance, security and monitoring of closed and sealed repositories
- Decommissioning of each repository including decontamination and site restoration.

It is the ONFA Reference Plan that sets the level of contributions to be paid into the Used Fuel Fund (UFF) and the Decommissioning Fund (DF). The full 2012-2017 ONFA Reference Plan is apparently some 4,000 pages long and contains highly detailed technical evaluations and cost estimating information for thousands of work program elements. It is also a confidential document and not publicly available. In its place, in October 2016 the OPG provided OEB summary level report information for the currently approved 2012-2017 Reference Plan Update. From this, I constructed Table 5 showing changes in approved total cost estimates for used fuel long-term management (also known as Used Fuel Disposal).

Table 5: Change in approved cost estimates for OPG long term management of used nuclear fuel

ONFA Reference Plan	# Fuel Bundles M	$ M in current year dollars – April 1, 1999 forward	$ M in constant 2012 dollars – April 1, 1999 forward	Change $ M in constant 2012 dollars
1999	2.23	8,766	12,460	
2007 - 2012	2.95	14,234	16,317	3,857
2012 - 2017	4.02	21,291	21,291	4,974

Source: Pages 34-48 of 2012 ONFA Reference Plan Update – 2011

From this we can again see just how large the estimated costs are for long-term management (disposal) of used nuclear fuel ($21.3 billion) and how costs can escalate as time marches on and the amount of used nuclear fuel increases.

HOW COSTS ARE PAID FOR MANAGING NUCLEAR WASTE

Costs for managing nuclear waste are paid for in several ways including use of special segregated/trust funds, Provincial contributions, and by hydro customers/ratepayers. Hydro customers pay most of the freight through electricity rates.

Through enquiries with the Ontario Energy Board (OEB), I was provided with links to certain documentation to be informed of the following basic things:

- The OEB sets payment amounts (rates) for production from Pickering and Darlington that reflect expenses related to nuclear liabilities.

- The OEB does not "rate" regulate Bruce Power. OPG leases the Bruce Nuclear Generating Stations to Bruce Power L.P. Ontario Regulation 53/05 provides that the OEB shall ensure that OPG recovers all the costs it incurs with respect to the Bruce Nuclear Generating Stations, and that any revenues earned from the Bruce Lease in excess of costs be used to offset the nuclear payment amounts for production from Pickering and Darlington.

- The total cost recovered from ratepayers with respect to nuclear liabilities was about $2.7 billion over the past eight years. The costs to manage nuclear waste as stored at nuclear stations or at nearby facilities (for L&ILW) are internally funded by OPG and factored into electricity rates in order to provide revenue for that purpose.

- In May 2016, OPG was seeking OEB approval for the recovery of $2.3 billion (after tax) with respect to nuclear liabilities for the period 2017 to 2021.

- The future costs for the long-term management of nuclear related waste are funded through segregated trust funds. OPG contributions to segregated funds for meeting future nuclear liabilities and such expenditures are also recovered from ratepayers.

I also searched through OPG documents (case EB-2016-0152) as provided to OEB as part of OPG's latest application for rate increases with regard to the Darlington Refurbishment Project (DRP). There are hundreds of documents. I focussed on those labelled application and indicating costs and then looked for costs in relation to nuclear waste. Here is a summary of what I saw:

- A breakdown (in Exhibit D2-2-8) of the Darlington refurbishment project costs of $12.8 billion is provided by category/work bundles. The largest single item is $3.6 billion for re-tube and feeder replacement. The next largest single item is a contingency of $1.7 billion followed by interest of $1.4 billion. Relatively small amounts are shown for fuel handling ($198 million), safety improvements ($205 million), and "nuclear safety" function ($83 million).

- The Darlington Refurbishment Project (DRP) includes Operating-Maintenance & Administrative (OM&A) expenditures for removal costs and low and intermediated level waste (L&ILW) variable expenses related to disposal costs (also referred to as tipping fees) as these costs are determined and charged to the project based on the volume of waste. OPG was seeking OEB approval of OM&A costs totalling of $126.9 million from 2017 to 2021. This is made up of mainly of $112.4 million in costs to remove assets plus $14.0 million for L&ILW variable expenses.

- OPG requested approval (per submission Exhibit F2) of nuclear fuel costs for 5 years from 2017 to 2021 totalling $1.1 billion for <u>both Darlington and Pickering</u>. In total, nuclear fuel costs for five years are forecast to include:

    1. The weighted average cost of manufactured uranium fuel bundles loaded into a reactor - $806 million in total - $333 million for Darlington and $473 million for Pickering. This translates to $4.15 per MWh to $4.48 per MWh for the two stations.

    2. Used nuclear fuel storage and disposal - $287.7 million.

    3. Fuel oil, which is used to run stand-by generators at OPG's nuclear stations - $22.5 million.

I was unable to identify anything specific for the long-term management of nuclear waste, in particular used nuclear fuel.

The OEB kindly provided public document C2-1-1 dated May 2016. This dealt with the revenue requirement impact of nuclear liabilities where OPG was seeking recovery of $2.29 billion over the five year period 2017 to 2021 (referred to as "test" period) with regard to both prescribed facilities (Pickering and Darlington) and Bruce facilities.

OPG's nuclear liabilities represent the present value of OPG's obligation for the life-cycle costs of <u>**five nuclear waste management and decommissioning programs**</u>:

1. Decommissioning of nuclear stations – placing stations into a safe state at end of their useful lives.

2. Used Fuel Storage – the <u>**interim**</u> storage of used nuclear fuel in dry storage containers at nuclear station sites prior to their ultimate long-term disposal

3. Used Fuel Disposal – <u>**long term**</u> management of used fuel based in the Adaptive Phased Management concept accepted by the Government of Canada.

4. L&ILW Storage – transportation, processing and **interim** storage of low-level and intermediate level waste (L&ILW) at the OPG owned and operated Western Waste Management Facility (near the Bruce nuclear site), prior to long-term disposal.

5. L&ILW Disposal – **long term** management of L&ILW generated at nuclear sites – a proposed deep geologic repository adjacent to the Western Waste Management Facility.

I also found a public document providing supplementary evidence (to Exhibit C2-1-1) on nuclear liabilities as provided by the OPG to the OEB in February 2017 (re: EB-2016-0152 Exhibit C2). This 27 page document reveals important but complicated long-term funding and accounting arrangements regarding OPG's nuclear waste management and decommissioning liabilities. What I took from this document elaborates on information provided earlier in this paper:

- Since 2003 there is an Ontario Nuclear Funds Agreement (ONFA) between the Province and OPG. This bilateral agreement sets out OPG's funding obligations for the **long-term programs of lifecycle nuclear liabilities through contributions to segregated funds**. This recognizes the fact that such liabilities will be discharged many years after nuclear generating stations have closed. The agreement also provides for the Province to limit OPG's financial exposure in relation to the cost of used fuel management and for the Province to support financial guarantees to the Canadian Nuclear Safety Commission.

- There are **two segregated funds** for purpose of funding future costs. The funds are held in third-party custodial accounts:

    1. **Used Fuel Fund** (UFF) to fund the life-cycle costs of long-term nuclear used fuel management. OPG has made quarterly contributions to this fund ever since the fund's inception in 2003 and effectively as of OPG's creation in 1999. As at December 31, 2015 the UFF had a reported balance of $8.6 billion. This includes the $3.4 billion Ontario NFWA Trust as required by the *Nuclear Fuel Waste Act* (Canada).

