USED FUEL MANAGEMENT IN CANADA, FINLAND AND SWEDEN – SIMILARITIES AND DIFFERENCES

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Abstract

Of the nations that have comprehensive programs in place for long-term management of used nuclear fuel, Canada, Finland and Sweden have chosen similar reference concepts: the used fuel will be encapsulated in copper containers, which in turn will be surrounded by bentonite clay and emplaced in a deep geological repository (DGR).

With regards to implementation status, Finland – as the first country in the world – received a construction licence for its DGR in November 2015. In Sweden, the site selection process has also concluded and the licence application is currently undergoing regulatory review. In Canada, site selection was initiated in 2010 and remains in progress.

By comparing key features of the countries' respective prerequisites, selected approach, current status and future plans, similarities and differences between the Canadian, Finnish and Swedish programs are explored. Relative advantages and disadvantages are highlighted and discussed.

1. Introduction

As part of their respective plans for long-term management of used nuclear fuel, three countries – Canada, Finland and Sweden – have selected copper to act as a corrosion-barrier in containers designed for long-term isolation of the used fuel bundles. Following encapsulation in the copper containers, the used fuel will be transferred down into the bedrock to a depth of approximately 500 m and, surrounded by highly compacted bentonite clay, emplaced in a DGR.

The three countries have several common characteristics: low population density; aboriginal communities; nature and climate that have made outdoor activities like canoeing, fishing, hiking and skiing popular; extensive experience in mining and metal industries; and geologically stable but requiring a design that can withstand future ice ages. While at the same time, key differences exist in terms of nuclear reactor programs, used fuel inventories, and systems in place for interim storage and transportation.

The aim of this paper is to shed light on key similarities and differences by comparing a range of aspects related to prerequisites, selected approach, current status and future plans. The scope is primarily focused on technical and organizational aspects. It is limited to management of used fuel, although it is recognized that parallels worth exploring also exist with regards to facilities and plans for managing low- and intermediate-level waste (L&ILW).

Unless specified, information in the tables below has been obtained or derived from: (a) the latest report under the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* [1] [2] [3] [4]; or (b) the respective implementing organization's web sites in February 2016 (www.nwmo.ca, www.posiva.fi/en and www.skb.se). To facilitate comparisons, applicable numbers have generally been rounded and converted to the same units.

2. Nuclear power programs

All three countries have been operating large-scale reactors since the 1970s and rely on nuclear plants for a significant portion of their power supply. Both Canada and Sweden embarked on developing and commissioning their own reactor designs, whereas Finland has opted to rely on foreign suppliers. In Table 1, key aspects of the respective country's nuclear power fleet are highlighted; smaller reactors also exist in all three countries, but given that large-scale reactors are the main driver of a nation's need for a long-term management solution, Table 1 includes only power reactors considered commissioned at full scale.

Table 1 Large-scale nuclear power plants in Canada, Finland and Sweden.

	Canada	Finland	Sweden
Large reactors completed to date	22	4	12
Sites with large reactors	5	2	4
Reactor type	CANDU	BWR (2) VVER (2)	BWR (9) PWR (3)
Total installed capacity to date	15,150 MWe [5]	2,750 MWe	10,620 MWe*
Start year range	1971-1993 [5]	1977-1981	1972-1985
Large reactors shut down to date	3	0	2
Planned to shut down in < 10 years*	6	0	4
Current new build plans	Uncertain	2** (new reactor types)	Cancelled
Total planned to operate > 2026	13	6	6

* Information derived from statements on the various reactor owners' web sites in February 2016 (www.opg.com, www.vattenfall.se, www.okg.se and www.barsebackkraft.se).

** Refers to Olkiluoto 3 and Hanhikivi in Pyhäjoki, whereas it is understood that Olkiluoto 4 has been cancelled.

Although the extent of the three countries' reactor programs can be viewed as comparable, some key differences with impacts on used fuel management are noted:

- With two or more reactor types, Finland and Sweden are expected to have greater complexities associated with accommodating different fuel geometries, both with regards to copper container design as well as equipment for handling, storage and transportation.

- Canada and Sweden – both having already shut down a few reactors and planning to shut down even more within the next 10 years – are experiencing a decline in the rate of used fuel generated; Finland, on the contrary, will be increasing its rate in the coming decade.