    2. **Decommissioning Fund** (DF) to fund the life-cycle costs of nuclear decommissioning (reactor shut down/closure) and long-term low & intermediate level waste management (L&ILW). The Province made a substantial contribution to this fund in 2003 in amount of $2.4 billion via the Ontario Electricity Financial Corporation. OPG has not made a contribution to the DF since it has been fully funded or overfunded each time a new contribution scheduled was established based on an approved ONFA reference plan which is updated every five years. The DF had a reported $6.5 billion in it as at December 31, 2015.

- Since OPG owns Bruce and leases it to Bruce Power, OPG obligations and segregated funds are intended to cover that station as well as the Pickering and Darlington stations operated by OPG.

- ONFA requirements for the UFF is that the costs for the first 2.23 million fuel bundles – the estimated lifecycle quantity expected to be produced by the stations since OPG's inception in 1999 – be funded over assumed operating periods of the nuclear stations. These operating periods did not contemplate subsequent station refurbishment and extended operation decisions. Therefore, reference plan operating periods were shorter than the operating lives now expected. ONFA required OPG to make a special one-time payment of $334 million into the UFF in 2007 to accelerate the funding of the underlying liabilities.

- The Province guarantees the rate of return earned by the UFF for the portion of the UFF attributed to the first 2.23 million used fuel bundles at a specified rate of 3.25% over the change in the Ontario consumer price index. The 2.23 million bundle level was exceeded in 2013. The portion of the UFF attributable to used fuel bundles above the 2.23 million bundle threshold is not subject to the Province's guaranteed return and earns a return based on the market performance (investment earnings) of the fund's assets. This portion is intended to only fund the incremental costs associated with the fuel bundles in excess of 2.23 million, which currently represents about one-quarter of the used fuel funding liability. The incremental costs do not include the fixed costs of the used fuel long-term management program.

- There is no Provincial guarantee with respect to rate of return for the Decommissioning Fund (DF) which earns a return based on market performance of the Fund assets. The target rate of return for the DF is 3.25% over the Ontario consumer price index.

- As at 31 December 2016, the UFF was considered by OPG to be marginally (<1%) overfunded (for the first time) and the DF overfunded (approximately 121%) relative to the corresponding funding liabilities per the 2017-2022 ONFA Reference Plan that is pending Provincial approval. This could change relative to funding requirements of a new ONFA Reference Plan (five years from now), either as a result of changes in the funding liabilities or due to below target fund asset performance. The ONFA Reference Plan is updated every five years.

- Costs for interim/temporary storage of nuclear waste (high, intermediate and low) incurred during the station's operating lives are internally funded from OPG's operating cash flow. These costs are not ONFA funded and cannot be drawn from segregated funds.

- Given the long-term duration of nuclear liabilities and evolving technologies, there is inherent uncertainty surrounding the cost estimates and economic indices underpinning the liabilities which may increase or decrease over time as plans and assumptions are refined and conditions change. Cost estimates for major projects can continue to change as the quality of estimates improves, impacting future funding requirements. This especially for a used fuel deep geological repository that is in design phase and undergoing a long-term siting process.

- The OEB is required to ensure that OPG recovers the revenue requirement impact of its nuclear waste management and decommissioning liabilities arising from the current approved ONFA Reference Plan. The OEB is not involved in the development of the ONFA Reference Plan.

A chart is included in the document showing estimated amounts collected from ratepayers versus amounts expended by OPG. The amounts are summarized in Table 6 following.

Table 6. Estimated amounts collected from ratepayers versus amounts expended by OPG for nuclear liabilities – from April 1, 2008 to December 31, 2016

Prescribed Facilities – Pickering & Darlington nuclear	**$ million**
Total amounts recovered from ratepayers	1,748.8
OPG contributions to segregated funds	1,188.9
OPG internally funded expenditures on nuclear liabilities	600.7
Total amounts expended by OPG	1,789.6
Excess of Amounts Expended over Amounts Recovered- Prescribed Facilities (pre-tax)	40.9
Bruce Facilities	
Actual Bruce Lease Net Revenues Impact	1,011.2
OPG contributions to segregated funds	802.9
OPG internally funded expenditures on nuclear liabilities	449.6
Total amounts expended by OPG	1,252.5
Excess of Amounts Expended over Amounts Recovered- Bruce Facilities (pre-tax)	241.3
Summary	
Total OPG contributions to segregated funds	1,991.8
Total OPG internally funded expenditures on nuclear liabilities	1,050.2
Total OPG expenditures	**3,042.0**
Total amounts recovered	2,760.0
Total excess of amounts expended over amounts recovered	282.0

MAIN POINTS SO FAR

Time for a stop – check – and recap. The following key things are taken from all the preceding thus far:

- Ontario is highly dependent on nuclear power and continues accumulating a large amount of nuclear waste. And, Ontario is staying with CANDU heavy water technology and not light-water reactors as used in other countries.

- Nuclear waste lasts essentially forever and is a multi-generational, multi-dimensional, and multi-billion dollar governance and management problem. It poses political, social, scientific, technological, safety, environmental, and financial challenges unlike any other.

- The costs for managing nuclear waste are in the billions, roles and responsibilities are shared among various players, and costs spread out for payment over decades – making accountability and transparency more difficult to achieve.

- As included in electricity rates, hydro customers pay almost all OPG expenditures associated with nuclear waste liabilities/costs.

- Large costs loom for two deep geological repositories for the long-term disposal of nuclear waste. A repository for used nuclear fuel is estimated to cost $18 to $28 billion.

- Funding and cost estimations for nuclear liabilities/costs will change over time creating uncertainty about what the eventual costs will be for the long-term management of nuclear waste.

- There is a potential funding gap. This is discussed further in the next section.

POTENTIAL FUNDING GAP FOR USED NUCLEAR FUEL DISPOSAL

There is exposure to a funding gap or shortfall given the large difference between the Used Fuel Fund (UFF) balance and the estimated total costs for long term management/disposal of used nuclear fuel waste. A potential funding gap or lag is apparent in two ways:

a. **An accounting gap**. As measured by established accounting and detailed earlier in Table 3, there is a difference/gap of $4.2 billion between OPG's used nuclear fuel related **fund assets** ($8.6 B) and corresponding nuclear **liabilities** ($12.8 B) as at December 31, 2015. This gap is covered in the sense that OPG had a total equity of $10 billion (total of all assets is greater than total of all liabilities). Also, the Annual Report and Financial Statements of OPG for the year ending December 31, 2016 are not yet published and perhaps the gap changed during 2016.

b. **An apparent funding gap relative to total cost estimates.**

   The current approved ONFA Reference Plan estimated costs for long-term management of used nuclear fuel to be $21.3 billion (in 2012 $). Similarly in the same ballpark, the Nuclear Waste Management Organization (NWMO) estimates the cost of a deep geologic repository (DGR) to be between $18.3 billion (base case) to $28.4 billion (in 2015 $).

   When the 2015 NWMO base case estimate of $18.3 billion (in 2015 $) is compared to the $8.6 billion in OPG's Used Fuel Fund (UFF) as of December 2015, the result is a difference/gap of about $7.9 billion when costs are adjusted for a 90% Ontario proportion (see Table 7 following).