Table 2 Used fuel inventories – current and projected.

	Canada	**Finland**	**Sweden**
Fuel bundle length – large reactors	0.5 m	3.2 m 4.1 m 4.9 m [6]	4.3 m 4.4 m [7]
U-235 enrichment – large reactors	Natural uranium	Up to 5% [6]	Up to 5% [7]
Average burnup – large reactors	8.3 MWd/kgU [5]	43 MWd/kgU 57 MWd/kgU (max) [6]	40-45 MWd/kgU 60 MWd/kgU (max) [7]
Used fuel inventory – other reactors*	Various types 490 tU	One type 0.004 tU	Various types 45 tU
Mass currently in storage*	50,000 tHM	1,900 tHM	6,300 tU
Bundles currently in storage	2,500,000	13,000	32,000
Total mass* projected for DGR	90,000 tHM [5]	6,500 tU**	12,000 tU
Total bundles projected for DGR	4,600,000 [5]	30,000*** [6]	54,000*** [7]

* Units stated in accordance with the source; for purposes of this paper, tonnes of uranium (tU) and tonnes of heavy metals (tHM) can be used interchangeably.

** Excluding used fuel from the planned Hanhikivi nuclear power plant in Pyhäjoki, since its owner (Fennovoima Oy) is not a co-owner of Posiva and the plan for used fuel disposal is not yet known [3]. The amount is understood to be in accordance with the maximum amount in Posiva's construction licence.

*** Number of bundles in the source provided in the context of a different total mass than above (9,000 tU in Finland and 11,000 tU in Sweden); as such, the total number of bundles currently projected for the respective DGR is anticipated to be fewer than 30,000 in Finland and more than 54,000 in Sweden.

3. Used fuel inventories

Given the differences in nuclear power programs, corresponding differences emerge when comparing the three countries' used fuel inventories. Of the aspects outlined in Table 2, the following differences are particularly noteworthy, since they constitute key considerations for implementing a nation's used fuel management program:

- Compared to the CANDU fuel design, bundles used in the Finnish and Swedish reactor programs are much longer (6 to 10 times longer). Without prior fuel reprocessing or compaction, this gives Canada larger degrees of freedom in terms of copper container design. It is further noted that Finland has a significant difference between its shortest and longest bundles (1.7 m), compared to Sweden's modest difference in length (0.1 m).

- By the use of natural uranium in Canada's reactors, two interrelated consequences occur: the average burnup is several orders of magnitude lower, and the mass of used fuel is several orders of magnitude greater – all else being equal; the difference in mass is further enhanced since Canada has the largest nuclear power program of the three:

    - Compared to Sweden, Canada's both current and projected inventory is in the order of 8 times greater in terms of mass.

    - Compared to Finland, Canada's current inventory is in the order of 25 times greater, whereas this difference decreases to less than 15 times for the overall mass projected for emplacement in the DGR. This change in relative mass can be explained by a combination of: (a) the Finnish reactors' generally later start year; (b) the previous practice of transporting used fuel from the Loviisa plant to the Russian Federation (from 1981 to 1996) [3]; and (c) the Finnish new build plans.

- Given the small size of CANDU fuel, the differences in terms of number of used fuel bundles is even greater:

    - Compared to Sweden, Canada has – and is projected to continue to have – in the range of 80 times more bundles.

    - Compared to Finland, Canada currently has around 200 times more fuel bundles; at the end of life of the current and planned reactors, the difference is expected to decrease to around 150 times more for the same reasons as above.

- The total inventory projected in Sweden is larger than in Finland, both in terms of mass and number of bundles, but compared to Canada, the amounts are more comparable.

- The natural uranium and associated low average burnup of used CANDU fuel translate into comparative advantages for used fuel management in Canada: decay heat is easier to accommodate and criticality safety easier to assure. This simplifies handling and makes more compact designs conducive during all steps of the used fuel management process, including enabling layouts with higher 'used fuel density' in the DGR.

Regarding used fuel from reactors other than large-scale power reactors:

- Finland's situation is the simplest since it has a small amount (4.45 kgU from the FiR 1 research reactor), which by contract can be returned to the United States [3].