   Noted are:

   1. Amounts contributed by OPG into the UFF appear to be relation to an inventory of 2.23 million used nuclear fuel bundles. OPG's financial exposure with respect to the cost of used fuel is capped for the first 2.23 million used fuel bundles. This

level was exceeded in 2013. In June 2016 OPG had approximately 2.5 million used nuclear fuel bundles.

2. The 2.23 million bundle level is below the projected planned level for a deep geologic repository (DGR) for permanently storing between a 3.6 million and 7.2 million bundles.

3. UFF contributions are not provided for the fixed costs of a deep geological repository (DGR) for used nuclear fuel waste and funding of incremental costs is limited to the return earned on nuclear fund assets.

4. While cost estimates factor in transportation, it is not clear that funding contributions include the future eligible cost of safely transporting millions of used nuclear fuel bundles by road over very long distances from station sites in Ontario and elsewhere to a deep geologic repository likely somewhere in Ontario.

5. After searching websites, I was unable to identify who, if anyone, has oversight responsibility for independently assuring that funding for nuclear waste management is appropriate and sufficient. It does not appear as a tasking for any of CNSC, OEB, or the Independent Electricity System Operator (IESO as now merged with Ontario Power Authority). These entities are not party to the Ontario Nuclear Funds Agreement. As mentioned earlier, the OEB is involved only from a regulatory cost perspective in approving how OPG's nuclear liability costs are recovered in payment amounts, which is not necessarily based on the contributions OPG makes to segregated funds.

For these reasons, there is potential that funds set aside for eventual long-term management of used nuclear fuel would not be sufficient relative to the full costs for storing ever increasing amounts of used nuclear fuel in a DGR and safely transporting used nuclear fuel to it over many years.

While noting this potential, the OPG had in February 2017 reported to the OEB that the UFF, for the first time, was marginally (<1%) overfunded as of December 2016 relative to funding obligations as per the new 2017 ONFA Reference Plan as submitted to the Province on January 30, 2017 and pending approval. OPG expects this to result in overall zero required contributions to the UFF (and also to the Decommissioning Fund) until the next ONFA reference plan is approved. Prior to 2017, the OPG made quarterly contributions to the UFF ever since the fund's inception. How UFF overfunding is determined is not discerned from documentation reviewed.

Table 7 following presents current and future value calculations. This to project funds and costs into the future to see how the UFF balance might stand up relative to estimated total costs for long-term management of used nuclear fuel by use of the proposed DGR.

Assuming everything the same and no further contributions to the UFF, the following table assumes a 15 year time period (two years before construction on a DGR might commence), UFF earnings of 5% compounded half yearly, and an annual 1.7% CPI increase (latest annual CPI change for Ontario excluding energy costs) to account for inflation on 2015 dollar cost estimates for the APM-DGR project. Values are calculated for each of three scenarios. The midrange values are calculated using a simple midpoint between the NWMO base case of 3.6 million used nuclear fuel bundles and the upper alternative of 7.2 million bundles.

Table 7: Comparing the UFF with total estimated costs for permanent safekeeping of used nuclear fuel – $ Million

	Base Case – 3.6 million bundles		Midrange – 5.4 million bundles		Alternative – 7.2 million bundles	
	2015	**2030**	**2015**	**2030**	**2015**	**2030**
NWMO estimated costs for deep geologic repository (DGR)	18,328	23,601	23,288	29,989	28,249	36,376
Adjust costs to 90% Ontario proportion	16,495	21,241	20,960	26,990	25,424	32,738
Balance in Used Fuel Fund (UFF)	8,587	18,012	8,587	18,012	8,587	18,012
Difference – shortfall	7,908	3,299	12,373	8,978	16,837	14,726

This is only a conservative and simple projection to see if $8.6 billion in the UFF as of 2015 holds up over time relative to total costs as presently estimated by NWMO. It does not. As calculated, the best/base case scenario is a $3.3 billion funding gap by 2030 relative to 3.6 million bundles. The latest NWMO reference level of 4.6 million bundles would produce a gap closer to the midrange – around $5 billion by the year 2030. The actual results will of course depend on many factors between now and 2030 – including the amount of used fuel to be stored.

Effective as of 2015, there was an apparent $7.9 billion gap between the segregated UFF and total estimated costs for the long-term management of used nuclear fuel. This gap does not close within the assumptions made for Table 7. This was a puzzle as it was seemingly inconsistent with the UFF being fully funded/marginally overfunded as of December 2016.

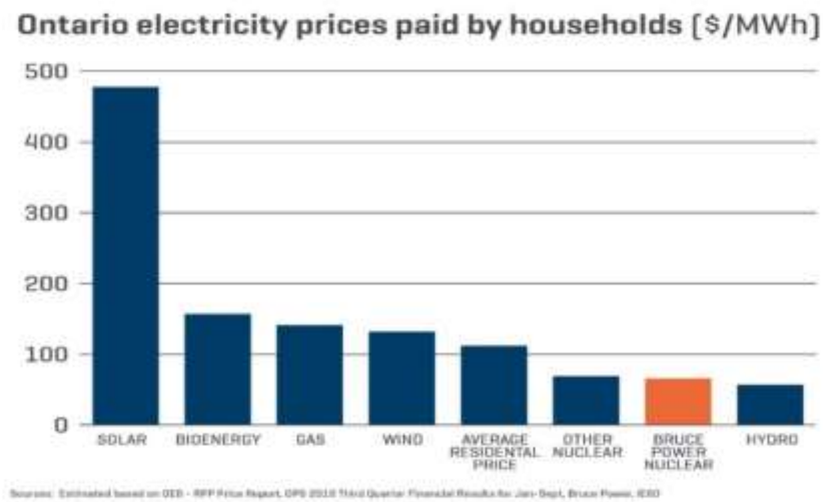
The puzzle might be explained since the UFF is apparently only intended to cover the period up to start of construction of a DGR and the post construction license costs. The costs to construct the DGR and transport fuel bundles are apparently not provided for at this time. Presumably then the cost to construct a DGR and safely transport used fuel to it would need to be financed at a future date. If so, then the cost would fall on future generations of ratepayers or taxpayers. At the moment, a measure of such deferment is $7.9 billion.

OPG indicates the costs now incurred for the Adaptive Phased Management (APM) project translates to only about 0.1 cents per kilowatt hour of electricity produced. By that measure the consumers of electricity today seem to be getting off “light”. But over time and megawatts of volume, pennies become billions of dollars.

IMPACT OF NUCLEAR WASTE ON ELECTRICITY RATES

As shown in a previous section and Table 6, hydro consumers (ratepayers) have been covering almost all of OPG's expenditures on nuclear liabilities/costs for managing nuclear waste. This to the tune of about $2.7 billion over past eight years and possibly $2.3 billion for the next five years, assuming OEB approves OPG requested payments – for a total of $5 billion over 13 years.

Nuclear energy is only slightly bettered by hydro – as shown in the follow chart as available on the website of Bruce Power. Bruce Power prominently promotes that it generates 30% of Ontario's electricity at 30% less than the average residential cost. It provides the following comparisons on its website.



The above comparisons are limited in as much that nuclear has uncertain long-term risks and costs. And, it appears the full long-term costs of managing nuclear waste are not as yet fully factored into current electricity rates. Also, since nuclear power accounts for about 60% of the volume of Ontario's electricity and hydro about 24%, the others do not have the benefit of large economies of scale that would tend to lower electricity prices per MWh.

NUCLEAR POWER PROFIT

Results also take on a different perspective when we look at revenue and profit yielded from nuclear and hydroelectricity generation. The following data is taken from information contained in OPG's 2015 Annual Report at page 11 and pages 36-39.

In terms of regulated revenue rates effective in 2015, Ontario Power Generation (OPG) was receiving $71.46 per megawatt hour (MWh) for nuclear generation and $45.12 per MWh for hydroelectricity generation (both include rate riders $12.17 for nuclear and $3.19 for hydro).

Table 8 compares operating results for OPG by three prime business segments. Surprisingly, nuclear did not yield OPG any profit for the two years 2014 and 2015 after taking into account losses from nuclear waste management. These financial results indicate hydroelectricity is carrying nuclear.

Table 8: Ontario Power Generation operating results by nuclear and hydro electricity

Nuclear regulated business segments - #1 generation and #2 waste	**2015 $million**	**2014 $million**
Revenue from nuclear electricity generation	3,245	3,015
Expenses (including $3M other loss in 2015)	3,247	2,798
Net income (loss) from nuclear electricity generation business segment #1	(2)*	217
Net (loss) on nuclear waste management business segment #2	(186)	(76)
Combined nuclear net income (loss) before interest & income taxes	**(188)**	**141**
Hydroelectricity regulated segment #3	**2015**	**2014**
Revenue	1,619	1,417
Expenses and other loss ($3m for 2015, $2m for 2014)	969	915
Net income from hydroelectricity generation before interest, income taxes, & extraordinary item for 2014	**650**	**502**

Source: OPG Annual Report 2015 – pages 36 to 39

*Compared to 2014, there was a drop in nuclear generation net income of $219 million due to an increase in outage days and outage activities in 2015.

Regulated hydroelectricity is more profitable/efficient for OPG than regulated nuclear generated electricity – at least for the past two reported years. For two years combined (2014 & 2015), nuclear business segments yielded a combined net loss of $(47) million compared to a profit on hydroelectricity of $1,152 million for the same two years – all before interest and income taxes.

For completion purposes, the other two business segments of OPG that are not price regulated are:

- The contracted generation portfolio yielding a net income of $264 million for 2015, and
- The services, trading and other non-generation business segment yielding a net loss of $(37) million for 2015.

Overall, OPG had a net income of $703 million in 2015 ($784 million in 2014) before other income, interest, and income taxes. After those, OPG had an operating net income of $417 million ($811 million in 2014).

COMMENTARY – FUEL FOR THOUGHT

A draft of this paper was reviewed by some professional colleagues and I thank them for their comments and encouragement. One, an international consultant to large corporations on environmental liabilities, asked – given facts, now what? Had to think hard.

Long-term nuclear waste management is not an immediate need and Ontario has had some 40 years to plan for it – with about 20 years remaining to site and begin constructing a deep geological repository for used nuclear fuel. To use an analogy, what is the game plan going into the third period? Some between period commentary follows:

1. Governments prefer to spend for positive outcomes within the political cycle to enhance chances of election rather than for long-term outcomes – so spending on nuclear waste management would likely not be a priority for the foreseeable future. However, at some point optimism collides with reality so the sooner the focus on reality the better.

2. Ontario just reduced hydro rates in response to public pressure and rates are going up for refurbishing Darlington – so increasing rates to further provide for nuclear waste disposal is likely a hard sell. However, sooner or later there is a price to pay for everything.

3. Disposal of nuclear waste cannot be project managed in conventional ways as there is no end date and many uncertainties. For example, according to a European Parliamentary Committee the long-term monitoring, maintenance and repair of deep geologic repositories is an impossibility. There is no ideal solution.

4. Other countries (e.g. UK, France, Japan) using light-water reactors recycle used nuclear fuel. Canada does not and apparently for three reasons – high cost, no need since Canada has large uranium reserves, and concern that plutonium could be diverted into nuclear weapons (source: TechNuclear.ca). It is also possible that recycling of used nuclear fuel creates a whole other set of waste posing additional risks to be managed.

5. Montreal's SNC-Lavelin jointly with China is developing "The Advanced Fuel CANDU Reactor" (AFCR) – a design that can make use of recycled uranium more efficient; a solution that is particularly good for China that imports uranium and uses light water reactors (source: Canadian Nuclear Association). Why not Canada? Apparently because CANDU reactors are more efficient than other reactors and there isn't enough uranium-235 left in Canadian used fuel to make economic sense. So it seems economics and security trump recycling of used nuclear fuel. I do not know whether the cost of long-term management of nuclear waste is factored into the economic/cost equations when assessing recycling of used nuclear fuel and whether or not AFCR was considered as an alternative to refurbishing existing CANDU reactors. As it is, Ontario is staying with CANDU and no sign of recycling – no new players off the bench.

6. When it comes to disposing of nuclear waste, in particular used nuclear fuel, we have only one chance to get it as "right as possible" given there is no ideal solution and circumstances change with new knowledge and technologies. Doing it cheap is far from

right and claims of savings should be examined with healthy skepticism. Hopefully it is done as cost-effectively as possible and with much transparency and accountability.

7. There is always the unexpected, human error, and a healthy need to fear certainty. The builders of the Titanic were certain it was unsinkable and Wall Street was too big to fail. Then, somehow no-one acted with counter-measures on new scientific information - 18 years before the March 2011 nuclear disaster – of the risk of a 15 metre tsunami wave breaching the Fukushima Daiichi nuclear station reactors on the north east coast of Japan that were built in the 1960's, but not to that specification. The reactors proved robust seismically, but vulnerable to tsunami (source: World Nuclear Association)

8. As with many large projects, the costs usually turn out much more than the budget. In this case, budgets are not as yet set – just cost estimates.

It comes down to whether or not Ontario's game plan for dealing with nuclear waste is robust and generally accepted by the public and we are prepared to pay for it.

Ontario's latest long-term energy plan (LTEP) of December 2013 is silent on nuclear waste. It spoke to reconfirming commitment to nuclear generation as the "backbone" of Ontario's supply-referring to refurbishment of Darlington and Bruce sites while cancelling plans to build two new reactors at Darlington. The LTEP emphasizes conservation and indicates a planned overall reduction in the proportion of nuclear power in the mix of energy sources.

At the same time, I did not see consideration of increased nuclear waste as part of the business case and analysis for refurbishing Darlington for another 30 years of service and extending Pickering. Maybe it is there in the background. We pay up front for recycling/disposal of electronics and tires, but not so for nuclear waste – it's buried in the price of electricity.

Perhaps the time is opportune for some innovation, hard thinking and openness and the plan for nuclear waste visibly integrated into long-term energy planning for Ontario. What can now, if anything, be incorporated into Adaptive Phased Management? Here are a few questions as fuel for thought:

- Less nuclear power means less waste to deal with. What progress is being made on the current plan to reduce nuclear energy production from 59% in 2013 to 42% by 2025, and increase renewables (including hydro) from 31% to 46% by 2025? Will this make a significant difference in the amount of used nuclear fuel being accumulated?