- Sweden's early reactor program was larger than Finland's and included a total of four reactors for research, demonstration, isotope production and/or combined heat and power. Some of that used fuel has been returned to the United States, but the majority (45 tU) is stored in water-filled pools (together with used fuel from the large reactors).

- Relative to the other two, Canada has the most complex situation with regards to used fuel from small reactors: the amount is 10 times greater than Sweden's (490 tU and increasing) and it is stored in a variety of structure types, distributed over multiple sites.

4. Interim storage facilities

Besides bundles that are being stored in pools directly adjacent to the reactors, all three countries have built stand-alone facilities for used fuel interim storage. In Canada and Finland, these facilities are located at each of the reactor sites, whereas Sweden has built a central interim storage facility on one of the four nuclear power plant sites. In Table 3, further aspects of the countries' current interim storage facilities and practices are highlighted.

Table 3 Interim storage of used fuel – current facilities and practices.

	Canada	**Finland**	**Sweden**
Storage location principle	On-site storage	On-site storage	Central storage
Sites with interim storage facilities	7*	2	1
Storage depth	Ground level	Ground level	In rock caverns, 30 m below ground
Storage environment	Wet and dry	Wet	Wet
Minimum storage period at reactor	6-10 years	1-5 years	0.75-1 year

* Including Chalk River and Whiteshell.

In terms of potential impact for long-term management, the following is noted:

- Of the three, only Canada has facilities for dry used fuel storage. Since the fuel needs to be dry when the copper containers are sealed, this is an advantage since it can reduce the need for drying, which is a potentially time-consuming step in the encapsulation process.

5. Implementing organizations

All three countries have established a separate organization for implementing a long-term management solution, see Table 4, but there are some key differences:

- In Canada and Finland, scope is limited to long-term management of used fuel, whereas Sweden has consolidated responsibilities. The larger scope in Sweden's case is reflected both in the number of employees and the number of facilities currently operated by SKB.
- In Canada, the responsibility to develop a repository concept was previously assigned to Atomic Energy of Canada Limited (AECL); in 2002, that responsibility shifted to the nuclear utilities, which were required to form a new waste management organization [2].

Table 4 Responsibilities for long-term management of used fuel.

	Canada	**Finland**	**Sweden**
Implementing organization	Nuclear Waste Management Organization (NWMO)	Posiva*	Swedish Nuclear Fuel and Waste Management Co (SKB)
Responsibility for funding	Used fuel owners	Used fuel owners	Used fuel owners
Organization form	Membership organization	Co-owned by reactor owners	Co-owned by reactor owners
Year established	2002	1995	1970s
Number of employees	140	100	500
Scope – time period	Long-term	Long-term	Interim storage and long-term
Scope – inventory	Used fuel	Used fuel	Used fuel and waste from operation and decommissioning
Facilities owned and operated	None**	Hard rock laboratory	Used fuel storage L&ILW repository Hard rock laboratory Canister laboratory Bentonite laboratory

* Excluding responsibility for used fuel from the future Hanhikivi nuclear power plant in Pyhäjoki, since its owner (Fennovoima Oy) is not a co-owner of Posiva and the plan for used fuel disposal is not yet known [3].

** AECL previously constructed and operated the Underground Research Laboratory (URL) in Manitoba. It has since been decommissioned and is undergoing closure [2].

6. Long-term management approach and implementation status

Canada, Finland and Sweden have all adopted direct disposal in a DGR as the reference concept for long-term used fuel management; that is, following a period of interim storage, the used fuel will be encapsulated and emplaced in a DGR – without prior reprocessing or compaction. At this time (February 2016), the key aspects of the respective reference design are understood to be as per Table 5 (with respect to the DGR) and Table 6 (with respect to the used fuel container and a plant where the encapsulation will occur). It is recognized that design development is ongoing in all the countries and that, as such, the reference designs outlined below are subject to change.

Table 5 Reference design – deep geological repository.

	Canada	Finland	Sweden
Bedrock type	Crystalline or sedimentary	Crystalline	Crystalline
Reference depth	500 m	400-450 m	500 m
Load-bearing component	Carbon steel	Cast iron	Cast iron
Used fuel container corrosion-barrier	Copper	Copper	Copper
Buffer material	Bentonite	Bentonite	Bentonite
Buffer emplacement	Ground level	At repository depth	At repository depth
Container transfer to repository depth	Hoisted/shielded	Hoisted/unshielded	By ramp/shielded
Footprint at repository depth	600 ha	300 ha*	300-400 ha

* Information received directly from Posiva.