- Seeking system connectivity and anticipating the unexpected, what system-wide risk assessment process is in place for nuclear power and its waste and what counter-measures are taking place as may be appropriate and how does this tie in with nuclear disaster planning? What disaster plans are in place?

- Should segregated funding for nuclear waste be increased with consequential increase in hydro rates – perhaps not politically palatable – but if justified – do not snow plow. People usually pay attention to what they pay for and should know they are.

- What else can be done to reduce eventual costs and minimize nuclear waste? In so doing, is there opportunity? For example, might:

  - ✓ Spent nuclear fuel recycling and/or partitioning and transmutation of long-lived radionuclides (e.g. uranium-235, strontium, caesium, americium-241, technetium-99, plutonium) be done so that the amount of fuel used is less and/or high level radioactive waste does not present as serious as a challenge to deep geological repositories?

  - ✓ Ontario begin further accelerating the reduction of nuclear energy in favour of renewables including modest or mini hydro-electric projects at a local level?

  - ✓ Ontario continue producing an oversupply of electricity that can be exported, or bring domestic production in line with domestic consumption – reducing need for nuclear?

  - ✓ Ontario be prepared to import more hydro-electricity from Manitoba and Quebec?

- Might the federal government share in the cost of long-term disposal of nuclear waste?

It is attributed that Albert Einstein said "Nuclear power is one hell of a way to boil water." Seems he was right in more ways than one.

CONCLUSION

There are many players involved in the management of nuclear waste including both federal and provincial government. The total cost is unknown for managing all radioactive waste in Canada and borne by taxpayers and/or hydro consumers. While nuclear energy is promoted as clean (no CO_2) and efficient for producing much of Ontario's electric power; nuclear waste is not.

Nuclear waste is virtually timeless and potentially dangerous of course if not well managed. It is a multi-generational and multi-dimensional governance and management problem. It poses political, social, scientific, technical, safety, environmental, and financial challenges unlike any other. Disposal of nuclear waste cannot be project managed in conventional ways as there is no end or walk away date and many uncertainties. It is a multi-billion dollar cost spread out for payment over decades. The cost is buried in electricity prices.

In such a structure and context, accountability and transparency for nuclear waste is difficult to achieve in a clear and comprehensive way.

Ontario hydro customers pay most of the costs for managing nuclear waste - about $2.7 billion over the past eight years and possibly $2.3 billion for the next five years; a total of $5 billion over thirteen years.

The dye is long cast for the use of nuclear generated electricity in Ontario. Ontario is married to CANDU technology and continues building up a large inventory of nuclear waste and the downstream costs for its long-term management.

A large bill looms on the horizon – this for a deep geological repository to store used nuclear fuel at a total estimated cost of between $18,3 billion and $28.4 billion (2015 $). At some point down the line, hydro consumers and/or taxpayers could be footing costs to construct such a repository and safely transporting used nuclear fuel to it. At the moment, there appears to be a deferral of costs to future generations in the order of $7.9 billion.

Surprisingly, nuclear is not all that profitable for OPG – reportedly losing about $47 million over years 2014 and 2015 on its two nuclear business segments compared to a hydroelectricity profit of $1,152 million. Hydro is carrying nuclear.

Lastly, the time is opportune to explicitly and more openly integrate planning for nuclear waste into long-term energy planning for Ontario. This would help bring the subject out of the shadows and into the light for all to better see.

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ATTACHMENT A: HOW NUCLEAR FUEL IS MADE

Source: **World Nuclear Association**

BRIEF OUTLINE

Uranium mines operate in some twenty countries, though about half of world production comes from just ten mines in six countries, in Canada, Australia, Niger, Kazakhstan, Russia and Namibia.

At conventional mines, the ore goes through a mill where it is first crushed. It is then ground in water to produce a slurry of fine ore particles suspended in the water. The slurry is leached with sulphuric acid to dissolve the uranium oxides, leaving the remaining rock and other minerals undissolved, as mine tailings.

However, nearly half the world's mines now use a mining method called in situ leaching. This means that the mining is accomplished without any major ground disturbance. Groundwater with a lot of oxygen injected into it is circulated through the uranium ore, extracting the uranium. The solution with dissolved uranium is pumped to the surface.

Both mining methods produce a liquid with uranium dissolved in it. This is filtered and the uranium then separated by ion exchange, precipitated from the solution, filtered and dried to produce a uranium oxide concentrate, which is then sealed in drums. This concentrate may be a bright yellow colour, hence known as 'yellowcake', or if dried at high temperatures it is khaki.

The uranium oxide is only mildly radioactive. (The radiation level one metre from a drum of freshly-processed uranium oxide about half that - experienced from cosmic rays - on a commercial jet flight.)

Yellowcake in a drum for storage or transport (Cameco)

Enrichment

The vast majority of all nuclear power reactors require 'enriched' uranium fuel in which the proportion of the uranium-235 isotope has been raised from the natural level of 0.7% to about 3.5% to 5%. The enrichment process needs to have the uranium in gaseous form, so on the way from the mine it goes through a conversion plant which turns the uranium oxide into uranium hexafluoride.

The enrichment plant concentrates the useful uranium-235, leaving about 85% of the uranium by separating gaseous uranium hexafluoride into two streams: One stream is enriched to the required level of uranium-235 and then passes to the next stage of the fuel cycle. The other stream is depleted in uranium-235 and is called 'tails' or depleted uranium. It is mostly uranium-238 and has little immediate use.

Today's enrichment plants use the centrifuge process, with thousands of rapidly-spinning vertical tubes. Research is being conducted into laser enrichment, which appears to be a promising new technology.

A small number of reactors, notably the Canadian CANDU reactors, do not require uranium to be enriched. CANDU reactors are heavy water reactors.

Fuel fabrication

About 27 tonnes of fresh fuel is required each year by a 1000 Megawatt Electric (MWe) nuclear reactor. Enriched UF_6 is transported to a fuel fabrication plant where it is converted to uranium dioxide powder. This powder is then pressed to form small fuel pellets, which are then heated to make a hard ceramic material. The pellets are then inserted into thin tubes to form fuel rods. These fuel rods are then grouped together to form fuel assemblies, which are several meters long.

Uranium dioxide in powder and pellet form (CANDU)

The number of fuel rods used to make each fuel assembly depends on the type of reactor. A pressurized water reactor may use between 121-193 fuel assemblies, each consisting of between 179-264 fuel rods. A boiling water reactor has between 91-96 fuel rods per assembly, with between 350-800 fuel assemblies per reactor.