Apart from the three DGR reference designs being strikingly similar, it is noted that:

- For the transfer down to repository depth, the countries have chosen different concepts.
- Despite the much larger inventory, the 'footprint' of Canada's used fuel DGR at repository depth is only about twice the size of Finland's and Sweden's. This can be attributed to the CANDU fuel's lower burnup and decay heat, as that enables more compact DGR designs (since heat load is a key limiting factor that drives distance required between containers – and consequently drives the overall DGR area at depth).

Table 6 Reference design – used fuel encapsulation.

	Canada	**Finland***	**Sweden**
Main container components	Steel basket Carbon steel pipe Copper coating	Cast iron insert 50-mm copper tube	Cast iron insert 50-mm copper tube
Container length	2.5 m	3.6 m 4.8 m 5.2 m	4.8 m
Container diameter	0.6 m	1 m	1 m
Container weight, including fuel	3 tonnes	19-29 tonnes	25-27 tonnes
Bundle capacity per container	48	12 4	12 4
Encapsulation plant location	At DGR	At DGR	At central interim storage facility
Total containers projected for DGR	100,000	3,325	6,000 [7]
Annual container throughput	2,500	25-40	150 (planning assumption)
Annual bundle throughput	120,000	480 (max)**	1,800 (max)**

* Data for the Finnish container reference design and throughput generally obtained or derived from [8].

** As different fuel types will be processed in a batched manner, the annual bundle throughput was calculated based on the assumption that only containers with 12-bundle configurations are processed during a given year.

With regards to the reference designs for used fuel encapsulation, the following is noted:

- The comparatively small and light container in the Canadian reference design will simplify lifting and transfer operations of both empty and filled containers. However, the annual throughput anticipated in the Canadian encapsulation plant is more than 15 times higher than in Sweden and in the range of 60-100 times higher than in Finland.

- In terms of fuel handling, the Canadian design will need to accommodate annual processing of around 70 and 250 times more bundles than the Swedish and Finnish plants respectively. The differences in scale is further enhanced by the Canadian prerequisites and container design, which require handling of: (a) used fuel modules (as most CANDU fuel is stored and will be transported in configurations of 96 bundles/module); and (b) steel baskets (in arrays of 12 bundles) prior to container sealing operations.

- Given the different fuel lengths, Finland's reference design includes three container sizes (in terms of length). This may complicate the design of encapsulation plant equipment, since each fuel type and associated container design will require process adjustments.

- With the prerequisite of a central interim storage facility in place, Sweden plans to build its encapsulation plant as an expansion to that facility – rather than at the DGR (although that option has also been considered). Consequently, the used fuel will arrive at the DGR site inside sealed, decontaminated copper containers (whereas in Canada and Finland, the used fuel will need to be transferred from a transport cask, prior to sealing the copper containers); as such, all handling of used fuel at the Swedish DGR site will be in the form of 'sealed sources.' This, in turn, means that no secondary waste will be generated at the Swedish site and that future decommissioning will be simplified.

Regarding status of site selection and licensing of a DGR, Finland is the first – and so far only – country in the world to have received a construction licence (in November 2015). In Sweden, the site selection process has also concluded and the licence application is currently undergoing regulatory review. In Canada, site selection was launched much later (in May 2010) but is now well underway. Further highlights regarding DGR site selection and licensing are provided in Table 7.

Table 7 Site selection and licensing.

	Canada	**Finland**	**Sweden**
Site selection status	In progress	Completed	Completed
Site selection timeline	2010-	1983-1999	1992-2009
Construction licence application status	Not submitted	Submitted end of 2012 Received November 2015	Submitted March 2011 Undergoing regulatory review
Scheduled start of used fuel disposal	Not specified; community-driven selection process	2020s	Early 2030s
Distance to nearest power plant site	To be determined	Co-located (Olkiluoto)	Co-located (Forsmark)
Distance to nearest interim storage site	To be determined	Co-located (Olkiluoto)	340 km (Oskarshamn)

7. Used fuel transportation – current experience and future plans

Key transportation aspects are outlined in Table 8, from which it can be concluded that:

- In Finland, a relatively small and simple transport system will be needed, since only a few casks per year will require off-site transportation – along one route – and over a relatively modest distance (straight-line distance of 270 km).
- In Sweden, the transport system is already in place (apart from special transport casks that will be required for containers), as SKB's second purpose-built ship (M/S Sigrid) will be able to accommodate the anticipated number of used fuel shipments to the DGR site.