ELBORATION

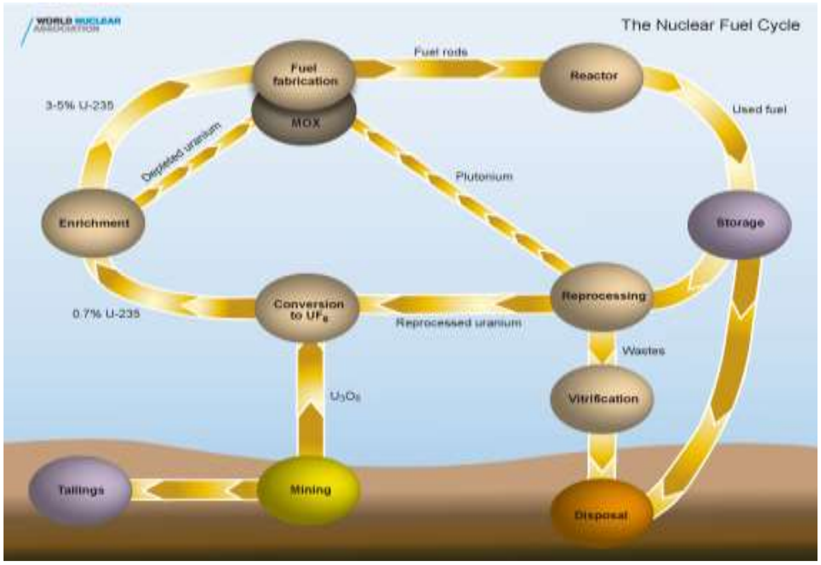
Nuclear reactors are powered by fuel containing fissile material. The fission process releases large amounts of useful energy and for this reason the fissioning components – U-235 and/or Pu- 239 – must be held in a robust physical form capable of enduring high operating temperatures and an intense neutron radiation environment. Fuel structures need to maintain their shape and integrity over a period of several years within the reactor core, thereby preventing the leakage of fission products into the reactor coolant.

The standard fuel form comprises a column of ceramic pellets of uranium oxide, clad and sealed into zirconium alloy tubes. For light water reactor (LWR) fuel, the uranium is enriched to various levels up to about 4.8% U-235. Pressurised heavy water reactor (PHWR) fuel is usually unenriched natural uranium (0.7% U-235), although slightly-enriched uranium is also used.

Fuel assembly performance has improved since the 1970s to allow increased burn-up of fuel. This is correlated with increased enrichment levels from about 3.25% to 5% and the use of advanced burnable absorber designs for pressurised water reactors, using gadolinium

The fabrication of fuel structures – called assemblies or bundles – is the last stage of the front end of the nuclear cycle shown in Figure 1, and represents less than 20% of the final cost of the fuel. The process for uranium-plutonium mixed oxide (MOX) fuel fabrication is essentially the same – notwithstanding some specific features associated with handling the plutonium component.

Figure 1: The closed nuclear fuel cycle, showing primary and recycled materials flow



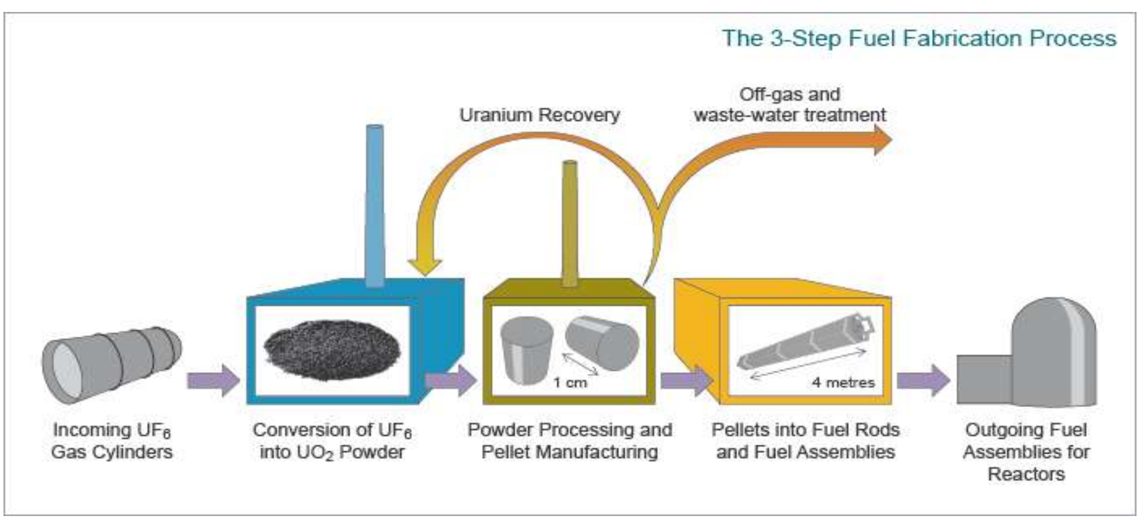
The industry is dominated by four companies serving international demand for light water reactors: Areva, Global Nuclear Fuel (GNF), TVEL and Westinghouse.

Nuclear fuel fabrication – process overview

There are three main stages in the fabrication of the nuclear fuel structures used in Light Water Reactors (LWR) and Pressurized Heavy Water Reactors (PHWR):

1. Producing pure uranium dioxide (UO_2) from incoming UF_6 or UO_3.
2. Producing high-density, accurately shaped ceramic UO_2 pellets.
3. Producing the rigid metal framework for the fuel assembly – mainly from zirconium alloy; and loading the fuel pellets into the fuel rods, sealing them and assembling the rods into the final fuel assembly structure.

Figure 2: The fuel fabrication process



UO_2 powder production

Uranium arrives at a fuel manufacturing plant in one of two forms, uranium hexafluoride (UF_6) or uranium trioxide (UO_3), depending on whether it has been enriched or not. It needs to be converted to uranium dioxide (UO_2) prior to pellet fabrication. Most fabrication plants have their own facilities for effecting this chemical conversion (some do not, and acquire UO_2 from plants with excess conversion capacity). Chemical conversion to and from UF_6 are distinct processes, but both involve the handling of aggressive fluorine compounds and plants may be set up to do both.

Conversion to uranium dioxide UO_2 can be done using 'dry' or 'wet' processes. In the dry method, uranium hexafluoride UF_6 is heated to a vapour and introduced into a two stage reaction vessel (e.g., rotary kiln) where it is first mixed with steam to produce solid uranyl fluoride (UO_2F2) – this powder moves through the vessel to be reacted with H2 (diluted in steam) which removes the fluoride and chemically reduces the uranium to a pure microcrystalline UO_2 product.

Wet methods involve the injection of UF6 into water to form a UO2F2 particulate slurry. Either ammonia (NH3) or ammonium carbonate (NH_3)2CO_3) is added to this mixture and the UO_2F_2 reacts to produce; ammonium diuranate (ADU, (NH_3)2U_2O_7) in the first case, or ammonium uranyl carbonate (AUC, UO_2CO_3. (NH_3)2CO_3) in the latter case. In both cases the slurry is filtered, dried and heated in a reducing atmosphere to pure UO_2. The morphology of UO_2powders deriving from the ADU and AUC routes are different, and this has a bearing on final pellet microstructure.

Wet methods are slightly more complex and give rise to more wastes, however, the greater flexibility in terms of UO_2powder properties is an advantage.

For the conversion of UO_3 to UO_2, water is added to UO_3 so that it forms a hydrate. This solid is fed (wet or dry) into a kiln operating with a reducing atmosphere and UO_2 is produced.

Manufacture of ceramic UO_2 pellets

The UO_2 powder may need further processing or conditioning before it can be formed into pellets:

- Homogenization: powders may need to be blended to ensure uniformity in terms of particle size distribution and specific surface area.
- Additives: U_3O_8 may be added to ensure satisfactory microstructure and density for the pellets. Other fuel ingredients, such as lubricants, burnable absorbers (e.g. gadolinium) and pore-formers may also need to be added.

Conditioned UO_2 powder is fed into dies and pressed biaxially into cylindrical pellet form using a load of several hundred MPa – this is done in pressing machines operating at high speed. These 'green' pellets are then sintered by heating in a furnace at about 1750°C under a precisely controlled reducing atmosphere (usually argon-hydrogen) in order to consolidate them. This also has the effect of decreasing their volume. The pellets are then machined to exact dimensions – the scrap from which being fed back into an earlier stage of the process. Rigorous quality control is applied to ensure pellet integrity and precise dimensions.

For most reactors pellets are just under one centimetre in diameter and a little more than one centimetre long. A single pellet in a typical reactor yields about the same amount of energy as one tonne of steaming coal.

Burnable absorbers (or burnable 'poisons') such as gadolinium may be incorporated (as oxide) into the fuel pellets of some rods to limit reactivity early in the life of the fuel. Burnable absorbers have a very high neutron absorption cross-section and compete strongly for neutrons, after which they progressively 'burn-out' and convert into nuclides with low neutron absorption leaving fissile (U-235) to react with neutrons. Burnable absorbers enable longer fuel life by allowing higher fissile enrichment in fresh fuel, without excessive initial reactivity and heat being generated in the assembly.

Gadolinium, mostly at up to 3g oxide per kilogram of fuel, requires slightly higher fuel enrichment to compensate for it, and also after burn-up of about 17 GWd/t it retains about 4% of its absorptive effect and does not decrease further. Zirconium diboride integral fuel burnable absorber (IFBA) as a thin coating on normal pellets burns away more steadily and completely, and has no impact on fuel pellet properties. It is now used in most US reactors and a few in Asia. China has this technology for AP1000 reactors.

Manufacture and loading of the fuel assembly framework

Nuclear fuel designs dictate that the pellet-filled rods have a precise physical arrangement in terms of their lattice pitch (spacing), and their relation to other features such as water (moderator) channels and control-rod channels. The physical structures for holding the fuel rods are therefore engineered with extremely tight tolerances. They must be resistant to chemical corrosion, high temperatures, large static loads, constant vibration, fluid and mechanical impacts. Yet they must also be as neutron-transparent as possible.

Assembly structures comprise a strong framework made from steel and zirconium upon which are fixed numerous grid support pieces that firmly hold rods in their precise lattice positions. These are made from zirconium alloy and must permit (and even enhance) the flow of coolant water around the fuel rod. The grid structures grip the fuel rod and so are carefully designed to minimise the risk of vibration-induced abrasion on the cladding tube – called 'fretting' wear.

All fuel fabricators have highly sophisticated engineering processes and quality control for the timely manufacture of their assembly structures.

Pellets meeting QA specifications are loaded into tubes made from an appropriate zirconium alloy, referred to as the 'cladding'. The filled tube is flushed with helium and pressurized with tens of atmospheres (several MPa) of this gas before the ends are sealed at each end by precision welding. A free space is left between the top of the pellet stack and the welded end-plugs – this is called the 'plenum' space and it accommodates thermal expansion of the pellets and some fission product gases. A spring is usually put into the plenum to apply a compressive force on the pellet stack and prevent its movement.

The completed fuel rods are then fixed into the prefabricated framework structures that hold the rods in a precisely defined grid arrangement.

In order to maximize the efficiency of the fission reaction the cladding and indeed all other structural parts of the assembly must be as transparent as possible to neutrons. Different forms of zirconium alloy, or zircaloy, are therefore the main materials used for cladding. This zircaloy includes small amounts of tin, niobium, iron, chromium and nickel to provide necessary strength and corrosion resistance. Hafnium, which typically occurs naturally with zirconium deposits, needs to be removed because of its high neutron absorption cross-section. The exact composition of the alloy used depends on the manufacturer and is an important determiner in the quality of the fuel assembly. Zircaloy oxidizes in air and water, and therefore it has an oxidized layer which does not impair function.

Safety considerations

Rigorous quality control measures are employed at all process points in order to ensure traceability of all components in case of failures.

The major process safety concerns at nuclear fuel fabrication facilities are those of fluoride handling and the risk of a criticality event if insufficient care is taken with the arrangement of fissile materials. Both risks are managed through the rigorous control of materials, indeed, fuel fabrication facilities operate with a strict limitation on the enrichment level of uranium that is handled in the plant – this cannot be higher than 5% U-235, essentially eliminating the possibility of inadvertent criticality.

CANDU REACTORS

Source: **Canadian Nuclear Association**

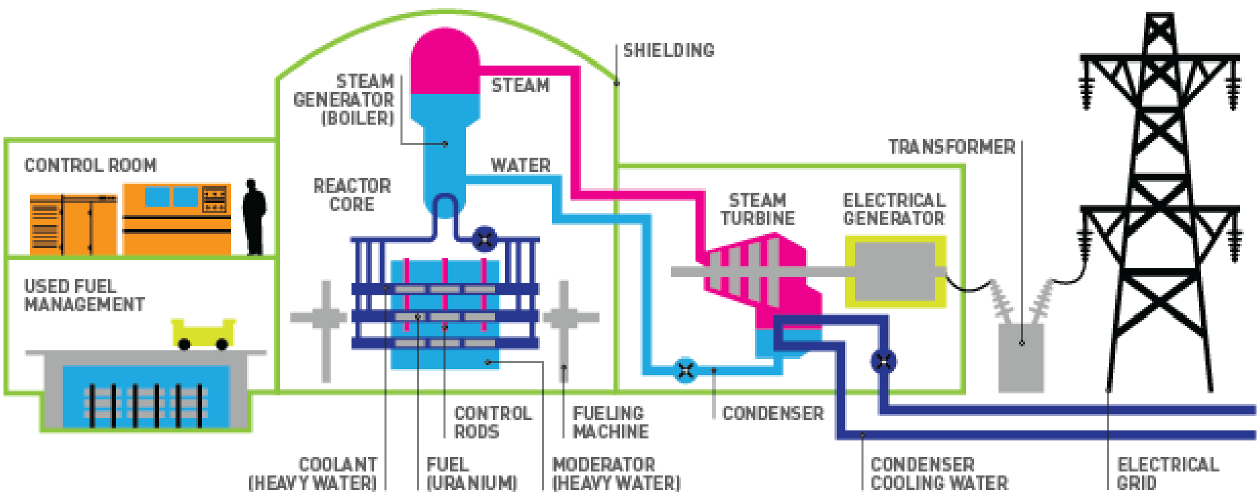
CANDU stands for Canada Deuterium Uranium, because it was invented in Canada, uses deuterium oxide (also known as heavy water) as a moderator, and uranium as a fuel.

CANDU reactors are unique in that they use natural, unenriched uranium as a fuel. With some modification, they can also use enriched uranium, mixed fuels, and even thorium. Thus, CANDU reactors are suited for using material from decommissioned nuclear weapons as fuel, helping to reduce global arsenals.

CANDU reactors can be refueled while operating at full power, while most other designs must be shut down for refueling. Moreover, because natural uranium does not require enrichment, fuel costs for CANDU reactors are low.

CANDU reactors safety systems are independent from the rest of the plant, and each key safety component has three backups. Not only does this redundancy increase the overall safety of the system, but it also makes it possible to test the safety system while the reactor is operating under full power. A schematic follows.