Since a site has not yet been selected in Canada, no conclusions can be drawn, other than that a larger and more complex transport system will be required – since distances, number of routes and number of casks involved will be greater, regardless of where the DGR will be located.

Table 8 Used fuel transportation – current practices and plans.

	Canada	Finland	Sweden
Current experience and transport mode – on-site	Routinely Road	Routinely Road	Routinely Road
Current experience and transport mode – off-site	Small quantities Road	No current system; routinely 1981-1996 Rail	Routinely; national system in operation since 1982 Sea
Transport mode from storage site to DGR	Road and/or rail	Road planned; rail and sea also considered	Sea
Transport cask cargo	Bundles	Bundles	Copper containers
Number of transport routes	7*	1**	1
Distance to furthest interim storage site	To be determined	270 km**	340 km
Annual transport cask shipments – off-site	Dependent on transport cask design	4**	150

* Assuming that the used fuel DGR will not be co-located with an interim storage site.

** Excluding used fuel from the future Hanhikivi nuclear power plant, since its plan is not yet known [3].

8. Conclusion

Developing and implementing a long-term solution for used fuel is inherently challenging. Many of the countries that have developed comprehensive programs have paused – reorganized – and relaunched; those who to date have not are typically experiencing decade-long delays. Given the 'reset' that occurred at the turn of the millennium[1], Canada is generally viewed as belonging to the first of those categories. Sweden belongs to the second. Of the nations that have a program in place for long-term used fuel management, there is arguably only one that belongs to neither: Finland.

Given the similarities in characteristics and used fuel management approach, all three countries, however, would seem to have comparable prerequisites for reaching implementation – albeit with some relative advantages and disadvantages:

- Although Canada's significantly larger amount and longer transport distances pose challenges – relative advantages include: (a) bundles with short length and low decay heat, which give flexibility and enable compact designs; (b) a large portion of the used fuel already being in a dry state; and (c) the country's vast land mass.

- In Finland, the variation in fuel types and the new build plans add to the complexities and uncertainties – whereas relative advantages include: (a) having the smallest amount and number of fuel bundles; (b) the prospect of no 'other' used fuel requiring disposal (apart from the large reactors); and (c) the limited extent of off-site transports required.

- In Sweden, complicating factors include multiple fuel types and the annual amount of fuel requiring drying (as part of the encapsulation process) – but relative advantages include: (a) having the same organization responsible for both the existing storage and planned DGR; (b) 'in-house' research laboratories for all barriers in the DGR system; and (c) a transport system that already is in place, with decades of operating experience in transporting annual volumes comparable to when the DGR will be fully operational.

Yet, it is clear that the pace in Finland has been significantly faster than in both Canada and Sweden. This begs the question of whether there are other aspects than those explored in this paper that might explain this difference, including social and cultural factors. In this context, it may therefore be worth mentioning the national spirit for which each of them is known: (a) Canadian 'nice' – that is, treading carefully and trying hard not to upset anyone; (b) Swedish 'jante law' – meaning: do not think that you are better than others and it is best to blend in with the crowd; and (c) Finnish 'sisu' – which entails not giving up under any circumstances – even when faced with extreme adversity. Regardless of whether these national traits have contributed or not, it is a fact that only Posiva has proceeded to the construction licence stage. On that note: Congratulations, Posiva!

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[1] Following the Seaborn Panel report in 1998, the Government of Canada announced that producers and owners of used fuel will be required to form a waste management organization [2]. In 2002, the Canadian Parliament passed the *Nuclear Fuel Waste Act*, which required the waste management organization to study and propose "approaches for the management of nuclear fuel waste" and said approaches included "deep geological disposal in the Canadian Shield"; "storage at nuclear reactor sites"; and "centralized storage, either above or below ground" [9].

9. References

[1] IAEA, "Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management", INFCIRC/546, 24 December 1997.

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