CANDU REACTOR SCHEMATIC



Canada has 19 CANDU reactors and has exported CANDU reactors to Argentina (1), China (2), India (2), Pakistan (1), Romania (2), and South Korea (4). In total, there are 31 CANDU reactors in operation globally, not including 16 reactors in India that are based on the CANDU design, but are not technically CANDUs.

ATTACHMENT B: URANIUM MINING IN CANADA

Source: World Nuclear Association

Canada was the world's largest uranium producer for many years, accounting for about 22% of world output, but in 2009 was overtaken by Kazakhstan.

- Production comes mainly from the McArthur River and Cigar Lake mines in northern Saskatchewan, which are the largest and highest-grade in the world.
- With known uranium resources of 582,500 tonnes of U_3O_8 (493,900 tU), as well as continuing exploration, Canada has a significant role in meeting future world demand.

Canada is a country rich in uranium resources and a long history of exploration, mining and generation of nuclear power. To 2014, more uranium had been mined in Canada than any other country – 485,000 tU, about one-fifth of world total.

Current production

Canada's uranium production is tabulated below, and while relatively constant over the last few years, its share of world production has dropped from about 20% to 15%.

The main uranium producers are Cameco and Areva Resources Canada. Cameco was formed in the 1988 merger of Saskatchewan Mining Development Corporation and the government-owned Eldorado Nuclear Ltd. The company issued its first public shares in 1991 and was fully privatized in 2002.

In the early 1990s, the Saskatchewan government had considered phasing out uranium mining in the province. This policy was later reversed after a joint Federal-Saskatchewan study panel on health, safety, environment and socio-economic impact found that the jobs provided by the industry would be hard to replace and that the environmental impact of mining could be minimized. Today, the provincial government actively supports uranium mining, and all new Saskatchewan uranium mines have international ISO 14001 environmental certification.

Annual uranium production (tonnes U_3O_8)[a]

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
McArthur River	8492	8492	7528	8654	9029	9064	8868	9135	8675	8673	8173
Cigar Lake	-	-	-	-	-	-	-	0	156	5124	7863
McClean Lake	814	867	1476	1637	785	0	0	0	51	0	0
Rabbit Lake	2326	1821	1613	1706	1726	1721	1744	1872	1889	1912	505
Total	11632	11180	10617	11997	11540	10785	10612	11007	10771	15709	16541
cf. World	46499	48680	51611	59772	63285	63085	68805	70015	66297	71343	

ATTACHMENT C: REPOSITORIES IN OTHER COUNTRIES

SOURCE: WIKIPEDIA

The most long-lived radioactive wastes, including spent nuclear fuel, must be contained and isolated from humans and the environment for a very long time. Disposal of these wastes in engineered facilities, or repositories, located deep underground in suitable geologic formations is seen as the reference solution. The International Panel on Fissile Materials has said:

> *It is widely accepted that spent nuclear fuel and high-level reprocessing and plutonium wastes require well-designed storage for periods ranging from tens of thousands to a million years, to minimize releases of the contained radioactivity into the environment. Safeguards are also required to ensure that neither plutonium nor highly enriched uranium is diverted to weapon use. There is general agreement that placing spent nuclear fuel in repositories hundreds of meters below the surface would be safer than indefinite storage of spent fuel on the surface.*

However, even a storage space hundreds of metres below the ground would, in many parts of the developed world, have to be able to withstand the pressures of one or more future glaciations with thick sheets of ice resting on top of the rock, deforming it and creating internal strains, which is being taken into consideration by agencies preparing for long-term waste repositories in Sweden, Finland, Canada and some other countries that would have to expect a renewed ice age.

Despite a long-standing agreement among many experts that geological disposal can be safe, technologically feasible and environmentally sound, a large part of the general public in many countries remains skeptical.[One of the challenges facing the supporters of these efforts is to demonstrate confidently that a repository will contain wastes for so long that any releases that might take place in the future will pose no significant health or environmental risk.

Nuclear reprocessing does not eliminate the need for a repository, but reduces the volume, the long-term radiation hazard, and long-term heat dissipation capacity needed. Reprocessing does not eliminate the political and community challenges to repository siting.

Deep geologic disposal has been studied for several decades. Major underground test facilities are listed below followed by a list of countries having repositories or considering them.

UNDERGROUND TEST FACILITIES

Country	Facility name	Location	Geology	Depth	Status
Belgium	HADES Underground Research Facility	Mol	plastic clay	223 m	in operation 1982[10]
Canada	AECL Underground Research Laboratory	Pinawa	granite	420 m	1990–2006[10]
Finland	Onkalo	Olkiluoto	granite	400 m	under construction[11]

Country	Facility name	Location	Geology	Depth	Status
France	Meuse/Haute Marne Underground Research Laboratory	Bure	mudstone	500 m	in operation 1999[12]
Japan	Horonobe Underground Research Lab	Horonobe	sedimentary rock	500 m	under construction[13]
Japan	Mizunami Underground Research Lab	Mizunami	granite	1000 m	under construction[13][14]
Korea	Korea Underground Research Tunnel		granite	80 m	in operation 2006[15]
Sweden	Äspö Hard Rock Laboratory	Oskarshamn	granite	450 m	in operation 1995[10]
Switzerland	Grimsel Test Site	Grimsel Pass	granite	450 m	in operation 1984[10]
Switzerland	Mont Terri Rock Laboratory	Mont Terri	claystone	300 m	in operation 1996[16]
USA	Yucca Mountain nuclear waste repository	Nevada	tuff, ignimbrite	50 m	1997–2008[10]

REPOSITORY SITES

Country	Facility Name	Location	Waste	Geology	Depth	Status
Argentina	Sierra del Medio	Gastre		granite		under discussion[17]
Belgium			high-level waste	plastic clay	~225 m	under discussion
Canada	OPG DGR	Ontario	200,000 m^3 L&ILW	argillaceous limestone	680 m	license application 2011[18]
Canada			spent fuel			under discussion
China						under discussion
Finland	VLJ	Olkiluoto	L&ILW	tonalite	60–100 m	in operation 1992
Finland		Loviisa	L&ILW	granite	120 m	in operation 1998
Finland	Onkalo	Olkiluoto	spent fuel	granite	400 m	under construction
France			high-level waste	mudstone	~500 m	siting
Germany	Schacht Asse II	Lower Saxony		salt dome	750 m	closed 1995

Country	Facility Name	Location	Waste	Geology	Depth	Status
Germany	Morsleben	Saxony-Anhalt	40,000 m^3 L&ILW	salt dome	630 m	closed 1998
Germany	Gorleben	Lower Saxony	high-level waste	salt dome		proposed, on hold
Germany	Schacht Konrad	Lower Saxony	303,000 m^3 L&ILW	sedimentary rock	800 m	under construction
Japan			high-level waste			under discussion
Korea	Gyeongju		L&ILW		80 m	under construction
Sweden	SFR	Forsmark	63,000 m^3 L&ILW	granite	50 m	in operation 1988
Sweden		Forsmark	spent fuel	granite	450 m	license application 2011
Switzerland			high-level waste	clay		siting
United Kingdom			high-level waste			under discussion
USA	Waste Isolation Pilot Plant	New Mexico	transuranic waste	salt bed	655 m	in operation 1999

Country	Facility Name	Location	Waste	Geology	Depth	Status
USA	Yucca Mountain Project	Nevada	70,000 ton HLW	ignimbrite	200–300 m	proposed, canceled 2010